The Consumer Goods FORUM

GFSi

GFSI Science Technology Advisory Group Report - 2022

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Welcome to the Global Food Safety Initiative's (GFSI) Science and Technology Advisory Group (STAG) report.

Why does GFSI need a Science and Technology Advisory Team?

The GFSI vision of **"safe food for people everywhere"** is already at the heart of many businesses and organisations. Food retailers and manufacturers, suppliers, the agriculture industry, academics, governments, and many others across the world have signed up to the **GFSI Race to the Top framework**, which proposes an enhancement in the oversight of the GFSI ecosystem to improve **trust, transparency and confidence** in the GFSI-recognised certification and audit outcomes.

Additionally, GFSI seeks to stay true to its core purpose as a benchmarking and harmonisation organisation responsible for the 'what' – not the 'how' – of food safety.

Critical to this vision and the Race to the Top framework is to have the right science and technical guidance. The STAG was introduced to GFSI in March 2021 as part of a series of collaborative enhancements to the GFSI governance and operations and will assume the critical responsibility to provide an **expert** and **independent outlook** on any science and technology developments that may impact GFSI's food safety activities.

Indeed, new technologies and advances in science promise exciting new capabilities and opportunities; however, many of these developments may present their own risks and challenges.

What is the role of the STAG?

The mission of the STAG is **to provide the essential insight and foresight to enable the in-depth and high-quality review of science and technology trends using independent experts to create relevant, actionable, and timely recommendations.**

With the help of its own and external experts (whether individuals or networks), the STAG will provide GFSI and its members with the essential **objective and independent** analysis of those trends and developments, enabling GFSI to be prepared and help to **define a sustainable future for food safety**.

How does the STAG work?

The newly formed STAG has been refining its remit and ways of working. Diagram 1 illustrates the STAG "process", identifying its Inputs, Guides, Outputs and Enablers. All of these elements must be in place to achieve the necessary outputs.

As well, we must recognise that the world is changing at an incredible pace: challenges to the food supply that we haven't experienced in recent generations abound, as evidenced by the COVID-19 pandemic, recent geopolitical events, and, of course, the existential pressure of climate change. Our current operating environment is far from stable and we wanted to ensure that the STAG can respond and be sufficiently agile to meet its stakeholder needs. Our ambition is to move to the operating model shown in Diagram 2 using the STAG to catalyse working groups composed of subject matter experts and looking to report at a frequency and in a way that is both impactful and relevant.

Diagram 1:
STAG - Inputs, Guides, Outputs & Enablers

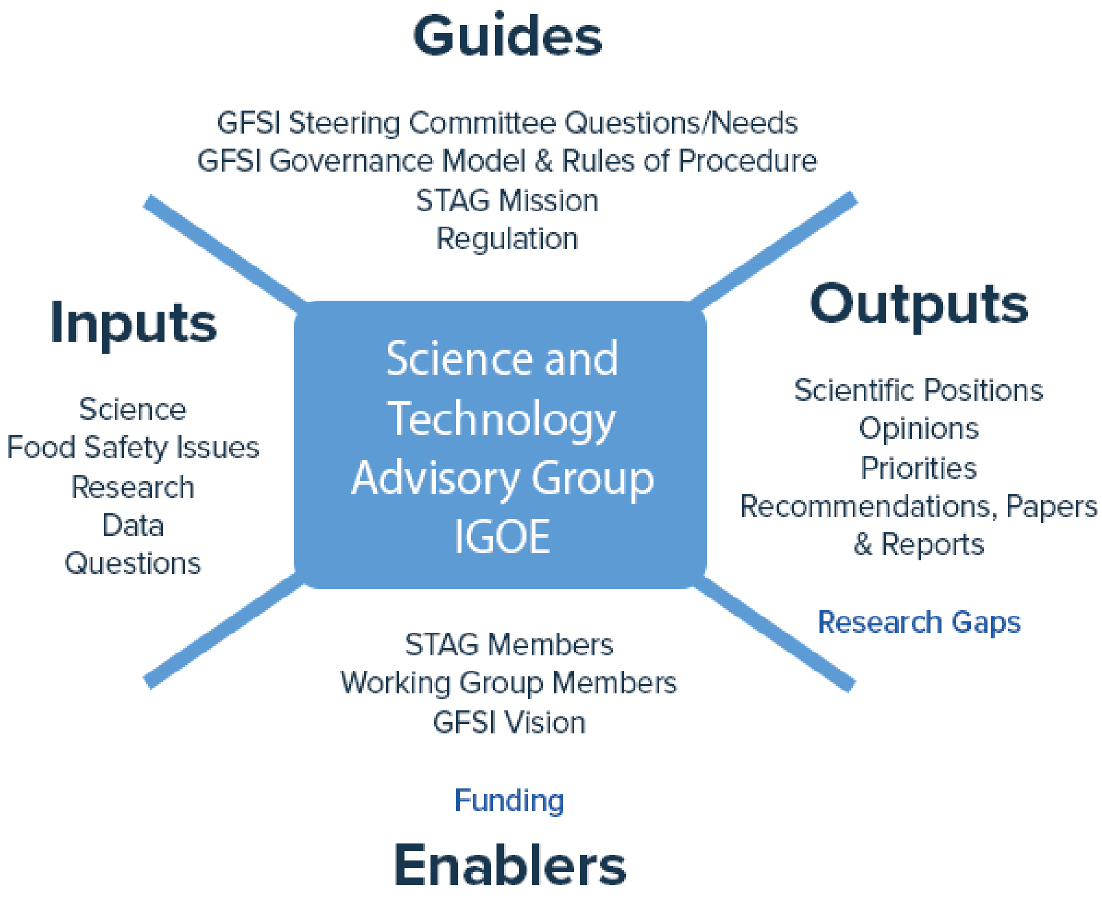
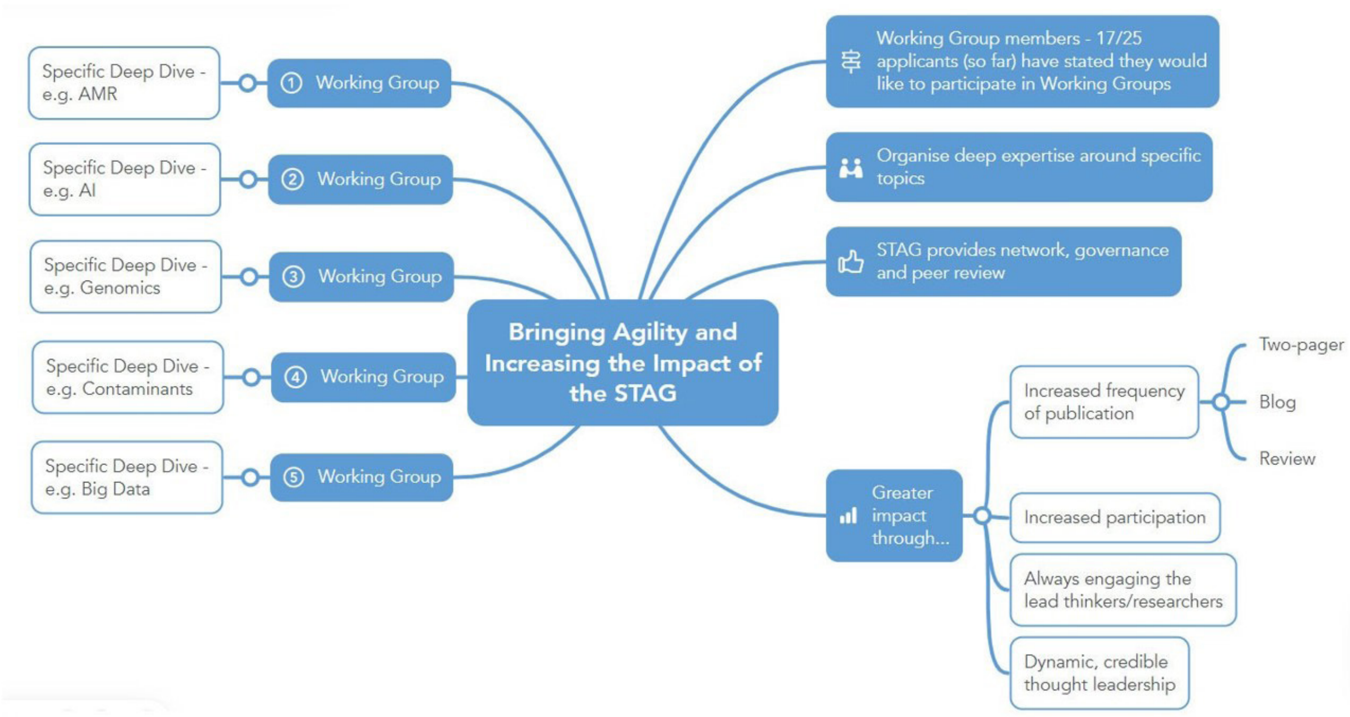


Diagram 2:
GFSI STAG - Working Model Relevance & Agility



What has the STAG delivered so far?

