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Commentary

Food safety for food security: Relationship between global megatrends and developments in food safety

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A B S T R A C T

Background: There is an urgent need to drive improvements in the efficiency and effectiveness of food chains. The global population is expected to reach at least 9 billion by the year 2050, requiring up to 70% more food, and demanding food production systems and the food chain to become fully sustainable. This challenge is complicated by a number of overarching issues, including increasing complexity of food supply chains, environmental constraints, a growing aging population and changing patterns of consumer choice and food consumption. Within this context, food safety must be an enabler and not inhibitor of global food security.
Scope and approach: This paper will highlight how recent developments and trends related to food safety will impact the food sector and ultimately the ability of the sector to deliver food security.
Key findings and conclusions: Global megatrends including climate change, a growing and aging population, urbanisation, and increased affluence will create food safety challenges and place new demands on producers, manufacturers, marketers, retailers and regulators. Advances in science and technology such as whole genome sequencing, active packaging, developments in tracing and tracking technologies, information computing technology and big data analysis has the potential to help mitigate the challenges and meet demands, but will also create new challenges. Overcoming a number of these challenges will be difficult for developed economies and large food companies, but even greater for small and medium-sized enterprises (SMEs), developing economies and smallholder farmers, noting that each is a critical component in the global food supply.

1. Introduction

The need to reduce the complexity of and drive improvements in the efficiency and effectiveness of food chains has never been greater. Sustainable nutrition and food security are front and center on the global agenda and key themes within the recently announced United Nations Sustainable Development Goals (UN, 2015). The world will need to feed around 9 billion people by 2050 and to do so through safe sustainable food chains (Godfray et al., 2010). With the global middle class estimated to grow from about 450 million in 2005 to 2.1 billion in 2050, demand for protein-rich foods such as meat and dairy could more than double from current needs (van der Mensbrugghe, Osorio-Rodarte, Burns, & Baffes, 2009).

The global food sector operates in an environment where policies, standards, regulations, guidelines, education and advice relating to food, including those related to the safety of food, are continuously being either developed or updated. Such developments can be either aligned with and be supportive of increased efficiency and effectiveness of food chains, or add to complexity and confusion if they are not globally harmonized and consumers are not better informed about food safety and nutrition.

An anticipated doubling of the global demand for food and

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international trade in food in the next few decades is considered as the most significant factor that will drive an increase in foodborne disease with a high degree of certainty (Quested, Cook, Gorris, & Cole, 2010). A number of other factors will also pose significant challenges to global food safety; including climate change, the emergence of new pathogens and toxicants, an increasing population of at-risk (immunocompromised and aging) consumers and, changing patterns of human consumption as fresh and minimally processed foods are currently preferred by consumers. A number of emerging technologies offer the promise of revolutionizing the way we produce, process and package food. However, public perceptions and safety concerns around the use of emerging food technologies will continue to present a challenge to the food industry and regulators. The magnitude of the changes required along the entire food supply chain to meet these intersecting challenges, has been likened to those which occurred during the 18th- and 19th-century Industrial and Agricultural Revolutions and the 20th-century Green Revolution (Godfray et al., 2010).

As food trade expands throughout the world, food safety has become a shared concern among both developed and developing countries. Aside from the value of life and health, foodborne disease negatively impacts on the economy, trade and industries of affected countries. The costs associated with a foodborne outbreak can be significant and include medical costs, nonmedical costs, productivity losses, costs incurred by the implicated manufacturer and costs incurred by the responding local/provincial/territorial/federal agencies and public health and food safety authorities (Thomas et al., 2015). The implicated manufacturer can also suffer from temporary and sustained negative financial impacts due to product recall and disposal, business interruption and damage to their brand (Shavel, Vanderzeil, & Zheng, 2016). While food security is a matter of equal importance to importing and exporting countries, a number of countries have inferior food safety standards and have not yet established adequate surveillance or reporting mechanisms to identify and track foodborne illnesses. Enforcement of food safety standards and effective surveillance networks at country, regional and global levels are required (WHO, 2015b). In addition, harmonization and equivalence of standard and regulatory frameworks will be critical. These systems also need to be practical and affordable to enable and facilitate more cross-border trade and the integration of smallholder-based agricultural production that will be required for food security. Ultimately, improving food-import safety will strengthen free trade and improve the overall global level of food safety and public health (Zach, Ellin Doyle, Bier, & Czuprynski, 2012).

Aside from the global standardization and enforcement of food safety standards, new analytical and omics technologies hold the promise of improving food safety by facilitating enhanced surveillance. For example, routine, real-time, and widespread application of whole-genome sequencing (WGS) in food safety and public health is on the horizon (Deng, Bakker, & Hendriksen, 2016). However, technological, operational, and policy challenges are still present and need to be addressed by an international and multidisciplinary community of researchers, public health practitioners, and other stakeholders (Deng et al., 2016).

The spread of information and communication technology and global interconnectedness, is also representing a challenge in the communication of food safety issues to consumers. The media's coverage of foodborne outbreaks and chemical contamination has undoubtedly increased awareness, resulting in increased reporting and better diagnosis of foodborne illnesses (Nyachuba, 2010). Public perceptions of the consequences of foodborne illness have also seemingly increased (Callaway & Sheridan, 2015). However, while the World Health Organisation (WHO) has estimated that each year as many as 600 million people in the world fall ill after consuming contaminated food (WHO, 2015b), there is insufficient evidence to support claims that the numbers of actual foodborne illness outbreaks and cases are increasing (Byrd-Bredbenner et al., 2015; Nyachuba, 2010). According to the Centers for Disease Control and Prevention (CDC), the increase in both reported outbreaks and foodborne illness cases in recent years is likely a reflection of enhanced surveillance rather than a true increase in incidence (Gould et al., 2013). Clearly, opportunities exist for food safety communicators to use online communication channels to more effectively engage, inform and educate consumers on food safety issues.

2. Global megatrends and food

In Megachange: The World in 2050 (Franklin & Andrews, 2012), the fundamental trends that are shaping the world are analysed and discussed. One of the key challenges will be global food security as we look to not only produce but also provide access to enough of the right foods to meet the nutritional requirements of the global population.

2.1. Global food security

The global population is expected to reach 9 billion by the year 2050 (Godfray et al., 2010) and a number of pathways have been explored to keep food supply and demand in balance (Keating, Herrero, Carberry, Gardner, & Cole, 2014). In order to meet the increased demand for food associated with the growing human population worldwide, industrial-scale and centralized production systems, including large-scale farming, intensified animal production, and large-scale food processing and distribution, have drastically increased over the past several decades. The fact that these systems are needed in order to meet the demand for food is undisputable. In addition, systems will also need to account for smallholder agriculture given the socioeconomic and nutritional importance of smallholder farming systems in many developing countries, systems will also need to account for smallholder agriculture. However, these systems will be constrained by the Earth's finite resources (Godfray et al., 2010). There is also a need to curb the many negative environmental effects of food production on the environment; including but not limited to, the release of greenhouse gases, environmental pollution due to nutrient run-off, water shortages due to over-extraction, soil degradation and the loss of biodiversity through land conversion or inappropriate management and, ecosystem disruption due to the intensive harvesting of fish and other aquatic foods. It is also now widely recognized that food production systems and the food chain in general must become fully sustainable (Godfray et al., 2010).

Food producers are also facing challenges with the growing complexity of global food supply chains (see Fig. 1) introducing variations in food safety regulations across countries and a lack of uniform requirements from one commodity to another. Also complicating matters is the fact that food safety challenges may differ by region due to differences in income level, diets, local conditions and government infrastructures.

The role of developed countries in assisting developing countries must be clearly defined as an increasing volume of imported food, the increasing percentage of imports from less developed countries, and the complexity of global food supply chains, pose numerous challenges to ensuring the safety of imported foods (Zach et al., 2012, pp. 303–334).

