FACULTY OF BIOSCIENCE ENGINEERING

RESILIENT FOOD SAFETY MANAGEMENT TO ANTICIPATE ON RELATED MICROBIOLOGICAL FOOD SAFETY CHALLENGES

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INDEX

ABBREVIATIONS

BRC	British Retail Consortium
EFSA	European Food Safety Authority
EU	European Union
FBO	Food Business Operator
FSMS	Food Safety Management System
FSMS-DI	Food Safety Management System Diagnostic Instrument
HACCP	Hazard Analysis and Critical Control Points
HSMS	Horticulture Safety Management System
HSMS-DI	Horticulture Safety Management System Diagnostic Instrument
GAP	Good Agriculture Practices
GMP	Good Manufacturing Practices
MO	Micro-Organisms
PI	Performance Indicators
QA	Quality Assurance
QC	Quality Control
STEEP	Social, Technological, Environmental, Economic, Political
SQF	Safe Quality Food

ABSTRACT

Introduction In this rapidly changing world, drivers of change impact our food consumption patterns and food production systems. These drivers can also influence the emergence of microbiological food safety hazards. Food Business Operators have the end responsibility for food safety of their output, so operating under the pressure of these drivers calls for adapted food safety management. This research focuses on this impact on food safety management, and how this can be used to asses a business's resilience under these drivers accurately. The goal is to provide a basis for the updating of the Food Safety Management System Diagnostic Instrument, a tool that is constructed to assess maturity and identify strengths and weaknesses of a business's Food Safety Management System through indicators.

Materials & Methods A literature study is conducted to get a feel for the considered drivers of change and their possible influence on food safety management, and also to find a definition for resilience in food safety management. To get acquainted with the working of the diagnostic instrument in its current form, an interview using the tool is done in an alternative food system. Based on this background information, a methodology for the update of the diagnostic instrument is proposed. First, to get an insight into the consequences of the impact of drivers for food safety management, food business operators are consulted in an online workshop. They are asked to give their opinions on which drivers can have an impact on food safety management and in what way. They are also asked to provide a top 5 of the most important drivers to consider. From this, mechanisms can be constructed linking drivers to particular activities in the Food Safety Management System. This coupling is also done through a structured literature review, to provide a scientific background for the mechanisms observed by food business operators. These mechanisms will form the basis for the construction of new indicators that define the impact level of external context factors. Lastly, the resilience definition as defined in the literature study is translated into a resilience level to score indicators on.

Results & conclusion The workshop and literature study results were translated into mechanisms at play when drivers and subdrivers impact Food Safety Management Systems. Differences were observed between the results of both methodologies. An overall ranking was made up of the most important subdrivers to consider in food safety management. Resilience of food safety management was defined based on literature. These results were then translated into a suggestion for an update of the diagnostic instrument, where the impact of the most important subdrivers is included in external context indicators and a resilience level for maturity of FSMS activities. Further research and adaptation of the results is needed to update the diagnostic instrument completely.

SAMENVATTING

Introductie In deze snel veranderende wereld, hebben drijfveren van deze veranderingen ook een invloed op onze voedselconsumptie patronen en voedselproductie systemen. Deze drijfveren zorgen ook voor de opkomst van voedselveiligheid gevaren. Food Business Operators zijn de eindverantwoordelijken voor de voedselveiligheid van hun producten, dus werken onder de druk van deze drijfveren vraagt om een aanpassing van hun voedselveiligheidsmanagement. In dit onderzoek ligt de focus op deze impact op voedselveiligheidsmanagement, en hoe dit kan gebruikt worden om de weerbaarheid van een bedrijf onder de druk van deze drijfveren op een juiste manier te beoordelen. Het doet is om het de basis te leggen voor een update van het diagnostisch instrument dat is opgezet om de maturiteit van een bedrijf zijn managementsysteem voor voedselveiligheid te bepalen, en om sterktes en zwaktes te identificeren aan de hand van indicatoren.