This report is the first STAG output and covers four topics:

1. Big Data in Food Safety – Jeffrey Farber
2. The role of the Microbiome in Food Safety – Kaye Burgess
3. Emerging Foodborne Pathogens – Francisco Diez-Gonzalez
4. Food System Resilience: Impacts on Food Safety – Robert Scharff

The STAG identified these areas as likely having a significant impact on food safety. A lead author has written each paper with input and assessment from the other team members. Before publishing, they have been formally reviewed by a different independent group.

These papers are not exhaustive reviews but rather an overview or introduction into these crucial areas of science and technology, allowing the food professional to understand why these areas are important, their scope and likely impact. We hope to follow this initial work by forming working groups to "deep dive" into these topics and produce more detailed outputs. Further subjects are being discussed and other papers are being written.

Who is in the STAG?

The STAG members are:

- Kaye Burgess, Senior Research Officer and Principal Investigator, Teagasc Food Research Centre – Food Safety Department, Ireland
- Francisco Diez-Gonzalez, Professor and Director, Center for Food Safety, University of Georgia, USA;
- Jeffrey Farber, Adjunct Professor in the Department of Food Science at the University of Guelph, Ontario, Canada
- Lise Korsten, co-Director of the DSI/NRF Centre of Excellence Food Security, University of Pretoria, South Africa
- Robert Scharff, Professor and Consumer Sciences Graduate Studies Chair, Ohio State University, USA.
- Dr Yunbo Luo, Director of the Special Food Research Center and Professor and Member of the Academic Committee of the College of Food Science and Nutritional Engineering at China Agricultural University (CAU), China.

I want to thank the team for their hard work and excellent contribution so far, and I know I speak for all the team when I say that we are very much looking forward to our future work and contributions.

Dave Crean
Chair, GFSI STAG

Big Data in Food Safety

I. Background – why should we be interested in this topic?

There are many different definitions of "Big Data", but broadly it refers to large volumes of different types of data. The applications of big data are numerous and in the food safety area, big data can be, and often is, collected along all steps of the food supply chain, i.e., from farm to fork or boat to throat.

There are a number of areas in which big data is having or will have a huge impact on food safety as well as other aspects in food systems. Some of the types of big data include whole genome sequencing, metagenomics, metabarcoding, sensors, online food safety databases/data sources, predictive analytics, social media and e-commerce data on the Internet, as well as data being collected all along the food supply chain, such as at the farm, processing and retail levels. In terms of the beneficial outcomes being observed from analysing and using big data, we continue to see advances being made in: i) food traceability; ii) weather data and predictions for best harvest times; iii) in-situ verification during manufacture, e.g., CIP, environmental monitoring, in-pack sensors to monitor attributes in real-time during manufacture or transport; iv) digital pest management; v) source attribution; vi) better detection and control of foodborne illness outbreaks; vii) understanding host-pathogen interactions; viii) reductions in food spoilage and ix) the detection of food fraud.

The application of big data technologies in food safety control is well placed to have a tremendous impact and to drive continuous improvements in the food industry, now and into the future. Big data technologies can improve and link the sustainability, safety and quality aspects of food – starting from achieving better quality, preventing food waste and ensuring safety, to nourishing a growing world population.

II. What do we know today?

Many of the areas in the food supply chain where big data is being collected are already having a positive impact on food safety. The following include some salient examples of what we currently know.

Blockchain

With the growth in international food trade, and the growing interest in driving continuous improvement in areas such as food recalls, food safety, food security, authenticity, sustainability, and consumer trust, comes an urgent need for a new cutting-edge technology. Blockchain is one promising technology that can help to achieve progress in many of these areas. It in fact makes the food industry more transparent at all levels, by storing data immutably and enabling quick product tracing across all areas of the food supply chain. Blockchain creates a highly transparent environment so that the need for trust is theoretically completely removed. Retailers and large food processors are currently experimenting with and using blockchain to improve the traceability of their products. Case studies examining the latter usage with many different products, have found that blockchain-based traceability can provide cost-savings, improved security, greater compliance with government regulations and reduced response time to food incidents and foodborne outbreaks.

With regards to the latter, **the origin of a foodborne outbreak can now be determined much more quickly**. In 2006, it took almost two weeks for health officials in the US to identify the source of an *E. coli* outbreak linked to contaminated spinach (https://www.cdc.gov/ecoli/2006/spinach-10-2006.html). This wasted time, energy, and resources of the entire food supply chain, led to significant and lasting economic harm to spinach farmers and to an erosion of consumer trust in the food supply chain.

The increasing use of big data technologies such as blockchain will enable investigators to rapidly track and trace the source of contaminated product involved in recalls or human illnesses.

Dynamic Risk Management

Big data can be used for dynamic risk management (DRMS) in food safety control. For example, scientists have described how a DRMS system, having food safety-relevant data from different points in the value chain, could be used in real-time to identify hazards and control Shiga toxin-producing *E. coli* in leafy greens (Donaghy et al., 2020).

Furthermore, much progress has been made in the area of predictive analytics and the tools available to assess, e.g. recalls, outbreaks, border rejections and RASSF alerts, in order to predict peaks of hazard findings. A number of companies are active in the space of producing dashboards for early warning systems, as well as risk profiling of suppliers.

Global Supply Chains

Supply chain disruptions can lead to delays in shipping/transport, which can increase the incidence of spoilage - big data could be used to prioritise shipments subject to spoilage. For example, import inspections could use supply chain information to prioritise inspections. In situ sensors during transport (freight or truck) are regularly used as alerts for corrective action by haulers/drivers, helping to prevent food waste, spoilage or safety issues.

Next-Generation Sequencing-Based Platforms

1. WGS

Scientists can now analyse and compare thousands of complete genomic sequences of bacterial pathogens. There are many examples of how one can use WGS to accurately link a foodborne outbreak to a suspect food, even if the outbreak occurred in the past (Brown et al., 2019; Koutsoumanis et al., 2019, Li et al., 2021). This enormous amount of big genomic data gathered from performing WGS can allow scientists to gain a better understanding of important information on foodborne pathogens such as i) virulence traits; ii) host-pathogen interactions; and iii) antimicrobial resistance factors.

In addition, food safety regulators are now routinely using big data in their enforcement activities. As examples:

1. US FDA inspectors will perform large scale environmental swabbing for L. monocytogenes in a food operation, referred to as a swabathon, as part of a routine inspection, for some reason after an inspection, or as part of an epidemiological investigation
2. European regulators are conducting extensive environmental sampling for root cause analysis
3. Government participation in programmes such as GenomeTrakr (https://www.fda.gov/food/whole-genome-sequencing-wgs-program/genometrakr-network), and PulseNet (https://pulsenetinternational.org/), with the sequences and metadata being collected by NCBI and other agencies. The GenomeTrakr data can be accessed by researchers and public health officials for real-time comparison and analysis that can help to speed up foodborne illness outbreak investigations and reduce foodborne illnesses and deaths. With regards to the latter programme, a recent FDA study found that in relation to the financial benefits of the GenomeTrakr Whole Genome Sequencing Network, by 2019, the programme was already estimated at providing nearly $500 million in annual health benefits, compared to an approximately $22 million investment by public health agencies (Brown et al., 2021).

2. Metagenomics

The potential of metagenomic-based methodology approaches such as culture-independent diagnostic testing (CIDT), shotgun and long-read metagenomics as well as metabarcoding is enormous, and can lead to, among other things, the ability to directly identify entire microbial communities in environmental samples, foods and food ingredients (Forbes et al, 2017; Billington et al., in press).

Shotgun metagenomics has already been successfully used for the detection of foodborne pathogens such as pathogenic E. coli in fermented milk, Shiga toxin-producing *E. coli* in spinach and *L. monocytogenes* in outbreak-associated ice cream samples (Koutsoumanis et al., 2019). In addition, it has been shown that quasimetagenomic sequencing can be a valuable hybrid surveillance tool for the food industry that can lead to the faster identification of foodborne pathogens such as *L. monocytogenes* (Wagner et al., 2021).