The increasing percentage of imports from less developed countries also poses significant food safety challenges. Practices prevalent within many developing countries include the use of faecal contaminated irrigation water for fruit and vegetable

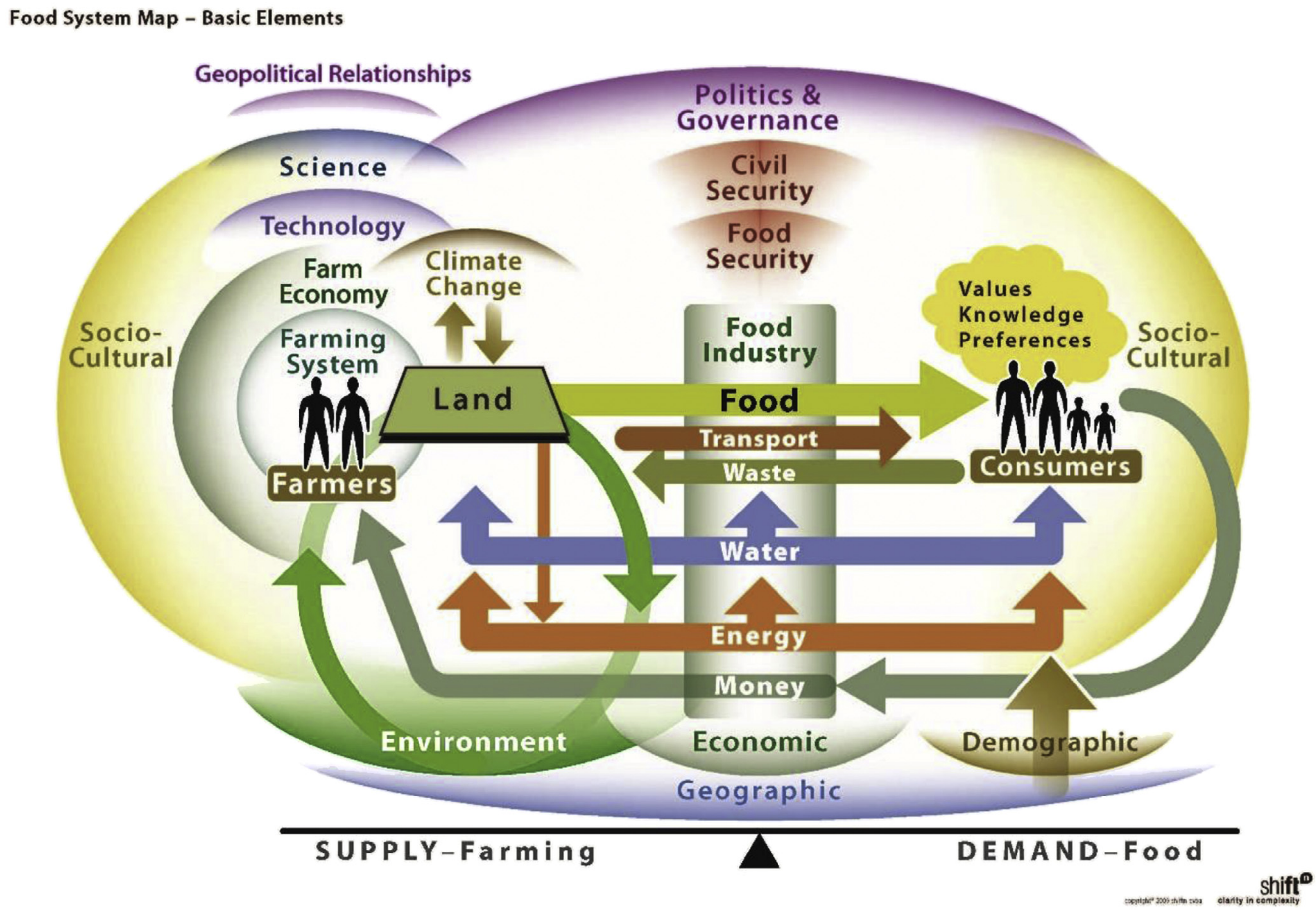

Fig. 1. The global food system.

production, and the use of untreated chicken manure and human faeces in aquaculture production (Doyle et al., 2015). In addition, production and processing establishments in developing countries often lack hygienic controls, various types of cleaning and sanitizing equipment, and quality assurance management systems (Doyle et al., 2015). Lack of documentation or traceability in the exporting country can exacerbate the situation (Zach et al., 2012, pp. 303–334).

2.2. Climate change

Climate change is a current global concern. Climate change may rise with globalization of the food supply with, for example, increased greenhouse gas emissions associated with increased production and food transport (Godfray et al., 2010). While there is continuing controversy about the magnitude of its effects, in general, weather conditions have become more variable with extreme weather events increasing in regularity and intensity (Stewart & Elliott, 2015).

Local climatic conditions influence local vegetation and so, as the climate changes, growing seasons may change and biological consequences will be inevitable with variations in the crops that are cultivated and animals farmed (Stewart & Elliott, 2015). This could lead to changes in plant and animal epidemiology and transformations in entire ecosystems (Stewart & Elliott, 2015). Erratic and extreme changes in climate can also affect the microbiological safety of the food supply by impacting the dispersion of pathogens in the environment and by modifying environmental conditions in which pathogens or their competitors must adapt to survive and/or grow (Baker-Austin et al., 2016; Doyle et al., 2015). Many aspects of food safety and security are in turn likely to be affected by climate change, ranging from spoilage organism prevalence, changes in existing plant and animal pathogen epidemiology, and migration, introduction and invasion of novel pests and diseases (Lennon, 2015; Vezzulli et al., 2016). Climate change will, in particular, affect the introduction of biological or chemical contaminants at the pre-harvest stage of fresh produce production (Uyttendaele, Liu, & Hofstra, 2015). The emergence and re-emergence of pathogens may lead to a greater use of veterinary medicines in livestock management (Kemper, 2008) and consequently an increase in antimicrobial resistance (AMR). Pesticide residues may also increase in plant products due to increasing pest pressure (Uyttendaele et al., 2015). It is also likely that trace element and/or heavy metal contamination may increase due to heavy rainfalls, floods and droughts (Uyttendaele et al., 2015).

To counter the impacts of climate change, political, technical and investment support and incentive measures will be needed to help develop diverse and resilient land use systems to feed the expanding population. New technologies, animal remedies and pest control measures will be needed to combat more invasive and resistant pest species as will assistance to agri-food chains in developing countries to minimise the impact of climate change on food safety. Similarly, more multi-disciplinary research is needed to enhance our understanding of the ecological mechanisms behind, for example, seafood security and safety concerns (Lloret, Rätz, Lleonart, & Demestre, 2016; Tirado, Clarke, Jaykus, McQuatters-Gollop, & Frank, 2010).

Climate change is likely to create new safety issues or exacerbate existing issues to the point where, at least temporarily, we may need to reassess our tolerance to risk and safety limits in order to allow time for our regulatory environments and food chains to cope and adjust. This may entail temporal adjustments to increase tolerable levels of many contaminants (microbial, chemical, and radiation) presently established for the human food chain.

2.3. Mega-cities and mega-regions

Analyses of the evolution of global poverty and demographic patterns looking at the 2050 horizon have highlighted the emergence of what was called a new global middle class in many developing countries and emerging economies (van der Mensbrugghe et al., 2009). The global middle class is estimated to grow from about 450 million in 2005 to 2.1 billion in 2050, corresponding to 8.2–28.4% of the global population (van der Mensbrugghe et al., 2009) and will be accompanied with higher purchasing power, higher consumption and a greater demand for processed food, meat, dairy, and fish, all of which add pressure to the food supply system (Godfray et al., 2010). In addition, there will be a growing demand for convenience and pre-cooked and ready-to-eat meals.

A larger number of middle income consumers and a major increase in the number of people living in cities, could facilitate a higher proportion of the population having access to modern food chains including modern retail systems such as supermarkets and with these, more formalised and regulated food safety. This could improve food safety and decrease foodborne illness. Alternatively, more people living in close proximity could increase foodborne disease in cases where humans can act as a vector, or where microbiologically or chemically contaminated food is distributed widely as a result of large scale manufacturing and distribution.

2.4. Growing aging population

Foodborne illness is known to affect vulnerable populations, including the aged, more severely. With a rapidly aging populace and a growing population of immunocompromised persons, the deleterious impacts of outbreaks are likely to become more significant from a public health perspective. This is particularly concerning, considering current consumer and retailer pressures to develop foods that have no preservatives, lower salt concentrations, are closer to neutral pH and are suitable for 'ambient storage' (Parkin, Shepherd, Hall, & Hill, 2007). One possible solution proposed to address this dilemma, is the design of "extra-safe" food products, such as irradiated, sterilized, or pasteurized foods, that are targeted to higher-risk populations (Doyle et al., 2015). However, a number of innovative technologies entail uncertainties, safety concerns and/or suffer from a lack of consumer acceptance, which must be overcome.

Food manufacturers and marketers will need to become more aware, that a population with increased susceptibility is eating their foods, pay closer attention to how they determine the shelf life of foods, etc. and design foods with built-in hurdles. Effective education campaigns will need to be designed for the higher-risk groups; and hospitals and elderly care facilities should review their menus continually with more emphasis on food safety, and not just on nutrition.