Materialen & Methoden Een inleidende literatuurstudie wordt uitgevoerd om kennis te maken met de mogelijke invloeden die de drijfveren kunnen hebben op management van voedselveiligheid, en ook om een definitie op te stellen voor weerbaarheid in voedselveiligheidsmanagement. Om voeling te krijgen met het diagnostische instrument in zijn huidige vorm, wordt een interview gedaan bij een alternatief voedingsbedrijf. Met deze achtergrondinformatie kan dan een methodologie uitgezet worden voor de update van het diagnostisch instrument. Eerst worden Food Business Operators geraadpleegd in een online workshop, om inzicht te krijgen op de mogelijke gevolgen van de impact van de drijfveren op voedselveiligheidsmanagement. Ze worden gevraagd om hun mening over welke drijfveren een impact kunnen hebben en op welke manier. Ook moeten ze een top 5 geven van welke drijfveren het belangrijkste zijn om rekening mee te houden. Uit deze resultaten kunnen dan de mechanismen worden uitgezet waarmee de drijfveren gelinkt zijn aan activiteiten binnen voedselveiligheidsmanagement. Deze koppeling wordt ook gemaakt op basis van een gestructureerde literatuurstudie, om een wetenschappelijke achtergrond te voorzien voor de antwoorden van de Food Business Operators. Deze mechanismen zullen dan de basis vormen voor het opstellen van nieuwe indicatoren rond de impact van externe context factoren. Daarna wordt de definitie voor weerbaarheid, die is opgesteld in de literatuurstudie, vertaald in een score niveau voor weerbaarheid voor de indicatoren.

Resultaten & conclusie De resultaten van de workshop en de literatuurstudie werden gebruikt om mechanismen op te stellen van de impact van drijfveren op voedselveiligheidsmanagement. De twee methodologieën vertoonden gelijkenissen, maar ook verschillen. Een algemene rangschikking van de drijfveren die het meest in het oog moeten gehouden worden in voedselveiligheidsmanagement werd opgesteld. Weerbaarheid in voedselveiligheidsmanagement werd gedefinieerd op basis van literatuur. Deze resultaten geven een aanleiding voor het updaten van het diagnostisch instrument, waar de impact van drijfveren gevat zit in indicatoren voor externe context, en voedselveiligheidsmanagement activiteiten beoordeeld worden op weerbaarheid dankzij een nieuw niveau voor weerbaarheid. Meer onderzoek is nodig om de update van het diagnostisch instrument te vervolledigen.

INTRODUCTION

Over the last few years, the world has been changing rapidly. The population keeps growing, our consciousness about climate change rises every year, and major world events like the COVID-19 crisis have had a significant influence on our mindsets and actions. The internet has given us access to tons of information in a fast and convenient way, and with the enormous popularity of social media, news and opinions travel all around the world in a matter of milliseconds. This has opened a whole new way of gathering knowledge but has also been a source of fake news and misinformation. Technology is ever changing, and new advancements take over the world faster than ever. All these elements also have an impact on the food industry.

Food consumption has changed due to changing consumer knowledge and a growing awareness of the environmental footprint of consumption choices. Concrete examples of this are consumers' avoidance of food additives due to concerns about the safety of consuming additives being spread through the media (Keptan & Kayisoglu, 2015), and the evolution towards more plant-based foods as a more eco-conscious alternative to animal food products (Toth et al., 2021). 'Zero-waste' strategies such as aquaponics are born out of the evolution towards a more circular economy (Nenciu et al., 2022) and a growing population with equally growing needs call for continuous technological advancements in food production and processing to keep up with these needs. COVID-19 changed the way people view hygiene and food safety, and created a rise in the use of delivery and pick up services (Ferreira Rodriguez et al., 2021). Climate change has a significant impact on weather and soil conditions and thus on food production (Duchenne-Moutien & Neetoo, 2021). All these context factors can be classified into five categories of drivers: Social, Technological, Environmental, Economic and Political (STEEP). They put pressure on the macro-environment in which Food Business Operators operate.