Metagenomics can also be used to help with the detection of foodborne outbreaks of unknown causes and/or caused by non-culturable, (e.g., viable but non-culturable cells), difficult to grow bacterial pathogens. It can also help in cases where there is a mixed infection, for example, two different bacteria or one bacteria and one virus in the same food causing the illnesses (Koutsoumanis et al., 2019).

3. Microbiome

Big data can be used to reduce food spoilage. For example, companies are using the “big data” inherent in examining and cataloguing the microbiome of food products they produce, e.g., if a batch of cheese spoils too quickly or unexpectedly, they can then compare the microbiome of the spoiled cheese with the unspoiled cheese, to try and prevent such spoilage from occurring again.

Sensor Technology

The appropriate collection and use of big data such as indicators and sensors along the whole food chain can help everyone in the food chain access real-time information on a product’s quality. This can help tremendously to inform decision-making and thus, for example to reduce food spoilage and improve the speed of food recalls.

Furthermore, by characterising the presence of foodborne pathogens such as *Listeria monocytogenes* on farm fields and combining this with meteorological and environmental data, researchers have been able to predict the presence of *L. monocytogenes* on farm fields (Strawn et al., 2013; Weller et al., 2016).

Social Media

Big data can be used to help predict the occurrence of a foodborne outbreak or stop it in its tracks. A number of studies have shown that although they do differ in significance, correlations do exist between Twitter, Google search scores, Yelp data and foodborne outbreak cases. Machine-learning methods such as artificial neural networks have also shown promising results (Tao et al., 2021). As research in this area continues to grow, we will be able to develop lessons-learned and recommendations for improving public health by using big data from social media to enable early warning and mitigation of foodborne outbreaks.

Smartphones and Handheld Devices

Big data can be used **at the retail level to improve food safety**. One major retailer uses handheld information technology, Bluetooth communication, and state-of-the-art temperature measuring devices to check the internal temperatures of every batch of rotisserie chickens cooked, ensuring a safe internal temperature, and thus reducing the occurrence of foodborne illness linked to poultry. A study done in Canada used smartphones to examine the food safety behaviour of vendors at farmers' markets (Young et al., 2020). In addition, the use of retail store cards and swipe payment methods are being used to alert consumers about recalls.

III. What are the key gaps in our knowledge?

Some of the key gaps or issues that still need to be resolved to take full advantage of the "Big Data" revolution include:

1. data ownership/privacy, interoperability, especially between suppliers, manufacturers and retails, global accessibility and completeness of the data being collected;
2. identifying relevant data within a data source and linking it to other data sources;
3. the need for big data standardisation, e.g., nomenclature, reporting, in the food supply chain;
4. understanding that it can be very difficult for LMICs to adopt some of the newer big data technologies; for example, on its own WGS technology has little value in improving public health – an existing surveillance system and outbreak response network is needed;
5. challenges in using AI/machine-learning to solve food safety problems including the need for efficient real-time data collecting, quickly and meaningfully unravelling massive or complex data and the automation of decision-making without human intervention;
6. vgenomic methods (e.g., WGS pipelines) are not standardised and neither is the interpretation of results; and
7. issues surrounding the lack of harmonised methods, the apparent low sensitivity of detection, and the choice of bioinformatics pipelines when using metagenomics for routine diagnosis and surveillance.

IV. What is the potential impact on the food supply and food businesses?

The potential impacts on the food supply and food businesses are enormous. These include, among other things:

1. being able to understand precisely why your food is spoiling;
2. examining the microflora in the plant environment and in the foods you produce to improve shelf-life;
3. tracking how a pathogen got into your plant and how it is being transferred from one location to another;
4. tracking where an ingredient/ lot of food in your store/establishment came from;
5. having better assessments of risks related to food/commodities based on origin, harvest, transport, etc.
6. making sure that it is not your product that is involved in a foodborne outbreak; alternatively, if it is your product, identifying the contaminated lot quickly to reduce the size and scope of any resulting recalls.
7. authenticating your products, and
8. using social media for the early warning and mitigation of foodborne recalls and/or outbreaks.

Issues that companies need to be thinking about as well are the key skills gaps, e.g., in the area of bioinformatics and what access do companies have to big data. In addition, thought needs to be given to whether the labs providing sequencing and data interpretation are qualified to do so.

V. What should businesses be doing/thinking?

- Food businesses need to be **cognizant of how big data can help in their drive for continuous improvement, and what the limitations and gaps are**. The use of big data will not always lead to significant improvements right away or down the line.
- **Middle to large-size businesses need to have personnel who can recognise when and where it makes sense for the company to collect, store, analyse and visualise big data.**
- Food businesses should have mechanisms in place to be able to take decisions based on outputs from data analytics, i.e., collating data with nice dashboards needs to bring added value to the company, e.g., early warning, root cause analyses of incidents, supplier risk profiling, manufacturing reaction, etc.
- Governments and businesses in LMICs need to try and keep pace with all the emerging big data technologies and educate some of their key staff, and/or use any available funding through UN agencies to hire experts to "train the trainers". They also need to understand what applications are most likely to be useful in the LMIC context.
- **The increased sharing of data globally and between agencies is creating a much more interconnected regulatory system.** Thus, we now have better tools to monitor the flow of pathogens through supply chains globally, and better than ever attribution of point source outbreaks.
- One of the key questions is **do businesses understand the strategic impact of big data on their operations and do they have an appropriate talent strategy for these changes?**

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The Role of the Microbiome in Food Safety

I. Background

Microorganisms, including human pathogens, exist and adapt to survive in a wide range of environments and are present throughout the food chain from primary production to the consumers' plates. The composition of the microbial community present in an environment, along with its activity, will vary in different ecological niches depending on the conditions. Enabled by advances in sequencing technologies and associated bioinformatics analysis tools, there has been an increasing interest in understanding the composition and role of the microbiome in different environments, ranging from extreme environments, to foods, to the human gut microbiome.

There has been considerable debate about the definition of microbiomes, with a recent review on the topic leading to an updated definition (Berg et al, 2020). The ***microbiota*** is usually defined as the assemblage of living microorganisms present in a defined environment (Marchesi and Ravel, 2015). The ***microbiome*** however is more complex, in that the host and the environment are both integral ecological components of the microbiome. In a paper focusing on the application of the food microbiome for authentication, safety and process management, the microbiome is defined as the ecological community of commensal microorganisms that exist within any environmental sample (Weimar et al, 2016). Berg and colleagues defined the microbiome as 'a characteristic microbial community occupying a reasonable well-defined habitat which has distinct physio-chemical properties. The microbiome as envisioned by Berg et al. (2020) not only refers to the microorganisms involved but also encompasses their "theatre of activity", which results in the formation of specific ecological niches. This term, theatre of activity, includes microbial structures, metabolites, mobile genetic elements such as transposons, phages, and viruses, and relic DNA embedded in the environmental conditions of the habitat. (Berg et al, 2020).

This definition demonstrates the complexity in terms of addressing questions such as 'who's there?', 'what can they do?' and 'what are they doing?'. Nonetheless, such questions are crucial in the context of food microbiology and more particularly for providing food quality and safety assurance. Whilst conventional culture-based analysis is still the gold standard for pathogen detection, it has limitations, due to the time it takes and due to the lack of culturing options for all microorganisms in a given habitat. Culture independent approaches, facilitated by advances in high throughput sequencing (HTS) technologies have greatly enhanced our ability to truly understand the microbiome composition and function in different environments and products, and more recently, how it may be manipulated or utilised to our advantage.

II. What do we know today?

Advances in HTS technology have very quickly led to the widespread uptake of whole genome sequencing of individual pathogens by regulatory authorities for outbreak investigations. The large number of genomes now available is an important resource that can be used to identify the geographic origin and food source of a pathogen as part of an outbreak. Databases such as GenomeTrackr in the USA now contain data for over 750,000 isolates. Sequencing and analysis of microbiomes is more complex than that of individual isolates. Cao and colleagues (2017) reviewed the advances in sequencing technologies and their potential uses in providing a deeper understanding of food related microbiomes. Recent years have seen an increased focus on microbiome-based research for use by the food industry and new start-up businesses in a broad range of applications. There follows by no means an exhaustive list but it provides a brief overview of some of the potential applications of microbiome analysis in a food safety context.