2.5. Digital food and the internet of food

Technological advancements, such as 3D printing of food, may be on the brink of transforming the food industry. In addition, continued global increases in mobile adoption and broadband penetration, have transformed the way we make informed decisions about the foods we consume and have boosted online grocery sales. The Internet purchase of food is likely to grow with increases in urbanisation especially in countries like China where a relatively higher percentage of the population already purchase goods over the Internet. This could improve food safety by enabling food companies with robust food safety systems to have greater reach, but have the opposite effect if systems suffer transportation failures with foods not being held at the right temperatures, or other breakdowns or inadequacies. What is clear is that Internet-based purchase of food will need to be audited to the same standard as 'bricks and mortar'-based systems.

With 3D printing of food, 'everyone' can become a food manufacturer (Pallottino et al., 2016; Sun et al., 2015; Yang, Zhang, & Bhandari, 2017) with the potential to create new combinations of ingredients, at higher than normal water activities, reduced acidity or lower/zero levels of preservatives, or moreover without any risk assessment being undertaken as normally would be the case in the manufacture of such foods. It could be argued that everyone can currently 'cook up' whatever combinations of ingredients using the tools in a conventional home kitchen without any formal risk assessment or training in food safety management. However, unlike conventional cooking that uses millennia of knowledge, recipes, practices and traditions, 3D printing may not rely on such a wealth of knowledge to create safety hurdles. Nor as is the case with other domestically produced foods will formal audit be feasible. Food safety needs to be an important consideration in the uptake of 3D printing for food. Regulatory environments and food safety management systems will need to evolve to take into account advances in digital processing, including such things as personalised nutrition (see following), e-commerce and 3D printing. Whilst empowering consumers, such innovations and technologies have the potential to circumvent established mechanisms of providing consumer protection.

2.6. Rising demand for personalised foods, diets, service and experience

The food industry must focus on innovation to meet consumers' new demands, as they are looking for food products that are highly sensory, healthy, specific to their nutritional needs and are easy to prepare, amongst other things. Rising ethical consumerism is also fuelling the demand for seasonal, locally grown and organic and/or sustainable food products. This represents an increasing challenge for the food industry, as trends become cumulative, in that consumers "want it all". Because of this demand, the convergence between science and medicine, gastronomy and industry is today more necessary than ever.

Personalised diets focus more on the nutritional aspects than on food safety; the use of, for example, different types of microbiomes to try and cure people of certain diseases could create unintended food safety issues, by changing the gut microflora in unexpected ways. A totally empirical approach could be dangerous and more systematic research is needed including the use of nutrigenomics, metabolomics and toxicogenomics. The challenge of delivering personalised nutrition in a personalised manner to the masses will require novel, less heavily processed foods that preserve heat labile nutrients. The equivalency of new less traditional food preservation technologies will require safety to be designed in and based on risk management principles.

3. Emerging food safety issues

3.1. Antibiotic resistance

The rates of antimicrobial resistant bacteria causing serious and life-threatening infections are rapidly rising (WHO, 2014). This development is accelerated by selection pressures from the use and misuse of antimicrobial drugs (Holmes et al., 2016; WHO, 2014). The rapid transmission of resistance genes between bacteria, combined with an increasingly connected world, further accelerates the spread of resistant strains on a global scale (Holmes et al., 2016). The potential for antimicrobial resistant livestock pathogens to pass their resistance onto human pathogens, represents an alarming concern for the treatment of human infections with antibiotics that may already be rendered ineffective. To support the global surveillance of AMR, in May 2015, the WHO set up the Global Antimicrobial Resistance Surveillance System (GLASS) to establish a global standardized approach to the collection, analysis and sharing of data (WHO, 2015a). However, this initiative will not capture and provide insight into the use of antibiotics by all smallhold farmers, who are estimated to account for more than 90% of all farms worldwide (Lowder, Skoet, & Singh, 2014). The preservation of antimicrobial efficacy and appropriate use of key agents and processes in the animal production environment is critical to ensuring we keep pace with the increasing global demand for protein food sources (Shaban, Simon, Trott, Turnidge, & Jordan, 2014).

Due to the widespread problem of antibiotic resistance coupled with the paucity of new antibacterial drugs, a number of alternative methods have been proposed (Cheng et al., 2014; Endersen et al., 2014; Sulakvelidze, 2011). However no 'magic bullet' replacement exists (Allen, Levine, Looft, Bandrick, & Casey, 2013). In order that AMR does not derail food security and severely undermine human disease control, scientists and industry must foster innovation and research in the development of new measures and solutions to avoid the emergence and spread of antibacterial resistance.

3.2. Viruses

Enteric viruses are major contributors to foodborne disease, with norovirus (NoV) and hepatitis A virus (HAV) being the most significant. Globally NoV accounts for the largest number of cases of foodborne disease (Ahmed et al., 2014; WHO, 2015b). While HAV infection attributed to food is in the range of around 5% (FAO/WHO, 2008), HAV is associated with more serious illness.

Viruses survive well in the environment and are much more resistant than bacteria to some of the current procedures used to mitigate bacterial infections during food processing, preservation and storage (Baert, Debevere, & Uyttendaele, 2009; Koopmans & Duizer, 2004; Li, De Keuckelaere, & Uyttendaele, 2015). It is therefore of paramount importance that we gain a better understanding of how a combination of technologies may be used to inactivate foodborne viruses.

Virally contaminated food and water generally display no organoleptic changes. The ability to detect virus particles, which are often present in low numbers in contaminated food, is also hampered by the fact that there are no universal or rapid culture-based methods available for the cultivation of foodborne viruses. In the absence of culture methods, harmonized methods are required for the molecular detection of foodborne viruses; especially for NoV and HAV (Stals, Baert, Van Coillie, & Uyttendaele, 2012).

Most problems with foodborne viruses arise due to contamination of food products during manual handling in combination with subsequent minimal processing of foods (Koopmans & Duizer, 2004). Changes in food processing and consumption patterns that lead to the worldwide availability of minimally processed high-risk foods (Koopmans, von Bonsdorff, Vinjé, de Medici, & Monroe, 2002) and the increasing import of products from HAV-endemic regions to non-endemic countries (Todd & Grieg, 2015), pose a significant issue. It is clear that we need better surveillance of foodborne viruses, especially in ready-to-eat (RTE) foods. However, it is not clear whether routine monitoring of food specimens for viral contamination will be feasible and given the difficulty of excluding food handlers likely to be shedding virus at any one time, infections from foodborne viruses are likely to increase in significance in the future (Carter, 2005). The global expansion of livestock production and encroachment of wildlife habitats by invasive agricultural land use, have also emphasised the need for increased awareness around the potential for emerging zoonotic viruses in food production areas; especially where bats and primates are in contact with humans (FAO, 2011; Locatelli & Peeters, 2012).

A particular viral issue is Avian influenza virus (AIV). Effort must be focused on identifying and understanding situations or drivers where AIV's could potentially mutate into a form that is more zoonotic and/or more easily transmissible from human to human. It is clear that intensive One Health approaches are required to further guarantee farm-to-table food security and to prevent AIV contaminated products from reaching the food chain (Harder, Buda, Hengel, Beer, & Mettenleiter, 2016). While antibiotic use and AMR is a significant issue within the poultry industry (Van Boeckel et al., 2015) and the WHO has focused considerable attention on tackling AMR, a similar level of focus must be given to the surveillance and development of control strategies for AIV.

3.3. Unintentional chemical contamination

Food represents one of the major routes of exposure to a myriad of environmental (natural and/or man-made) chemical substances, many of which are hazardous to humans and wildlife (Bergman, Heindel, Jobling, Kidd, & Zoeller, 2013). These contaminants include, but are not limited to, agrochemicals, environmental/industrial contaminants, processing/storage derived contaminants, contact-material derived contaminants and, biotoxins.

Chemical hazards can contaminate the food supply chain at any point, may be persistent and can bio-accumulate in animals and humans, as well as biomagnify to increasing concentrations in the tissues of organisms at successively higher levels in the food chain. However, acute impact on health is rare and it is well accepted that the largest impact on human health is through low-level repeated exposure. This makes the link between exposure and ill-health very difficult to establish, but there is increasing concern that chemical exposure may play a major role in the etiology of many disorders (Bergman et al., 2013).

Exposure to chemical hazards is rising steadily as global population and pollution are increasing. Other factors such as climate change (see previous) and global food transport (Ng & von Goetz, 2016) also add to the complexity of this problem, as traditional and emerging contaminants are now appearing in regions never seen before (Q. Li et al., 2012; McKinney et al., 2011; Zhu et al., 2013).