The baseline monitoring of the microbiome of raw ingredients can reveal changes that may be an indicator of an ingredient's quality or safety. Examples of the applications of metagenomic analysis of foods are included in a recent review by Sabater et al (2021). Many varied factors can influence a product's microbiome throughout the production and retail chain, as reviewed recently for poultry meat (Marmion et al. 2021). Looking at some specific examples, a US study examined the microbiome of retail chicken breast from four processing sites and found that the poultry breast microbiome displayed consistency over time and distinctiveness between the individual processing environments. They identified that packaging type and processing environment, but not antibiotic usage and seasonality, affected the composition and diversity of the microbiomes. Another recently published study focused on using metagenomic sequencing to analyse the microbiome of high protein powders from poultry meal collected over 18 months from two suppliers (Beck et al, 2021). In this study it was shown that a shift in the food matrix composition was associated with an observable shift in the product microbiome. An analysis of a number of these such research studies however indicates that more benchmarking is needed in food microbiome studies for pathogen detection, as culture-based methods in general result in much fewer positive results (isolations), compared to strictly genomic testing.

The built environment (BE) harbours diverse microbial populations including viruses, bacteria, fungi, and protozoa, which collectively constitute the microbiomes of the built environment (MoBE). The MoBE differs considerably in BE with different functionalities, including food processing facilities (Li et al, 2021). The microbial communities present in food processing environments can influence food quality and safety, as the bacteria in these microbiomes can colonise surfaces, providing the opportunity for microorganisms present to be transferred to the food product during and/or after production or processing. Food companies have robust cleaning and disinfection regimes in place, but these do not remove all microorganisms present. A recent review on the use of HTS sequencing in mapping the environmental microbiome in food manufacturing demonstrated the wide array of sectors where the technology has been applied, but it also points out that currently its application in routine practice can be challenging and that technical issues still remain (De Filippis et al, 2021).

Most food based HTS studies have focused on the monitoring of microbial populations during food fermentations. Kamilari and colleagues (2019) reviewed the use of HTS technologies for a range of different uses within cheese production. These include identification of the cheese microbiome components, their diversity, the temporal distribution of microorganisms during ripening and factors influencing the cheese microbiome formation and composition. However, the authors also outline the technology's potential usefulness for supporting products' Protected Designation of Origin (PDO) status and demonstrate authenticity, acting as an additional tool in food fraud prevention. Food safety, however, was the main focus of a recent study on the microbiome of Gouda cheese which included the use of *Listeria monocytogenes* contaminated raw milk to produce the cheese to examine the impact of the presence of a foodborne pathogen on the product's microbiome (Salazar et al, 2021).

As well as having the potential to be used for pathogen detection, environmental and process monitoring and product quality prediction, microbiome analysis provides the opportunity to also rapidly assess food products and processing environments for other traits of public health significance, such as the presence of antimicrobial resistance genes. There has been increasing focus on the role food production plays in the transmission of antimicrobial resistance determinants, but quantitative data for many commodities, particularly foods of non-animal origin, remains scarce. Metagenomic sequencing facilitates the identification of such determinants using several curated resistance gene databases. Recent studies, such as the studies by Li and colleagues (2020) and by Alexa et al (2020), have demonstrated the capacity of the methodology to define the resistance genes present on the product or within the production environment. Determining the clinical relevance of this remains challenging, as does determining the mobility of such resistance genes. Commonly used short read sequencing technologies are of somewhat limited utility when considering mobile genetic elements, which commonly encode antimicrobial resistance genes, but the advances in longer read technology are helping to address this. HTS can also play a role in understanding chemical safety concerns in the food chain, such as the impact of mycotoxins on the human and animal gut microbiome (Jin et al, 2021).

III. What are the key gaps in our knowledge or challenges we face?

- It is widely acknowledged that while there are multiple applications of food microbiome analysis, including in the context of food safety, many challenges are yet to be overcome.
- The microbial community interactions in a given environment influence pathogen survival. Understanding and finding ways to modulate those interactions would provide a significant advancement in providing food safety assurance. Indeed, it has been envisioned that in the future, advances in engineering of environmental microbiomes will have the potential to replace chemicals in agriculture, horticulture, and aquaculture, and stimulate a more sustainable use of environmental resources, as well as improving food processing (Berg et al, 2020). Such studies are in their infancy however, and need improved databases, integration of methodologies and appropriate analytical tools to come to fruition.
- Variation in results can arise from the use of different extraction methods, sequencing platforms, databases, and bioinformatics tools (Yap et al, 2021). Even the swab used to collect samples can also influence results (De Filippis et al, 2021). The databases used to identify the taxonomy of species present in a sample, or the functional annotation of the genes are as good as the quality of the inputs. As more and more data are submitted, the databases will become more accurate and useful. In such a scenario, the benefits of data sharing in a harmonised way become rapidly apparent. From a food industry perspective, however, this is not without its challenges, particularly in relation to commercial sensitivity. Notwithstanding this, there is an urgent need for the standardisation of methodologies, data analysis pipelines and curation of data repositories to ensure that the potential of food microbiome research for food safety and other applications can be realised.
- The issue of cell viability is crucial, particularly in relation to pathogen detection. Many microbiome-based studies focus on DNA, but the presence of DNA does not guarantee the presence of a viable organism from which it derived. The use of RNA provides a closer approximation, but is more challenging to work with. Other approaches such as coupling DNA extraction with the use of dyes such as propidium monoazide are also currently being investigated to address viability.
- In order to use food and environment microbiome analysis effectively, food industries need standard operating procedures (SOPs) for each element of the workflow from swabbing through to analysis. As noted by de Filippis et al (2021), the procedures will need to be versatile to reflect different processing environments and foods. Extracting sufficient DNA from processing environments can also be a challenge, as observed by McHugh and colleagues (2021).
- The utilisation and outputs from many metagenomics analysis tools remains complex. To incorporate effectively those outputs in a company's food safety management system, it will be necessary to translate the outputs into easy to interpret and quantifiable results to support rapid responses.

IV. What is the potential impact on the food supply and food businesses?

Food business operators are required to produce safe food and to take all appropriate steps to ensure that this is case. The production of safe food is influenced by multiple societal challenges, including climate change, water availability, the need for increased productivity and the necessity to move to a more circular bio-based economy, reducing waste and loss. All of these factors influence microbial communities and, accordingly, pathogen behaviour. Microbiome analysis provides the opportunity to understand these complex interactions and ensure that changes do not inadvertently affect food safety.

The potential for microbiome applications is undoubtedly vast within food production. For example, the use of tailored pre or probiotics may help prevent disease occurrence from foodborne pathogens. Strategic inclusion of biocontrol agents or modulation of microbiomes in primary production may target pathogens earlier in the food production chain. Whilst the regulatory landscape for such applications is complex and varies between countries, thereby challenging commercialisation, there is nonetheless significant interest. The benefits of environmental and ingredient monitoring to ensure food safety and quality using metagenomics approaches is evident and will undoubtedly become further integrated into food safety management systems in the years to come. Economic benefits of the enhanced use of HTS are evident already in some cases. For example, the net benefits of GenomeTrackr are estimated to be worth hundreds of millions of dollars annually and include reductions in the number of illnesses associated with the pathogens being sequenced. Similar will undoubtedly be observed for metagenomics approaches in the future.

V. What should business be doing?

For microbiome analysis to be beneficial for food safety purposes within a company, a robust sampling plan needs to be put in place, with sufficient sampling to build up a baseline for benchmarking. The analysis of metagenomic sequencing is complex and appropriate expertise is required, coupled with the capacity to analyse, and store extremely large datasets. Appropriate teams, infrastructure and budget need to be available to ensure that the application of food microbiome analysis is fit for purpose within their food safety management system.