3.4. Economically motivated adulteration of food

The intentional adulteration of food for economic benefit is a global phenomenon that has occurred throughout history (Wilson, 2008). High value food products/commodities are exclusively targeted in many economically motivated adulteration (EMA) cases due to the potential financial incentives. Food commodities with long and/or complex supply chains are also particularly vulnerable to EMA (Kennedy, 2008). According to the EMA Incidents Database, fish and seafood are by far the most impacted food category followed by dairy products, and oils and fats (FPDI, 2016). In contrast to unintentional contamination, EMA is often harder to detect and confirm as the motive is always to evade detection and adulterants are often employed that have a high degree of similarity to the product being adulterated.

Although non-toxic adulterants are often used, EMA incidents can have a devastating impact on health. In China in 2008, the intentional adulteration of infant formula with melamine, to raise its nitrogen content and therefore its value, affected an estimated 300,000 people and resulted in the death of 6 infants (Gossner et al., 2009).

The FDA Food Safety Modernization Act (FSMA) contains a final rule aimed at preventing intentional adulteration from acts intended to cause wide-scale harm to public health, including acts of terrorism targeting the food supply (FDA, 2011). However, a global whole-of-system approach with multidisciplinary input from scientists (e.g., testing methods), regulators (e.g., policy frameworks) and industry (e.g., simplification of supply chains), will be required.

3.5. Allergens and intolerances

Food allergies affect approximately 3.5–4.0% of the world's population (Leung, Shu, & Chang, 2014) and are increasing in developed and developing countries (Prescott et al., 2013). The complexity in protection of food-allergic consumers lies in the fact that, unlike bacterial or viral contamination which negatively affects everybody, the presence of allergens is only relevant to a susceptible segment of the population; of which the outcome of consumption could potentially be fatal. Most developed countries mandate labelling of the most common allergenic foods, as well as ingredients derived from those foods in accordance with the 1999 Codex Alimentarius (Codex) guidelines (CodexAlimentarius, 1999). However, more than 170 foods have been identified as potentially allergenic and novel food sources are now being explored in an effort to solve the future food insecurity problem (Houben et al., 2016; Verhoeckx, Broekman, Knulst, & Houben, 2016). Further complicating matters, is the fact that differences in dietary patterns between countries can also lead to differences in allergenicity to specific foods (Lee, Shek, Gerez, Soh, & Van Bever, 2008). There are also significant differences between countries as to what allergens are required to be disclosed and how this is communicated to the consumer (K. J. Allen et al., 2014). In addition, uncertainty over the risk posed to allergic individuals by even minute residual traces of allergen has prompted many food manufacturers to provide advice as to the potential for unintentional contamination with allergens during manufacture in the form of precautionary allergen labelling (PAL). However, in the vast majority of countries, the use of PAL is not regulated by legislation and a formal risk assessment is not performed (K. J. Allen et al., 2014). To this end, the VITAL (Voluntary Incidental Trace Allergen Labelling) Program of the Allergen Bureau of Australia & New Zealand (ABA), was created to provide a standardized allergen risk assessment process for the food industry. However, the global nature of food production and manufacturing makes harmonization of allergen regulations across the world a matter of critical importance. A framework has recently been proposed that allows categorisation and prioritisation of allergenic foods according to their public health importance, with the hope that it can be adopted by regulators (Houben et al., 2016).

3.6. Nanotechnology

Nanotechnology is still in its infancy with regards to research and development, but has the potential to penetrate every aspect of food production (for a Review see (Hannon, Kerry, Cruz-Romero, Morris, & Cummins, 2015)). To date, the application of engineered nanoparticles (ENPs) in the food industry has mainly centred on novel food packaging materials and there are a number of commercial products currently available (Bumbudsanpharoke & Ko, 2015; Hannon et al., 2015). However, due to a lack of specific regulations and harmonization in the nanotechnology area, it is difficult to approximate its overall use worldwide (Coles & Frewer, 2013).

Public concern exists around the use of ENPs in the food chain, due to the immense uncertainty which surrounds the potential for ENP migration from food contact materials (FCMs) and their associated health risks. Wide diversity exists in the current status of regulations and legislation on nanomaterials in food packaging by country (Bumbudsanpharoke & Ko, 2015). There must be international cooperation in the pursuit of nano-safety, since nanoparticles may well be difficult to detect in imported packaged goods (Bumbudsanpharoke & Ko, 2015). As the opportunities for the use of nanoparticles in the food production industry are infinite, more research in this space is warranted through a combined effort of food regulators, authorities and industry at a local and global scale.

3.7. Genome editing

Current applications of genome editing include some with immense potential impact on the security of the world food supply. Genome editing via technologies such as transcription activator-like effector nucleases (TALENs) and clustered regularly interspaced short palindromic repeat (CRISPR)/Cas systems (e.g., Cas9), allow directed modification of specific DNA sequences at their normal chromosomal locations; including changes as small as a single base pair or as dramatic as a large deletion (Carroll & Charo, 2015; Selle & Barrangou, 2015). The animal and plant products of these modifications are essentially identical to ones that could occur naturally or could be created by traditional breeding methods (Carroll & Charo, 2015). In terms of agriculture, this might win over public and regulator opinion (Ainsworth, 2015). In particular, CRISPR-based applications have the potential to revolutionize the whole area of food science (Selle & Barrangou, 2015).

While genome editing may not represent a food safety issue as such, however, it is certainly an issue that food safety regulators are grappling with. An emerging challenge for regulators is to accommodate new biotechnologies such as genome editing that do not fall neatly into the definitions of genetic modification laid down in existing legislations (Jones, 2015). In most regions of the world, it still remains unclear how or whether this fledgling technology will be regulated (Jones, 2015). This lack of consistency risks stifling innovation, exacerbating already difficult international trade issues and more importantly, undermining consumer confidence in both the risk assessment process and the safety of the biotechnology products (Jones, 2015). In addition, it might be difficult to overcome a fundamental resistance to intentional genetic manipulation. However, transparency of use and accuracy of outcomes may pave the way for sensible policies for their regulation and use (Editorial, 2016). Effective risk communication efforts out to the public related to the whole area of whole genome editing is definitely needed.

4. The current global regulatory environment

Legislation and regulation relating to food safety and trade has evolved as production systems have matured and international trade has become more widespread. Historically, legislation has been developed at a national level, resulting in differences between jurisdictions. Global food trade has grown to an excess of US$520 billion per year, bringing new challenges to global food safety regulation (MacDonald et al., 2015). Harmonization of regulations and equivalence of standards are major challenges in the global food safety regulatory environment. A global approach to food safety and security is necessary to ensure that differing standards do not present barriers to trade. At a global level, emphasis must be placed on a move towards outcome-based risk management rather than prescriptive food standards.

Global food supply chains add additional complexity for countries when assessing food safety. Traditionally, many countries have relied on the border inspection of imported foods for safety because they have no jurisdiction over process controls in exporting countries. However, end product testing does not assure food safety and greater assurance of safety can be achieved with hazard and risk-based through chain approaches. However, demonstrating equivalence of through chain approaches of some countries to food safety standards and criteria of other, often less developed, countries still provides many challenges internationally and may provide barriers to free trade. The use of ranking models to compare the food safety performance of different countries may help to clarify this, by focusing on overall performance rather than the specifics of the food safety approaches used by one country relative to another (Charlebois, Sterling, Haratifar, & Naing, 2014).

Globalization of food supply chains has also required improvements and innovations to traceability measures to secure food chains and identify safety failures in their integrity, with many countries implementing legislative requirements on robust through chain traceability. The CAC directions set out a one-step forward, one-step back approach: i.e., the previous source where the ingredient/food was obtained/purchased and where the next destination in the supply chain is. This legislation has been adopted by the EU in Regulation EC No. 178/2002 (EU, 2002), as well as many other jurisdictions including the US FDA (CFR Title 21) and Food Safety Australia New Zealand (Standard 3.2.2). This approach, however, can be slow and cumbersome and the repercussions can be severe in a food safety breakdown/crisis (Codex, 2006). To facilitate a more timely response, industry members may adopt an approach of greater visibility throughout the supply chain, by tracing back/tracking forward further than one step.

Data (see Big Data) can be used to perform informative risk assessments which can proactively refine and optimise food safety and legislation, rather than being reactive. One of the most notable efforts to address this was the FDA's FSMA (FDA, 2011), which aims to ensure that preventative measures are implemented by the food industry across the entire food chain based on robust science and risk assessment (Doyle et al., 2015). This strategy acknowledges that currently production and technologies do not allow production of food with no risk of contamination and so a quantitative microbial risk assessment approach is optimal to direct legislation and food safety interventions (Buchanan & Appel, 2010; Doyle et al., 2015).

Free Trade Agreements (FTAs) are common in global import and export markets, and facilitate increased trade between participating countries. An important component of FTAs is the negotiated regulatory requirements. The Transatlantic Trade and Investment Partnership (TTIP) aims to develop closer relationships between US and EU regulators to examine the implications of existing regulations on trade, and develop or harmonize these where required to foster increased trade (EU, 2016). This can be complicated by differing stances on food safety requirements. An example of this is the current legal requirements for *Listeria monocytogenes* levels in food. While the US has imposed a zero-tolerance rule, the EU allows a limit of 100 colony forming units per gram or millilitre of food product in those foods that cannot support growth or where the level will not exceed 100 cfu/g at the point of consumption (EU, 2005; FDA, 2003). Such examples represent challenges for both legislators and food producers to define and meet regulatory requirements.

In addition to differences in national regulatory requirements, the retail sector may have additional food safety criteria which must be satisfied by food producers wishing to supply them.

4.1. Private standards

Private food safety standards are generally set by private firms and standard setting coalitions, which contractually impose compliance with their standard to their suppliers. Private food safety standards are increasingly monitored and enforced through third party certification and may pertain to characteristics of the products themselves, or to process and production methods. The main drivers for the proliferation of these private food safety schemes have been: the clear assignment of legal responsibility to food chain operators for ensuring food safety; increasingly global and complex supply chains; and, increasing consumer awareness of food, health and food safety (FAO, 2010). In addition, private standards-setting bodies can move much faster than Codex to address new issues and establish new or revised standards (FAO/WHO, 2009). As global food retailers and processors become increasingly more concentrated, the implementation of private food standards will become even more widespread (FAO, 2010). The fierce competition that exists between products using standardization schemes, and the fact that those schemes have become a factor of differentiation between products, may lead to a standard becoming dominant on the market (Wouters, Marx, & Hachez, 2009). This has raised questions about the role of public and private institutions in establishing and enforcing food safety norms. One of the key criticisms of private food safety standards is that they can undermine the process of harmonization, introducing a new layer of governance that further fragments national markets (Henson, 2007). These requirements may provide barriers to trade and to this end, the Global Food Safety Initiative (GFSI) was developed with the view to standardizing these requirements and promoting increased trade and improved food safety (Crandall et al., 2012). Private standards also frequently go beyond the requirements of public standards by setting a higher standard for particular food product attributes, increasing the scope of activities regulated by the standard and, being more specific and prescriptive about how to achieve the outcomes defined by standards (FAO/WHO, 2009). In addition, it is alleged that private standards are often not based on scientifically backed risk assessments (WTO, 2007, p. 4). The costs of processes of compliance and conformity assessment also tend to be pushed down from standards adopters and towards their suppliers, notably developing country exporters and producers (FAO/WHO, 2009). Financial difficulties and a lack of expertise to comply with the requirement of the standard, can contribute to the marginalisation of weaker economic players including small and poor countries, small and medium-sized enterprises (SMEs) and, smallholder farmers (Webb, 2015). The ability of these smaller players to demonstrate equivalence of alternative food safety management measures could contribute to overcoming the challenges posed by overly prescriptive private standards (FAO, 2010). Overall, the adoption of private standards should not be encouraged unless they deliver genuine improvements over existing public standards. In order for big retailers to prove the benefits of the standards they are demanding of their suppliers, they must work with organisations such as the Food and Agriculture Organisation (FAO), the WHO, the World Organisation for Animal Health (OIE) and Codex. Better co-ordination and alignment is also required between organisations such as the GFSI, the Global Harmonization Initiative (GHI) and Codex.

5. Advances in food safety & technology

5.1. Whole-genome sequencing

WGS is the process of determining the complete DNA sequence of an organism's genome at a single time. WGS technology has the potential to play a significant role in the area of food safety and security (FAO, 2016). The global use of WGS technology across food, veterinary and human health sectors, would facilitate sharing and collaboration and lead to a significant increase in the availability of contextual data when interpreting results and recommending regulatory actions with scientific basis (FAO, 2016). WGS will enable the quick and accurate identification, mitigation and prevention of food safety problems and will translate into reduced economic losses and food waste, both of which are important contributors to food security (FAO, 2016). The GenomeTrakr network (FDA, 2017), which is the first distributed network of laboratories to utilize whole genome sequencing for pathogen identification, has already made significant impact by sequencing more than 113,000 isolates and closing more than 175 genomes to date (8/6/2017).

The genomic information WGS provides can also be used by industry as a tool for monitoring ingredient supplies, the effectiveness of preventive and sanitary controls, to develop new rapid methods and culture-independent tests as well as the broad-range detection of many pathogens (not only bacteria) in a single test; to determine and control the persistence of pathogens in the environment; to monitor emerging pathogens; and as a possible indicator of antimicrobial resistance. This will be of great benefit to industry, for example, WGS can allow industry to trace contamination within a food company back to an individual faulty process or piece of equipment. Data-mining of sequencing data will also enable more effective control of foodborne pathogens, by providing insight into the biology, ecology, transmission, evolution, emergence and control of new pathogens. WGS will also enable a deeper understanding of the changes and physiological shifts associated with the onset of food spoilage. This will enable the identification of microbial communities which inhibit the growth of spoilage microorganisms, the use of bacteriophages to control spoilage organisms, or the design of rapid assays or biosensors to detect the growth of spoilage organisms before they become a problem.

The transformative potential as well as existing bottlenecks in applying WGS in public health microbiology are well documented (FAO, 2016). For WGS to be implemented successfully, significant investment would be required in terms of equipment, application tools, competence building and method standardization. The political, legal and psychological obstacles to free data sharing must also be removed. Most importantly, there must be clarity on the regulatory response when suspect WGS profiles are found during foodborne illness investigations. In addition, the general public will need to be made aware that WGS technologies are enabling an enhanced surveillance system and that the food safety system has not likely failed.

5.2. Metagenomics

Metagenomics is defined as the culture-independent analysis of genomes contained within an environmental sample. Metagenomic tools offer the opportunity to enhance our understanding of complex, diverse and dynamic microbial communities in foods and food-associated environments (for a Review see (Bergholz, Moreno Switt, & Wiedmann, 2014)). The ability of next-generation sequencing to generate large amounts of DNA sequence data has considerably facilitated metagenomics studies. Broad-range 16S rDNA PCR assays, that target highly conserved nucleotide sequences that are shared by all bacterial species, can also be designed to assist with metagenomics studies (Oikonomou, Machado, Santisteban, Schukken, & Bicalho, 2012). One of the most promising applications of metagenomics is the ability to detect and identify previously unknown pathogens in food matrices and food-associated environments. The CDC estimates that around 80% of foodborne disease cases in the U.S. are caused by unspecified agents (Scallan, Griffin, Angulo, Tauxe, & Hoekstra, 2011), indicating that a better foodborne disease surveillance system is required to address the current knowledge gap concerning unknown and unidentified foodborne agents (Aw, Wengert, & Rose, 2016). In a shotgun metagenomic sequencing study by Aw et al. (2016), rotaviruses and picobirnaviruses were identified for the first time in both field-harvest and retail lettuce samples, suggesting a potential emerging foodborne transmission threat that has not yet been recognized (Aw et al., 2016). The adoption and widespread use of WGS technologies will undoubtedly reveal the presence of previously unforeseen food safety hazards. Questions remain as to how the food industry and regulatory bodies will act on these new findings, especially as the use of metagenomics tools for the detection of foodborne pathogens still faces several challenges (Bergholz et al., 2014; Stasiewicz, den Bakker, & Wiedmann, 2015).

5.3. Transcriptomics and proteomics

With the aim of developing rational control strategies for foodborne pathogens in the food supply, there is a need to determine the physiological state of pathogens when present on foods and in the food production environment (for a Review see (Bergholz et al., 2014)). Transcriptomic and/or proteomic studies have been undertaken to characterise the response of various foodborne pathogens during adaptation and growth on specific food matrices (for example, (Liu & Ream, 2008; Tang et al., 2015)) and to obtain mechanistic information into how microbes respond to different food processing treatments (for example, (Chueca, Pagán, & García-Gonzalo, 2015)). This information can shed light on how synergy works at a mechanistic level with hurdle technologies (Bergholz et al., 2014). In addition, biomarkers related to specific resistance characteristics of a pathogen can be identified and integrated into mathematical models to predict microbial behaviour, with the potential to improve control measures (Bergholz et al., 2014).

Insights from these studies could also pave the way for developing better detection methods (e.g., methods targeting highly expressed RNA molecules) and provide for improved risk assessments that account for the fact that the virulence of a given pathogen may be affected considerably by its physiological state (Tang et al., 2015). Therefore, companies and food regulatory agencies will be tasked with determining how best to use the information generated to tailor their processing and preservation processes used in-house.