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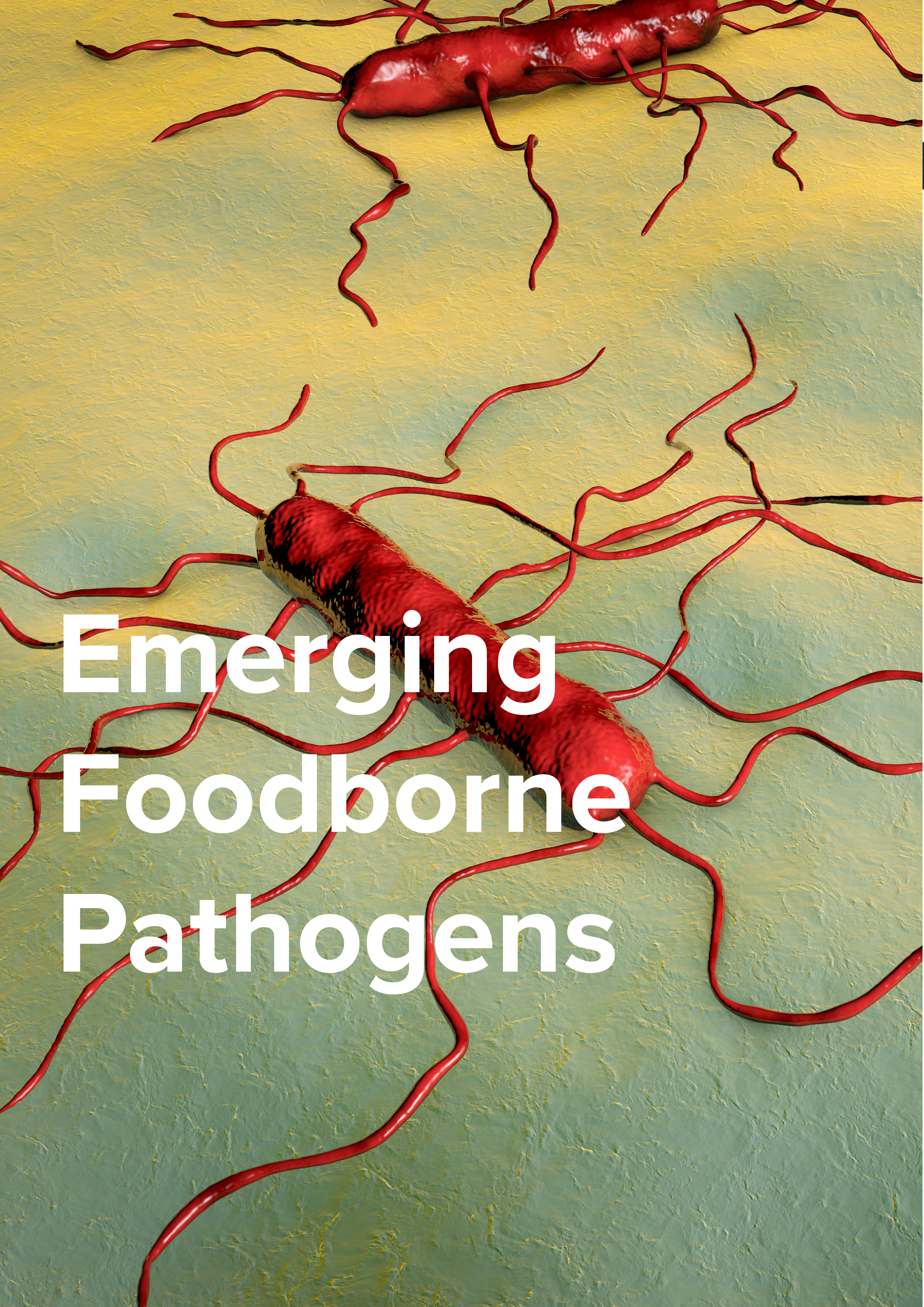
Emerging Foodborne Pathogens



I. Background

According to the Merriam-Webster dictionary the adjective "emerging" is applied to anything that has "newly formed or become prominent".[1] The US National Academy of Sciences' Institute of Medicine coined one of the first definitions of emerging infectious diseases as: "diseases of infectious origin whose incidence in humans has increased within the past two decades, or threatens to increase in the near future".[2] In 1996, Morse defined the term emerging infectious disease as "infections that have newly appeared in a population or have existed but are rapidly increasing in incidence or geographic range".[3] According to those definitions, any increasing trends in morbidity and mortality incidence meet the definition of emerging diseases.

The term emerging applied to foodborne diseases can include: 1) completely novel etiological agents, 2) known pathogens with increased ability for food transmission, 3) infectious pathogens that were not known because of the lack of detection methods, 4) known pathogens that had not been associated with foodborne transmission, 5) a disease that emerges in a new geographic region in which the population has not been previously exposed to the pathogen that causes the disease, and 6) novel clusters or strains that emerge periodically an cause pandemics.[4,5] Examples of each of these categories of foodborne pathogens include *E. coli* O104:H4, *Salmonella enterica serovar Infantis, Campylobacter jejuni, Cronobacter, Cyclospora* and norovirus, respectively.

The incidence and prevalence of human infectious diseases are constantly affected by multiple biological, human, and environmental factors. Numerous factors influencing the emergence of foodborne pathogens were compiled in a recent review by Smith and Fratamico.[4] That study identified as many as 19 possible factors which could be clustered into eight categories related to: 1) human demographics; 2) consumers; 3) food type; 4) specific pathogen; 5) agriculture and the environment; 6) education; 7) public health, and 8) social aspects. Other reviews about emerging diseases recognise that one of the most important factors that is affecting the food supply chain is globalisation, which is considered under the category of human demographics.[6] The kind of factors that impact a particular country or region is heavily influenced by their socio-political and economic status. For example, in many countries the lack of a public health infrastructure markedly prevents their ability to recognise emerging issues. Animal reservoirs are often a very important factor for the emergence of foodborne pathogens related to livestock. Adoption of food production practices such as the use of antibiotics have also influenced the emergence of pathogens.

II. Summary of knowledge on selected emerging pathogens

Antimicrobial resistance (AMR)

The United Nations' World Health Organization has declared antimicrobial resistance (AMR) one of the top 10 public health issues threatening all human populations in the world.[7] Among AMR, antibiotic resistance in bacterial pathogens is the most concerning issue. The Centers for Disease Control and Prevention has estimated that in the US more than 2.8 million antibiotic resistant infections and 35,000 deaths occur every year.[8] The development of AMR is a natural process that can be markedly enhanced by microbial exposure to large and frequent amounts of antibiotics. The emergence of AMR in bacteria populations is a very complex phenomenon that often involves the transfer of AMR genes from commensal to pathogenic bacteria via mobile elements. In food production, the use of antibiotics for livestock growth promotion has been identified as one of the most important contributors to this health problem and its connection with the emergence of multi-drug resistant (MDR) zoonotic pathogens is a major concern.

The majority of AMR human infections are largely due to infectious bacteria such as *Neisseria* *gonorrhoea, methicillin-resistant Staphylococcus aureus* (MRSA), vancomycin-resistant *Enterococcus*, and *Clostridioides difficile*, but the number and frequency of MDR foodborne pathogens has increased in recent years.[9] *Salmonella* Typhimurium phage type DT104 was one of the first MDR pathogens that emerged in the 1990's and was linked to cattle and food transmission that spread globally.[10] Quinolone-resistant *Campylobacter jejuni* infections related to consumption of chicken also emerged in the 1990's and it was one of the first examples of AMR bacteria linked to the use of antibiotics in livestock.[11] In recent years, the number of species and frequency of isolation of MDR strains has continued to increase in many countries.

MDR REP pathogens

As a result of widespread adoption of whole genome sequencing by the CDC and other regulatory agencies, the emergence of closely related MDR strains associated with specific commodities was first recognised in 2019 by CDC officials based on isolates collected during previous years.[12] These unique strain clusters have been designated as "Re-occurring, Emerging and Persisting" or REP strains and they all have exhibited resistance to multiple antibiotics. Phylogenetically, REP strains are sufficiently distant to be considered the same strain, but their genomic differences are relatively few, and they include clinical and environmental isolates from seemingly unrelated events. Currently, at least six REP strain clusters have been identified. They include MDR *E. coli* O157:H7 in romaine lettuce, MDR *Salmonella* serovar Infantis in poultry, MDR *Salmonella* serovar Reading in turkey products, MDR *Salmonella* I 4,5,12:i:-, related to swine, MDR *Campylobacter jejuni* in pet store puppies, and MDR *Shigella* among homeless populations. The public health and regulatory implications of these novel REP clusters are yet to be fully elucidated.

Highly-virulent hybrid strains

Among multiple emerging pathogens, there is possibly no other bacterium that exquisitely illustrates the enormous potential for natural creation of a highly-virulent microorganism than *Escherichia coli* serotype O104:H4.[13] Before 2011, *E. coli* O104:H4 had been known as a rare enteroaggregative *E. coli* (EAEC) serotype responsible for a handful of gastrointestinal infections in the world.[14] In 2011, one of the largest outbreaks of enterohemorrhagic colitis affecting approx. 4,000 people in multiple EU countries was linked to the consumption of contaminated fenugreek sprouts. Surprisingly, a completely novel MDR O104:H4 strain capable of producing Shiga-toxin was responsible for the outbreak in which 22% of the cases developed hemolytic uremic syndrome.[15] Genomic analysis of this EAEC serotype revealed that virulence had been enhanced by natural transformation with Shiga Toxin 2 genes and additional genes previously known in other enterohemorrhagic *E. coli.* This outbreak was also an example of international movement of pathogens because the fenugreek seeds had been imported from Egypt. Interestingly, since 2011, there have been no other recorded case of infection with this unique serovar.