5.4. Chemical risk assessment and safety evaluations

Safety assessment of food constituents and/or contaminants not only requires the evaluation of a hazard potentially exerted by a specific compound, but also needs to take into account the level of exposure to the consumer. By definition, a hazard in food means a biological, chemical, or physical agent present in food that may have an adverse health effect. The term also encompasses an inherent property of an agent or situation having the potential to cause adverse effects. By contrast, the term risk describes the probability of an adverse effect and its magnitude in an exposed system or (sub)population (Eisenbrand, 2015). Under emergency situations, when immediate estimates of potential health concern are required, a hazard-based approach can be of value. Hazard-based approaches also may apply to agents exerting potent non-threshold effects, such as certain strong genotoxic carcinogens. A hazard-based element also is intrinsic to the so-called threshold of toxicological concern (TTC) concept, which provides a generic approach to the safety assessment of chemicals with no or insufficient toxicological data (Barlow, 2005). The concept provides guidance about deriving acceptable risks by defining toxicologically insignificant exposures according to hazard and chemical structure (Cramer, Ford, & Hall, 1976; Kroes et al., 2004; Munro, Renwick, & Danielewska-Nikiel, 2008). The European Food Safety Authority (EFSA) and WHO recently embarked on a project to review the current approach and proposed some modifications (EFSA/WHO, 2015).

In general, for food safety assessments, risk based approaches are adequate, based on reliable exposure estimates, taking into account uncertainties in exposure assessment. Of equal importance is the elucidation and appropriate consideration of the mode of action (MOA), which needs to be put into perspective with an appropriate estimate of consumer exposure.

5.5. Advances in chemical analytical testing

The ability to accurately determine the concentration of a particular contaminant in a food matrix is critical for the evaluation of potential risk to the consumer. As a result, innovative analytical approaches are continuously being developed as a response to the ever growing number of contaminants already present in food or emerging risks threatening to enter the food supply chain. The main pursuit of many analytical approaches revolves around obtaining a higher sensitivity for difficult-to-detect contaminants and, a reduction in cost and analysis time per sample. Advances in the development of mass spectrometers have led to an increased capacity to accurately determine; quantitatively and qualitatively, numerous analytes with different physicochemical characteristics, simultaneously (for example, (Hird, Lau, Schuhmacher, & Krska, 2014; Wang, Wang, & Cai, 2013)). 'Dilute-and-shoot' quantitative multi-residue assays that target hundreds of analytes in one run with minimal sample preparation are now the rule rather than the exception (for example, (Stahnke, Kittlaus, Kempe, & Alder, 2012)). High-resolution mass spectrometers (e.g., Orbitrap, Time-of-flight) have enabled the identification and confirmation of previously unknown toxicants, and their metabolites in foods/biological fluids, with higher confidence (for example, (Knolhoff & Croley, 2016; Senyuva, Gökmen, & Sarikaya, 2015)). In addition, there have also been many advances in microbial testing (e.g., mass spectrometry is now commonly used for ID, etc.). While continuous progress in analytical specificity and sensitivity has made accessible the determination of just a couple of molecules in a given environmental matrix, this alone does not necessarily support dependable exposure assessment. In addition to reliable metrics relating to the amount of an agent present in food or other consumer items, its bioavailability from the matrix as well as duration, magnitude and frequency of exposure are major determinants of the knowledge needed for a risk assessment.

5.6. Advances in chemical hazard characterization

The continuing progress in genomics, transcriptomics, proteomics, and metabolomics in combination with novel tools in bioinformatics and system biology has brought about promising new avenues toward improved toxic hazards characterization and this is expected to be further developed in the years to come. While whole animal toxicity studies remain the centrepiece of current regulatory frameworks, animal welfare concerns, high cost, and questions around the ability to accurately predict *in-vivo* tissue functions in humans have fuelled interest in alternative approaches. For example, current alternative techniques in development include microfluidic organs-on-chips (Bhatia & Ingber, 2014), 'omics' techniques (e.g., transcriptomic fingerprinting of appropriate cell cultures) (Pielaat et al., 2013) and computational estimation methods for predicting acute and chronic systemic toxicity (Lapenna, Gatnik, & Worth, 2010).

The determination of suitable biomarkers in human/animal biological fluids (e.g., serum, plasma, urine, breast milk and others) or in tissue biopsies has also allowed for more accurate population exposure estimates for hazardous contaminants. It requires detailed knowledge of the metabolism of the respective compound to focus on specific metabolites as quantitative exposure indicators (Eisenbrand, 2015). An example is provided by the considerable database already available of human exposure estimates for the genotoxic carcinogen acrylamide (AA), based in part on biomarkers of exposure (EFSA, 2015). Uncertainties associated with the assessment of consumer exposure to AA were recently addressed in detail (EFSA, 2015) and research needs have been identified for the development and validation of biomarkers as adequate metrics for aggregate consumer exposure to genotoxic agents.

The DNA damage induced by such agents has been recognized as a valuable alternative exposure metric. Today, DNA adducts are amenable to specific determination at levels of about 1 adducted DNA base in 100 million DNA bases and this has allowed real-time measurement of DNA damage in humans. This methodology is being continuously refined, allowing for simultaneous detection of multiple DNA adducts (Monien et al., 2015). A new development in monitoring DNA adducts of known and unknown identity, termed "adductomics" (Balbo, Hecht, Upadhyaya, & Villalta, 2014), has enabled reliable dosimetry at low levels of consumer exposure (Eisenbrand, 2015). Appreciation of the substantial background of DNA damage in human tissues, consistently induced by endogenous genotoxic agents generated during normal metabolism, means that future risk assessments of exposure to genotoxic agents may evaluate the incremental contribution of a given exogenous exposure to the endogenous background DNA damage. This will provide a data based approach to risk assessment (bottom-up) in contrast to mathematical extrapolation over several orders of magnitude, from the dose range accessible by animal experiments down to consumers exposure (top down) (Lu, Gul, Upton, Moeller, & Swenberg, 2012; Swenberg et al., 2011; Watzek et al., 2012).

5.7. Processing and packaging

Thermal processing is the primary method for food pasteurization and sterilization. However, the application of heat impairs food quality. Food manufacturers are therefore continuously challenged by consumer expectations for products that are pathogen-free and minimally processed, in a globalised food market where supply chains are getting longer. Novel non- or mildly-thermal techniques, offer new possibilities for innovation to meet consumer drivers (Awad, Moharram, Shaltout, Asker, & Youssef, 2012; Barbosa-Cánovas & Altunakar, 2006; Farkas, 1998; Heinrich, Zunabovic, Bergmair, Kneifel, & Jäger, 2015; Ibarz, Garvín, & Falguera, 2015; Niemira, 2012; Turantaş, Kılıç, & Kılıç, 2015; C.-Y.; Wang, Huang, Hsu, & Yang, 2016). However, recent food preservation, processing or packaging technologies and trends, in spite of their benefits (mild treatment, extended product shelf-life, "fresher" quality, RTE pre-cooked convenience), also bring potential safety risks to the consumer level: incomplete microbial inactivation, possibly not respecting proper storage conditions and expiration dates, undercooking, and generation of stress-resistant microorganisms (Cheftel, 2011). Consequently, there is a risk that the effects of foodborne illnesses on the economy may increase, unless interventions can reduce the incidence of these illnesses. This emphasizes the need to develop and implement novel food processing and preservation methods to improve food safety throughout the food chain. As regulatory agencies move towards outcome-based regulations, it will become increasingly necessary for the food industry to have a variety of inactivation technologies at their disposal.

However, consumer acceptance is crucial to the development of successful food products. Not all technologies are equally accepted by consumers. For example, there are hardly any negative discussions about high-pressure processing (HPP) of food (Hurtado et al., 2015), while food irradiation is considered highly controversial (Siegrist, Keller, & Kiers, 2006). Consumers may not only have difficulties in assessing risks associated with novel food technologies, but the benefits of such technologies may also not be obvious (Siegrist, 2008). It is very important, therefore, that the public be informed and educated about possible benefits of novel food technologies so that they are more likely to accept it (Siegrist, 2008). In addition, in marketing the benefits of new alternative technologies, it will be important to ensure that the value of existing technologies are not undermined, along with food safety.

The food-packaging industry has also been challenged with respect to maintaining safety and quality, as traditional passive-barrier packaging systems have reached their limit with regards to further shelf life extension of packaged food (Mahalik, 2014; Siró, 2012, pp. 23–48). To provide such extension and to improve the quality, safety and integrity of the packaged food, innovative active and smart packaging concepts have been developed (for a review see (Siró, 2012, pp. 23–48)).

5.8. Big data

The response to foodborne disease outbreaks is complicated by the globalization of our food supply chains. The creation of a big data culture in the food industry could facilitate considerable advancements in global food safety, food quality and sustainability (Strawn et al., 2015). Big data represents high volume, high velocity, high veracity, and/or high variety information assets that require new forms of processing to enable enhanced decision-making, insight discovery and process optimization (Wiedmann, 2015). Most uses of large datasets and big data analytics in food safety and quality to date focus on providing improved root cause and retrospective analyses, but development and use of predictive analytics in food safety is likely to grow quickly in the near future (Wiedmann, 2015). As already discussed, one of the most mature examples of the use of large datasets in food safety is the use of WGS-based subtyping of foodborne pathogens by both public health and regulatory agencies to allow for better outbreak detection and source attribution. Similarly, word searches on Internet engines and online discussion sites and analysis of sales data may provide near real-time information on disease outbreaks, aiding in rapid initiation of product recalls and other consumer safety actions (Harris et al., 2014; Harrison et al., 2014). Integration of diverse data sources may not only allow for improved and accelerated root cause analysis, but this information could be used to adjust food safety and operational practices in near real-time to include additional barriers and controls. For example, the rapid public release of full sequencing data by public health and regulatory agencies means that industry can compare subtype data for isolates from processing facilities. For large companies, that are well resourced and have the capability and potential, the ability to quickly and reliably track the source of contamination from sourced ingredients would be of tremendous benefit. Subtype information in combination with other data, for example data automatically captured through recording devices in food processing environments (e.g., temperature data for refrigerated storage) and employment data (e.g., identifying the individuals that perform sanitation tasks), could also prove to be an innovative and effective way to enhance regulatory compliance and track compliance with desired standards. Geographic information system (GIS)-based datasets have also been used to predict and manage the spatial and temporal occurrence of foodborne pathogen contamination in produce production environments (Strawn et al., 2013).

The possibilities for big data to facilitate improved approaches to food safety and food quality are endless. However, rather than merely collecting increasingly large datasets and hoping that something materialises, it is essential for industry to critically evaluate its needs and high impact areas and define specific questions and issues (Wiedmann, 2015). Contributing to the challenge, is the fact that there are few trained data scientists who are also familiar with food systems type issues (or food systems scientists who can work with large datasets). It is unlikely that SMEs will be able to afford to train staff in this area. However, digital companies are getting involved in big data analytics and forming partnerships with large food companies to try and improve food safety and quality. There is a definite and important need for the industry to take action to prepare to take advantage of big-data tools and solutions for food safety and quality dilemmas. Data integration and ownership will be some of the most important challenges that the food industry will need to address. Big data processing and consequent outcomes will need to be shared amongst producers, retailers, health authorities and regulators.

5.9. Predictive microbiology, systematic reviews and meta-analyses

Predictive microbiology involves knowledge of microbial growth responses to environmental factors summarized as equations or mathematical models (TA McMeekin et al., 1997). Predictive microbiology has demonstrated a broad utility within the food industry and can aid in quantitative risk assessment and decision-making during Hazard Analysis for Critical Control Point (HACCP) planning, estimation of the shelf-life of foods and in the design or reformulation of food products. Predictive microbiology holds immense value for industry and government, for example, in challenge studies with *Listeria* and the determination of whether new food formulations support or inhibit growth of the pathogen. In addition, industry can benefit from obtaining an estimation of the kinetics of heat inactivation of an organism of interest within a specific food product. While many models have been developed and published, independent and industry-based trials are still required for validation. Transfer of the knowledge of predictive microbiology into real world food manufacturing applications will continue to rise with the development of open, community driven and web-based predictive microbial model repositories (Plaza-Rodríguez et al., 2015). The integration of omics data into mechanistic predictive models also holds the promise of providing more accurate predictions under specific physical and chemical changes and extending the model outside the range of space bounded by observations (Brul, Mensonides, Hellingwerf, & de Mattos, 2008; McMeekin, Olley, Ratkowsky, Corkrey, & Ross, 2013; Perez-Rodriguez & Valero, 2013). The use of systematic reviews in various aspects of food safety is also increasing (Aiassa et al., 2015). Systematic reviews will help industry and government, for example, to determine which interventions work and are most appropriate for adoption. A deeper understanding of supply chain risks, will also benefit the development of through-chain risk management strategies. With an enhanced knowledge of food safety risks and intervention strategies, the question remains as to how this information will be used, whether new regulatory requirements will be imposed and the subsequent consequences for the food industry.

5.10. Traceability tools and the supply chain

An increase in global trade of food items, has led to a heightened need to be able to trace affected products internationally and domestically when there is an incidence of foodborne illness or animal or plant disease. Traceback is essential during the initial stages of an outbreak, to quickly identify the potential source of the outbreak. Timely identification of the source of the outbreak can result in the outbreak being stopped in its tracks. This results in smaller outbreaks, a reduction in spoiled food due to the rapid identification of the right food involved in the outbreak, prevention of future outbreaks due to the ability to trace a problem back to a herd or a farm and, an enhanced ability to quickly implement measures to identify and eliminate the problem at its source. Many developed countries have implemented new legal requirements for traceability, and exporting countries are under pressure to comply with the regulations set up by importing countries. Charlebois et al. (2014) examined existing global food traceability regulations in 21 major OECD countries and found that none of the countries had an electronic tracking system for all commodities (Charlebois et al., 2014), highlighting the need for more advanced traceability systems for other domestic and imported products.

A number of technological advancements have shown promise in providing new opportunities for enhancing traceability systems. Current advancements in RFID technology and the incorporation of data logger capabilities and integrated sensors, has provided a new dimension to the application of RFID technology in the food traceability systems (Costa et al., 2013). Stable isotope analysis has emerged as a powerful tool for tracing the geographical origin of agro food products (Badia-Melis, Mishra, & Ruiz-García, 2015). Synergistic use of instrumental analytical techniques and chemometrics modelling represents a promising way for the development of authenticity and traceability models (Badia-Melis et al., 2015). An integrated high-throughput DNA sequencing and metabolomics approach would likely permit the determination of all the putative food-related pathogens within a foodstuff, as well as the presence of specific toxins, metabolites, antibiotics and pesticides, etc. (Ferri et al., 2015). Future advances in this area will determine to what extent this type of approach will be universally adopted.

Despite technological advancements, the design, implementation, and maintenance of a traceability system is often decentralized, and therefore self-interested parties need to be motivated to commit (Dai, Ge, & Zhou, 2015). In addition, while many food producers often have good electronic traceability systems internally, exchange of information between the links in the supply chain is very time-consuming or difficult due to the diversity and proprietary nature of the respective internal systems (Storøy, Thakur, & Olsen, 2013). There are new trends in traceability in the food sector focused on improving the processes (Badia-Melis et al., 2015). However, similar to above, cost is the overarching issue in the implementation of these systems. As traceability systems become more widespread, consumer preference for these products may side-line some smaller producers who are financially unable to deploy these technologies. Similarly, developments in regulatory requirements around traceability may also lead to some producers being excluded from the marketplace.

While the speed of information exchange has enhanced modern information management to enable traceability, so has the speed at which information about a food safety issue can spread. Consumers will demand transparency and rapid traceability, especially around perceived 'long and distant' food chains. It remains to be seen what future regulatory requirements and consumer expectations will be for the food industry, around accessing and responding to traceability data. However, it is likely that expectations around the rapidity of response will move from days to hours.

5.11. The role of traditional and social media in the public perception of food safety

Globalization has not only resulted in the ability of foodborne hazards to be transported and spread quickly, but the globalization of news (e.g., TV, Internet) has resulted in the ability for news to spread quickly and cause unfavourable economic consequences for producers. The media is widely reported as amplifying and misrepresenting the risk posed by food incidents, diminishing trust in the food supply (Henderson et al., 2014). The rush to publish and the strategies adopted for the construction of a 'newsworthy' story, may result in food issues not being fully researched prior to publication/transmission and the overstatement of the level of risk posed (Henderson et al., 2014). Therefore, the media may contribute to public anxiety about food risk and may be a poor source of food risk information (Henderson et al., 2014). As new technologies emerge to aid delivery of a safe, nutritious and sustainable food supply, news sources must be aware of the potential for generating or contributing to societal concern. For example, if more foodborne outbreaks and illnesses are detected because of an enhanced surveillance system through the adoption and implementation of WGS technologies, it will be important that information sources carefully communicate to the general public that the risk has not changed, it was there all the time and only our ability to detect and better quantify the risk has changed, i.e., they are at no more risk today than they were yesterday.