Parasites

Many gastrointestinal protozoan parasites are known to infect humans, but *Cryptosporidium* and *Cyclospora* were first recognised as human pathogens in the 1970's and 1990's, respectively.[16,17] In recent years, it has been extensively established that they are endemic in many parts of the world, in particular in low- and middle-income countries.[18,19] Protozoa have complex life cycles and in most cases the oocyst phase is the only infectious stage to humans. *Cryptosporidium* is capable of infecting multiple animal species, but the only host known for *Cyclospora cayetanensis is humans*.

The prevalence of endemic *Cryptosporidium* infections in the world has been estimated to be between 4.3% in developed and 10.4% in developing countries,[20] but there are concerns that climate change may be increasing these figures. In the last five years, several highly virulent and hyper-transmissible *Cryptosporidium parvum* and *Cryptosporidium hominis* subtypes, denominated as IIA15G2R1 and IbA10G2, respectively, have emerged in different parts of the world. One of those *C. hominis* subtypes is a major concern in low and middle-income countries.[20]

The prevalence of *Cyclospora* in endemic countries has been reported to be highly variable, from 0.2% to 24%.[19] For most healthy adults, infection with these parasites is self-limiting, but immunocompromised individuals can develop serious chronic complications. *Cyclospora* is not considered endemic in developed countries, but in the last 20 years, international travel and imported products have been linked to outbreaks in Canada and the US. The most recent outbreaks in these countries seem to indicate that this parasite has also been established in their supply chain.

Anticipating the next emerging pathogen

Human history has taught us that the emergence of infectious diseases is almost inevitable. The current COVID-19 pandemic is just a stark reminder of this certainty. For several decades, epidemiologists and virologists had been warning public health authorities of the risk of a pandemic due to zoonotic respiratory viruses, but sufficient prevention efforts were deployed before 2019. Similarly, scientists believe that we will continue to see new and emerging foodborne pathogens in the near future. The emergence of enterohemorrhagic *E. coli* (EHEC) illustrates the application of lessons learned from previous events in our efforts anticipating emerging pathogens. Before 1982, there had not been a documented case of enterohemorrhagic colitis caused by an *E. coli* serovar O157:H7, but by the 2000's, thousands of people were regularly infected in multiple countries by this bacterium due to consumption of contaminated foods.[21] As a result of the extensive characterisation of this unique serovar, regulatory controls (zero tolerance policy, testing, etc.) were extended to other recently known EHEC serovars anticipating their potential appearance. However, the abrupt rise of *E. coli* O104:H4 demonstrated that if multiple natural and human-linked factors are combined, it is a daunting task to anticipate the next emerging pathogen.

III. Gaps in knowledge about these issues

a. AMR

Several multi-country and multi-institutional analyses have been conducted to address missing knowledge about multiple aspects of AMR to be able to develop effective control strategies. In 2018, a white paper proceeding from the International Environmental Antimicrobial Resistance Forum organised by the US CDC, the UK Science and Innovation Network and the Wellcome Trust identified five major areas where knowledge generation on AMR would benefit greatly: 1) hospital waste management, 2) good hygiene and sanitation practices, 3) role of animal agriculture and aquaculture, 4) management of antimicrobial manufacturing waste, and 5) transparency in antimicrobial crop use.[22] The same year, a workshop organised by the Joint Programming Initiative on Antimicrobial Resistance that involves 27 countries (mostly from EU) identified multiple research needs related to the environment to better understand and control AMR.[23] These research gaps were clustered in four main groups: 1) the relative contributions of different sources of antibiotics and AMR bacteria to the environment, 2) the role of the environment as affected by anthropogenic inputs on the evolution of AMR, 3) extent of exposure of humans to AMR bacteria via different environmental routes, and the impact on human health, and 4) effective technological, social, economic and behavioural interventions to mitigate the emergence and spread of AMR via the environment.

b. MDR REP pathogens

The very recent recognition of REP epidemiological clusters has resulted in multiple questions that need to be addressed for better comprehension and possible control of these pathogenic groups. To date, the limited information that is available about these strains is their genomic characterisation and metadata that connect them to a particular commodity. One of the most immediate needs for research is the development of standardised taxonomic criteria for inclusion of strains responsible for infection into these REP clusters. The origin of strains is an important part of the investigation. For *S. Infantis* there is some evidence that it may have originated in Peru, but the origins are unknown for most other REP groups. The commodity-specificity of these REP clusters also needs to be elucidated. In addition to these pressing needs, the molecular evolution of their MDR profile is another critical knowledge gap. An estimate of public health burden as well as cost, can be determined to assess the extent of impact. Models can also be developed to assess the potential for future re-emergence.

c. Highly virulent hybrid strains

The abrupt emergence of a completely novel microorganism in public health such as *E. coli* O104:H4, provided a unique opportunity to illustrate the power of WGS. This outbreak was one of the first WGS applications that allowed an almost complete strain characterisation just a few days after the first isolate was obtained. Thanks to WGS, the unique combination of virulence factors, origin, and AMR genes were quickly elucidated. Although traceback investigations were capable of identifying the food vehicle (sprouts) and seeds as the source, many questions still remain regarding how the fenugreek seeds were contaminated and the particular reservoir of this strain.[24] Because the strain was never isolated from the seeds or the farms in Egypt where they were grown, it is believed that contamination could have taken place during post-harvest. Regarding its natural niche, cattle may not have been its natural reservoir since EAEC strains have been rarely detected from livestock. One of the most intriguing aspects of the emergence of *E. coli* O104:H4 is that after 10 years, there has been no further reported case or isolation anywhere in the world. Because of this sudden disappearance and its very unique hybrid genotype, there has been speculation of even a possible intentional introduction to the food supply.[25] In summary, it is clear that the enormous gaps in knowledge would preclude the development of prevention strategies against a similar novel emerging pathogen, although it is still important to try and understand what the drivers of emergence could be.

d. Parasites

The recurring outbreaks with *Cyclospora* infection in the US have prompted several initiatives from the FDA and the private sector. The FDA has released an action plan intended to address immediate actions as well as to outline the most urgent needs for knowledge advancement.[26] Recommendations intended to fill knowledge gaps by this action plan include the: 1) development of rapid and effective test kits, 2) deployment of surveillance sampling, 3) development of genotypic methods, 4) assessment of the prevalence in agricultural water, 5) investigation of the role of wastewater, and 6) encouragement of data sharing among producers, government, and scientists. In addition to this FDA action plan, the control of *Cyclospora* would greatly benefit from advances in in-vitro cell cultivation and development of animal models.[19]

Cyclospora and *Cryptosporidium* are protozoa that are predominantly transmitted via contaminated water in addition to fresh produce in endemic areas; thus, it is important to try and to acquire a better understanding of their interactions with water. A recent review identified several critical knowledge gaps concerning *Cryptosporidium* in groundwater: 1) prevalence in global water supplies, 2) mechanisms of transport and introduction into groundwater, 3) an assessment of oocyst infectivity, 4) determination of dose response, and 5) overall, a limited number of studies on this pathogen.[27]

In addition to these general concerns about the dearth of information about water and foodborne parasites, the recent emergence of hyper-transmissible subtypes of *C. parvum* and *C. hominis* calls for a closer investigation on their origins and their unique genotypes that may help anticipate a more widespread global dissemination.

e. Anticipating the next emerging pathogen

As mentioned in previous sections, the discovery of several emerging pathogens has been largely due to the development of high-throughput sequencing technologies in combination with enhanced bioinformatics capabilities that were applied to epidemiology investigations. Currently, the analysis of genomic information using advanced computational techniques such as machine learning and predictive modeling seem to be very promising for identifying potentially emerging issues. An example of these approaches is the analysis of WGS data using random forest regression and machine learning. Researchers at the Interagency Food Safety Analytics Collaboration (IFSAC) in the US are pioneering a random forest-based approach for predicting source attribution of sporadic cases of salmonellosis using a large collection of animal isolates.[28] Analysis of historic and current sporadic cases offer a huge opportunity to uncover emerging trends below epidemiology baseline data.

Artificial intelligence approaches for surveillance can also be combined with metagenomic technologies. The current need to find an alternative detection method after cultivation of single strains is phased out by using culture-independent diagnostic techniques (CIDT), will likely lead to an enormous possibility of detecting and identifying emerging pathogens. The development of these and additional enhanced surveillance technologies could contribute to anticipating the emergence of disease trends.

IV. Actual and potential impact on the food supply and food businesses

The supply chain of multiple commodities and food business have been disrupted by these emerging pathogens. Contamination of leafy greens with two major REP EHEC strains (REPEXH01, REPEXH02) has caused at least a major annual multi-state outbreak in the US in the last five years.[29] The impact on these recurrent outbreaks results in major economic and market losses for the producers and companies directly involved, but consumer trust has been eroded. The fresh produce industry has also been seriously affected by strings of *Cyclospora* outbreaks since 2014, involving different products such as cilantro, leafy green salads and berries.[29]

Investigations of outbreaks caused by EHEC REP strains have suggested irrigation water as the possible vehicle of contamination, but a more extensive root cause analysis needs to be conducted to conclusively identify the ultimate source. In the meantime, it is possible that the leafy greens industry will continue to be disrupted by future EHEC contamination. *Cyclospora* seems to be much more complex and harder to understand than EHEC. As a result, the development of interventions to prevent outbreaks of cyclosporiasis may take much longer.

The global burden of all AMR has been estimated to range from $300 to $1 trillion as loss of capital,[30] and a review supported by the UK government and the Wellcome Trust in 2014 predicted that the impact of AMR on the global accumulated GDP between 2014 and 2050 would reach $100 trillion.[31] The share of those global economic consequences has yet to be specifically calculated for foodborne AMR infections but given the current trends in increases of MDR resistance, they are currently a major global burden afflicting millions of people and causing enormous losses to the food industry.

V. Food business responses and prevention actions

Given the diversity of emerging issues and foodborne pathogens, there has been a wide variety of responses from the food industry as well as from government agencies. Examples of these are: enhancing stewardship of antimicrobial use or even bans of antimicrobial use for livestock, investment on research to provide solutions concerning surveillance, detection, ecology and control, and development of private and enhancement of public surveillance systems. The application of WGS continues to be one of the most effective tools to reduce the size of foodborne outbreaks and increase the surveillance sensitivity to reveal cases below baseline data.

Case studies of relative success such as the reduction of EHEC O157:H7 in beef, Listeria *monocytogenes* in RTE processed meats and more recently, overall *Salmonella* Typhimurium in the US, could offer some insights on possible interventions. Application of a combination of traditional approaches in combination with emerging technologies such as artificial intelligence, machine learning and predictive microbiology will probably lead to more effective measures. Incorporation of a systematic and holistic One Health approach will be likely indispensable to tackle these emerging pathogen issues.[32]

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Food System Resilience: Impacts on Food Safety

I. Background

As an integral part of global infrastructure, food systems and their resilience have gained increased attention following the emergence of the COVID-19 pandemic and resulting supply-chain disruptions.[1-5] The concept of food system resilience, however, covers a broad set of different types of crises and has more potential impacts on businesses and consumers than is commonly understood. This includes impacts on food safety, which should be of real concern to both policymakers and business leaders who hope to maintain brand value over current and future crises.[5-7]

The Food and Agriculture Organization of the United Nations (FAO) defines resilience as:

> "**The ability to prevent disasters and crises as well as to anticipate, absorb, accommodate or recover from them in a timely, efficient and sustainable manner.** This includes protecting, restoring, and improving livelihoods systems in the face of threats that impact agriculture, nutrition, food security and food safety." [8]

Central to the concept of resilience is the idea of recovering from or avoiding harm from a shock to the system that potentially threatens the availability of safe and nutritious foods in the marketplace. For the food system, businesses, households, government agencies, and non-governmental organisations (NGOs) all impact system resilience.

II. Why should we be interested?

Food system resilience is important both as an issue for businesses and as a broader social issue. Food is, perhaps, the most important determinant of human health. Disruptions in the quality or quantity of food provided to populations can have long term impacts on health, productivity, and economic growth. At its extreme, lack of food system resilience can cause or contribute to deadly famines.

Although the primary effect of a shock to a food system is on the quantity of food produced and distributed to communities, such a shock can also lead to reduced food safety. This can occur due to effects of malnutrition and adaptive actions by producers, consumers, and other stakeholders.

From a business perspective, lack of system or firm resilience can reduce sales and lead to negative effects on reputation and brand value. Crisis management efforts are reactive and are sometimes more focused on managing messaging than risk. Pre-crisis investment in practices that promote resilience can reduce both the likelihood and consequences from a crisis. Alternatively, negative effects from business' failure to successfully plan for and manage these events can lead to popular anger, which, in turn, can lead to ill-conceived government policies that undermine resilience in the long run.

Although system resilience is outside of the control of a single firm, it is important to understand how the system will react to a crisis to understand the risks to the individual firm. A resilient firm will be able to mitigate the effects of a wide array of shocks to the system. Industry organisations, government, and other NGOs can play a role in promoting system resilience.

III. What do we know?

Food systems.[9,10] Food systems are complex systems involving people and firms across a wide array of food production, distribution, and service industries. For the purposes of evaluating resilience, it is also important to address affiliated industries, such as those supplying food processing and packing operations with equipment and other supplies (e.g. cleansing agents and testing supplies).

Research on food system resilience. Researchers have examined food system resilience for its ability to mitigate the effects of a wide array of shocks to the system[9]. These shocks may have effects on local markets (e.g. extreme weather events, local conflict or instability, transportation disruptions, blights, insect infestations, repressive government rules) or global markets (e.g. pandemics, climate change, geopolitical conflict, global financial shocks).[1,9,11-13] Most recently, a large body of research has addressed supply chain disruptions caused by COVID-19.[1-5]

Effects of Low Resilience on Health: Malnutrition and Food Insecurity.[9,14] A food system that is not resilient will supply less food to the market after a crisis and the food it does supply may be less nutritious. Furthermore, it will take longer for the market to recover from losses if substitutes are not available and/or expansion of existing operations is not feasible. Eventually, constraints in the system may prevent full recovery, which would lead to long term food security issues.

Effects of Low Resilience on Health: Food Safety.[7,15-17] Lack of system resilience to external shocks can lead to food safety problems in three ways.

- Shocks can create shortages of food safety-related supplies or equipment.
- Shocks can create bottlenecks that severely reduce production. The strong incentives that exist to clear these bottlenecks may lead to the temporary abandonment of best practices and a corresponding increase in food safety risk.
- Malnutrition that results from system failures increases susceptibility to disease, leading to an increase in number and severity of illnesses.

The relationship between food security and illness can lead to vicious cycles that undermine long-term health prospects for a community or nation; especially in the developing world.

Sources of food safety problems due to low resilience. Businesses, consumers, and government can all contribute to resilience or lack thereof.

Food businesses face several challenges during a crisis.[2-5] The COVID experience is instructive. High worker absenteeism occurred at a time when greater resources were needed to adapt to the crisis. The use of replacement workers and fatigued experienced workers created conditions that incentivised reduced vigilance and lead to mistakes. Also, food processors hampered by supplier problems were forced to search for substitutes and, potentially, new relationships with less scrupulous suppliers; thereby increasing the risk of contamination. Even well-meaning companies with high standards for their suppliers faced new risks if unfamiliar new suppliers were willing to engage in economic adulteration of products or fraudulent misrepresentation of practices, certifications, audit results and other signals that purchasers used to evaluate product quality.

Consumer behaviour is also an important determinant of resilience and foodborne illness. Fear-induced hoarding and resulting price increases exacerbate food security risks and may lead to improper retention and storage of excess supplies.[1,18] Crises that affect critical infrastructure (e.g. electrical power) reduce consumer ability to mitigate risk through cooking and cooling, especially when consumers lack food safety knowledge.[19] Shock-induced changes in types of foods that are available can contribute to both food insecurity and food safety risk.[20] Finally, consumers unable to find foods in formal markets may turn to less safe informal markets.

Government is often seen as a force for good during crises – and it can be. During crises, governments can also be reactive in ways that are politically popular but undermine food security and food safety.[21] For example, crises often lead to price controls (to combat 'price gouging').[22] Though market failure leading to inflated prices can occur (e.g. due to the creation of a temporary local monopoly), governments may fail at differentiating between these cases and those where higher prices reflect higher costs of supplying an area in crisis or rising market demand for scarce goods. Controlling prices inhibits resilience by exacerbating shortages and slowing recovery. In competitive markets, a crisis impacting supply leads prices to be bid up. This acts as a strong incentive to attract supplies from more costly suppliers outside of normal distribution channels (increases flexibility).