Social media can be an asset to food safety risk communicators, and a hindrance as well (Chapman, Raymond, & Powell, 2014). Social media can change the discourse on food safety very quickly and online discussion of risk may lead to a social amplification of risk perception, wherein risks assessed by technical experts as relatively minor elicit strong public concerns (Chapman et al., 2014). Misinformation and false assertions may be easily disseminated via social media with or without malicious intent and be widely believed (Chapman et al., 2014). Of particular concern is the significant and expanding role of "influencers"; individuals (often with no background in food safety or food science) communicating about food safety issues through online social media and significantly influencing public perceptions of food safety. The challenge for influencers in online social media is to be conscientious about providing balanced, complete, and accurate food-related information to consumers (Byrd-Bredbenner et al., 2015). This may be easier said than done. Care needs to be taken, as the public may avoid certain foods which are not risky and eat other foods that are of a high risk, especially in high-risk households. For example, the public may avoid irradiated foods because of public perception; even though it is likely a safer product. In contrast, consumers may drink raw milk and unpasteurized juice because of the public perception that these are healthier foods.

The benefits of social media for food safety risk communicators include speed, accessibility and interactive capacity when raising awareness about an issue or during crisis communications (Chapman et al., 2014). Minimal research has been carried out on how best to use social media to communicate to the public about food risks and benefits (Rutsaert et al., 2014). Given that this is arguably one of the more critical aspects of creating a robust food safety environment, undertaking research in this area represents a huge opportunity. The reserved attitude towards social media witnessed amongst official bodies in the area of food risk/benefit communication may result from a lack of evidence-based guidelines advising officials on how to most effectively incorporate social media (Rutsaert et al., 2014). This is also likely to be the case for food safety professionals within the food industry. While the need for effective communication with the public via social media may arise from the contamination of foods, there are many additional opportunities for providing information related to food handling, preparation and consumption (Byrd-Bredbenner et al., 2015). Accurate and transparent communication about the application of specific agricultural practices or food processing technologies which have the potential to generate societal concern, could also help to win over public opinion and aid implementation of practices and technologies that enhance our ability to deliver global food security. Overall, it will be important for food safety professionals to be proactive in creating and maintaining social media channels and means of disseminating food safety information in a targeted manner to seek discussion and educate the media and consumers.

6. Conclusions

Without food safety, we cannot have food security and achievement of the Sustainable Development Goals. Availability of food has in the past and will remain pivotal to the development of human society. A reliable and adequate supply of healthy and safe foods not only means freedom from hunger. Relieving individuals, families and populations from laborious daily food procurement has been the major catalyst for individual and societal development and education in ancestral societies. Food security in fact may be seen as a prerequisite for societal development. In the foreseeable future the world will need to feed over 9 billion people, requiring substantially increased efforts towards dependable, safe and sustainable food production. Food safety systems will need to accommodate the needs of developed and developing economies with increased attention and support for food chains involving smallholder producers.

Technological development needs to cope with the great challenges posed by an anticipated doubling of the global demand for food and international trade in the next few decades. On a global scale, inadequate techniques of food production, storage, processing and distribution today pose the most substantial risks to food security and food safety. Significant challenges to global food security and safety encompass climate change, the emergence of new pathogens or unintentionally present food contaminants and other potential hazards, including those associated with consumer demand for minimally processed 'natural' foods, online ordering/3D printing of food and also adulteration and fraud. There is a need to develop new adaptation strategies to address climate change and its sequelae for food security and safety and to invest in *trans*-disciplinary research to enhance our understanding of the underlying ecological mechanisms of organisms and the environment.

The emergence of a growing global middle class in developing countries is accompanied by changing patterns in global consumption, with an increasing number of better nourished individuals shifting from basic staple consumption to more processed, ready for consumption/convenient food items. The ever increasing number of global megacities and megaregions may also increase the risk of foodborne outbreaks and illness by microbiological or chemical hazards. By the same token, the rapid aging of the population is associated with enhanced risk of age-related health deficiencies including a compromised immune system. Aging populations will be more susceptible to health hazards, especially when in suboptimal nutritional status. Food manufacturers and marketers need to pay closer attention to how they design and supply foods with the necessary built-in hurdles to aging populations.

Technological development has to adapt to future societal requirements of food security, safety and sustainability, at all levels of the food chain. For food safety, one of the most significant technological leaps will be achieved through WGS. The genomic information WGS provides will be used extensively, not only to rapidly determine sources and scopes of outbreaks, but also to speed up trace-back investigations. It is hoped that the creation of a central database for foodborne pathogens, accessible and supported by health authorities worldwide, will enable faster detection and targeted control of outbreaks globally. As an industry tool, WGS will be useful for monitoring ingredient supplies, effectiveness of preventive and sanitary controls, to develop rapid testing methodology, monitor emerging pathogens and to become an indicator for antimicrobial resistance. WGS is expected to become the major tool in detection of outbreaks at an earlier stage, when the number of outbreak-associated cases is still small. The great challenge is to build a global system to facilitate disease detection and surveillance and for food producers, manufactures, distributors and retailers to find practical and cost effective ways to incorporate WGS into food safety management systems.

Assessment of exposure is pivotal for health risk evaluation and is increasingly based on methodology of extreme specificity and sensitivity. Continuous progress in analytical specificity and sensitivity has made accessible the detection of just a couple of molecules in a given environmental matrix, but this alone does not necessarily support dependable exposure assessment, because in addition to reliable metrics relating to the amount of an agent present in food or other consumer items, its bioavailability from the matrix as well as duration, magnitude and frequency of exposures are major determinants of the knowledge needed for risk assessment. Significant progress has been made toward monitoring of exposure biomarkers in humans, reflecting aggregate exposure from all routes. Novel techniques, such as metabolomics, enable us to picture the totality of metabolites, the metabolome, in a given body fluid or compartment. This will allow the collection of comprehensive analytical information about specific food intakes and their biological impact.

We need to close the gap between consumer response and regulatory developments relating to food safety. The former can literally happen at the speed of light via the Internet, whilst the latter is glacial in comparison, especially the development of internationally harmonized food safety standards which can take years. A big challenge arises from consumer understanding, both of food safety risks and/or perception of novel/emerging processing technologies which could reduce food safety risks. In a world where societal discussion, often focusing on merely perceived health risks, is spread globally almost instantaneously, it becomes indispensable to provide consumers and other stakeholders with impartial, dependable, and strictly science-based information about risks and benefits. There is an urgent need for intensified communication and improved dissemination of timely consumer-relevant information, covering all aspects of the food chain, to create confidence within the stakeholder network, inviting media early on to get informed, and making increased use of appropriate social media channels. At a generic level, consumers (and the media) need to understand the difference between hazard and risk when it comes to food safety. Efforts should also be intensified to create more harmonized and equivalent food safety standards and regulations; and mechanisms to do this more quickly than is currently the case.

The same urgency should be allotted to the necessity to build a global data sharing system for food, regulatory and health authorities worldwide, providing real-time open access for all official institutions in charge of food safety. This should in the long run bring about a harmonized global platform of food safety surveillance and establish a common accountability system of safety control and management. Big data mining and processing and its outcomes with respect to food safety need to be shared by regulators, health authorities, producers, distributors/retailers and the inherent problems of data integration and ownership need to be addressed nationally and globally. These and other information and communications technology (ICT)-enabled developments should facilitate major improvements in food safety and food safety management and better connectivity with consumers. In contrast, developments in ICT could reduce the impact of formal food safety advice, with consumers instead relying on online information sources from non-experts, i.e., 'wiki'.

Developments in the way the world addresses all aspects of food safety covered in this paper, including the communication and connection with consumers, will either enable or derail global food security. This is due to the fact that food security is reliant on providing access to sufficient amounts of affordable safe food and the fact that the food safety related issues covered in this paper create complexity and inefficiencies in the food supply that are likely to limit our ability to provide this food affordably. To sustainably produce enough food to provide food security for 9 billion people, significant improvements will be required in the efficiency and effectiveness of food chains. Harmonization and equivalence of standard and regulatory frameworks will be critical. But in a world where information can travel at the speed of light, finding ways to better engage with, educate and inform consumers via social networks and other channels will be just as important. Overcoming all the challenges associated with global megatrends and food safety developments will be difficult enough for developed economies, mature supply chains and large food companies, but even greater for SMEs, developing economies and smallholder farmers, noting each will remain a critical component in the global food supply. Nevertheless, the global food community needs to find innovative ways to overcome these challenges. While it is tempting to prioritize the order of importance in addressing these challenges, this task is complicated by the fact that influence may be exerted by additional and often unpredictable factors; including political and social factors. A flexible and responsive approach will be needed to adequately address the food challenges of the future.

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