Factors affecting vulnerability and resilience. Several factors have been identified that may affect resilience. These include:

- **Reliance on sole sourcing or a small number of suppliers (diversification).**[1] By maintaining supply contracts with a single or a small number of suppliers, a firm leaves itself vulnerable to shocks affecting those suppliers.
- **Reliance on specific ingredients.**[1] Prescriptive recipes for complex foods that don't allow for use of substitute ingredients make food processors more vulnerable to shocks.
- **Longer/shorter supply chains.**[10,23] Shorter supply chains (e.g. use of local suppliers) are more vulnerable to shocks focused on a given area (e.g. severe weather). Longer supply chains are vulnerable to shocks that impact longer distance transportation networks (e.g. COVID-19).
- **Genetic diversity.**[24] Lack of genetic diversity in produce and livestock increases the chances that disease could have more widespread effects on production.
- **Infrastructure.**[10] Communities with infrastructure that relies on few transportation links to the outside world are vulnerable to shocks that may damage the infrastructure.
- **Trade Factors.**[23] Kummu (2020) suggests that resilience will be lower in countries with:
  - Low food production diversity (few types of food produced locally);
  - Low food supply diversity (few types of food sold locally - few substitutes);
  - Dependence on food imports (more vulnerable to shipping crises);
  - Few import connections (better to import from many different countries.
- **Inflexible government rules.**[15,21] Laws and regulations can reduce flexibility to respond to crises. Allowing for flexibility during crisis can enhance resilience.
- **Other Regulatory Incentives.** Regulation can create incentives for food firms to build supply chains that are not resilient or reduce competition in local markets, leaving processors and consumers susceptible to shocks that affect key suppliers.[15]
- **Low- and middle-income countries.** LMICs are generally more vulnerable to a less resilient food system. Not only do LMICs lack many of the above attributes of resilience, but they also host populations with high levels of food insecurity and disease.

The global food system. The global food system has been incredibly successful at increasing food production and feeding the world. Any attempts to remake or reform this system in the name of resilience need to be careful not to eliminate the market drivers behind this success.

IV. Gaps in Knowledge

Despite the recent growth in research dedicated to resilience, several gaps remain, suggesting that further research is needed. This is especially true with regards to food safety.

The economics of food system resilience needs more study. Little has been written about the economics of resilience and how it affects food safety.

Resilience at any cost is not a feasible option. Optimal resilience needs to be evaluated using risk-based (not hazard-based) criteria. Specifically, optimality depends on the probability of occurrence, adverse outcomes, and costs associated with efforts to promote resilience. Furthermore, what is optimal is highly context dependent; varying across regions and by type of shock evaluated.

There is also a need to better understand firm and worker behaviour during a crisis. If crisis-generated short-term incentives facing firms and their workers are not aligned with longer-term goals and incentives, Crisis management plans are likely to fail. Essentially, recovery plans must be incentive compatible with the firm's profit maximisation and employee's utility maximisation goals.

Empirical research on resilience is lacking. Although the theoretical and conceptual frameworks that are used in food system resilience research continue to improve, empirical validation is needed. There is also a need for a better understanding of how factors affecting resiliency vary across the food system due to a wider array of shocks. More complete food system analyses are needed. Most of the research examining food system resilience is focused on how the system provides food to the market. Equally important is how low food system resilience interacts with low household resilience to generate negative health consequences.

V. Impact on Food Supply and Food Business

As the experience with COVID-19 has demonstrated, food system resilience (or lack thereof) has a large impact on the food supply and food businesses. When a food system has resilience:

- The food system is robust. Crises may have localised impacts but are less likely to reduce food production and distribution as a whole. Diversity of sourcing is critical here.
- The food system has redundancies. Shortages of key inputs can be addressed by introducing substitutes. This includes inputs such as ingredients, equipment, supplies and transportation.
- The food system is flexible. The system is likely to recover quickly from a shock and can provide consumers with nutritious and safe foods because the incentives to make rapid change and maintain quality control are sufficiently high.
- The food system can adapt to long-run changes in market conditions in a sustainable way. This means that supply chains, in the long run, are not dependent on vulnerable or rapidly depleting supply chains.9

Food firms. External crises will have differential effects on firms. Those that are situated to make up for supply losses by others will do so if it is in the firms' long-term profit-maximising best interest to do so.

Food firms will be incentivised to make advance investments in resilience if:

- Preparedness decreases the chance for business failure.
- Preparation allows firms to recover quickly, maintain sales, and avoid some or all risks from supply chain disruption.
- Preparation reduces incentives for employees to cut corners on safety and quality; yielding fewer customer complaints and a reduced probability of foodborne illness outbreaks and recalls.

Food firms will be incentivised to increase production of safe and nutritious foods during a crisis if:

- Prices are allowed to rise to account for reductions in supply or increases in demand.
- Firms can market their enhanced efforts as good corporate social responsibility (CSR).
- Extra efforts are rewarded with new supply contracts and increased market share.

Working against investments in resilience and response are the costs of these activities, including:

- Investments in excess capacity. Maintaining excess capacity typically involves significant investments in both labor and capital.
- Loss of benefits from moving away from just-in-time inventory systems to a just-in-case approach.

Excess inventory is costly and is generally not needed during times of normalcy.
- Maintenance of a diverse set of suppliers, wholesalers, retailers, and transportation companies is costly in terms of administrative and legal expenses, auditing and inspections, and may lead to higher supplier prices when benefits from sole source contracts are lost or smaller local suppliers are used.

Government. Government action that would enhance resiliency includes:
- Investing in redundant infrastructure (e.g. ports, railroads, roads, bridges);
- Warehousing of foods for emergencies (if food stocks are nutritious, maintained to ensure food safety, and are easily distributed in times of crisis);
- Crafting regulation to ensure that new rules do not reduce food industry resilience;
- Being open to temporary relaxation of some rules that stifle flexibility in crisis response;
    - Though international regulatory rules, such as those embodied in the Codex Alimentarius can help contribute to food safety, lack of flexibility can lead to losses in health due to malnutrition and resulting susceptibility to disease (especially in LMICs)
- Recognising that local or private standards potentially have the advantage of allowing for more flexible means of achieving food safety goals; and
- Harnessing the power of the market by educating consumers, fostering competitive markets, and allowing the price system to attract resources in times of crisis.

In sum, lack of food system resilience can lead to supply disruptions, incentivisation of poor practices by businesses and employees, and the provision of less nutritious and less safe foods to the marketplace. Businesses and governments can both play a role promoting resilience and consequent food safety.

VI. What should business be doing/thinking

Businesses can improve food safety through enhanced resilience by examining the sources, actions, incentives, and consequences of food safety failures due to low resilience. Planning for food system shocks can reduce the impact of crises when they occur. Ideally, businesses should:

- Recognise that the global food system is **critical infrastructure** and system failures are likely to lead to enhanced scrutiny from government and civil society.
- Identify **risks from a variety of shocks** to the food system and recognise the differential effects on business operations (e.g. pandemic, crop failure, war, extreme weather).
- Identify **vulnerable points** and potential **bottlenecks** in supply chains.
- Identify **substitutes** for current inputs and, where needed, build relationships with multiple suppliers, wholesalers, retailers, and transport firms.
- Balance "**just-in-time**" with "**just in case**". Recognise potential costs from not having inventories of key inputs to production during crises. Conversely, firms with excess capacity may realise windfall profits and long-term benefits due to customer satisfaction (greater willingness to pay) and resulting growth of market share.
- Think about use of **big data** to improve responsiveness and recovery from system shocks, while maintaining safety standards.
- Examine how crises are likely to affect the **incentives** of employees, supply chain actors and consumers (and resulting impacts on food safety).
- Build a **culture of food safety** in parallel with a **culture of innovation** to promote adaptive, but safe, responses to crisis.
- Realise the enhanced need for **food safety messaging** during crises where employees are stressed and face incentives to take shortcuts.
- Promote a **regulatory framework** recognises risk trade-offs and allows for flexibility (while preserving safety) during crises.
- Ensure that there are **sustainable plans for long-run recovery** that are consistent with

maintaining food safety standards.
- **Learn from past crises**, but do not assume the next crisis will be like the last crisis (note: media reports/suggestions are invariably focused on the last crisis).

By considering the above and creating a resilience plan that is routinely updated and evaluated, a food firm can be best prepared for the next crisis it faces.

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About the Global Food Safety Initiative

The Global Food Safety Initiative (GFSI; the Coalition) is a CEO-led Coalition of Action from The Consumer Goods Forum, bringing together 41 retailers and manufacturers and an extended food safety community to help oversee food safety standards for businesses and help provide access to safe food for people everywhere. As one of the world's largest networks to help achieve safe food, GFSI is committed to making food safety everyone's business and the Coalition members are addressing challenges facing food safety systems in their supply chains and the markets they operate in, and are helping to raise the food safety bar globally. Its ambition is to strengthen and harmonise food safety systems so they are able to feed the growing, global population and develop markets that can deliver food safely, no matter where in the world the consumer is. To learn more, visit www.mygfsi.com

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