The effect of these drivers for emergence of food safety hazards on food consumption and production is of great concern to food business operators. Every food business in Europe is obliged to install a Food Safety Management System (FSMS) specific to their business, following a set of rules and regulations. One of the main objectives of the European General Food Law, Regulation (EC) No 178/2002, is to ensure a high level of protection of human health in food production. It states that the food business operator is responsible for ensuring compliance with the food safety requirements of all foodstuffs that he produces and that he has the primary legal responsibility to ensure food safety. Regulation (EC) No 852/2004 on the hygiene of foodstuffs lays down the principles of HACCP (Hazard Analysis and Critical Control Points) and good practices. Standards for the implementation of these principles are made by stakeholder associations, such as ISO and BRC. Audits for certification are executed where the FSMS is tested against these standards. The FSMS diagnostic tool presented by Jacxsens et al. (2011) serves to systematically analyze and assess the maturity of activities and the performance of a company's FSMS based on indicators. Core control and assurance activities, context factors and food safety output are evaluated through a scoring system and the results can be used to assess the weak and strong points of the current FSMS.

With the changing context that these food businesses operate in, the indicators based on which their FSMS can be evaluated should also change. In this thesis, the diagnostic tool will be revised to make it more future proof by investigating the most relevant drivers and using these to update the current indicators. To achieve this, an answer will be sought to the following research questions:

- **How do social, technological, environmental, economic, and political drivers affect microbiological food safety management on FBO level?** An overview will be given of the most important drivers in these five categories, and how these factors have changed over the last few years. Drivers and subdrivers were determined in context of the Horizon Europe FoodSafeR project To investigate the mechanisms in which these have an impact on food safety management, a workshop is set up with experts from the food industry. A literature review is conducted to support the results from the workshop and to give a scientific background to this question.

- **Which of these drivers are most relevant to food business operators to consider?** The answer to this question is sought through expert elicitation. Relevance in this sense is understood as the capability of food business operators to adapt to, cope with, prevent or intervene the impact of these drivers. It should be a combination of both the importance of the impact of this driver and the feasibility of considering this driver in food safety management. The impact of these drivers can then be incorporated into new indicators for the external context of a food business to include in the diagnostic tool as described in Jacxsens et al. (2011).

- **How can we most accurately assess the resilience of a business's food safety management system?** Resilience in food safety management systems is needed to cope with the impact of drivers. Through literature review, a framework is developed to find the definition of resilience in food safety management. This is then translated into a new "resilience level" in the diagnostic tool through literature review and group discussions. This will help to start updating the current diagnostic tool.

1 LITERATURE STUDY

1.1 Impact of drivers on microbiological food safety

1.1.1 Definitions of drivers and risks in food safety management

To start off this literature study, some important terms will be defined. **Drivers** used in this context are defined as drivers of change, context factors that influence trends and behaviour and thus lead to emerging challenges (FAO, 2022). Drivers are called the issues shaping the development of a society, organisation, research area, technology etc by the European Food Safety Authority or EFSA (2010). They can further be split up into more specific subdivisions called subdrivers. In this thesis specifically, drivers of change and their subdrivers leading to emerging risks in food safety are considered. EFSA (2012; 2014) defines **emerging risks** as the probability of harm to human, animal and/or plant health that results from either (a) a newly identified hazard of physical, chemical or microbiological nature to which a significant exposure of the target organism may occur, or (b) an unexpected new or increased exposure to a known hazard through the food chain for humans, the feed chain for animals or the environment for plants, and/or (c) increased susceptibility of the target organism to a known hazard. This threefold definition is shown in Figure 1. This thesis will focus on emerging risks for humans for hazards of a microbiological nature where an unexpected new or increased exposure to a known hazard occurs.

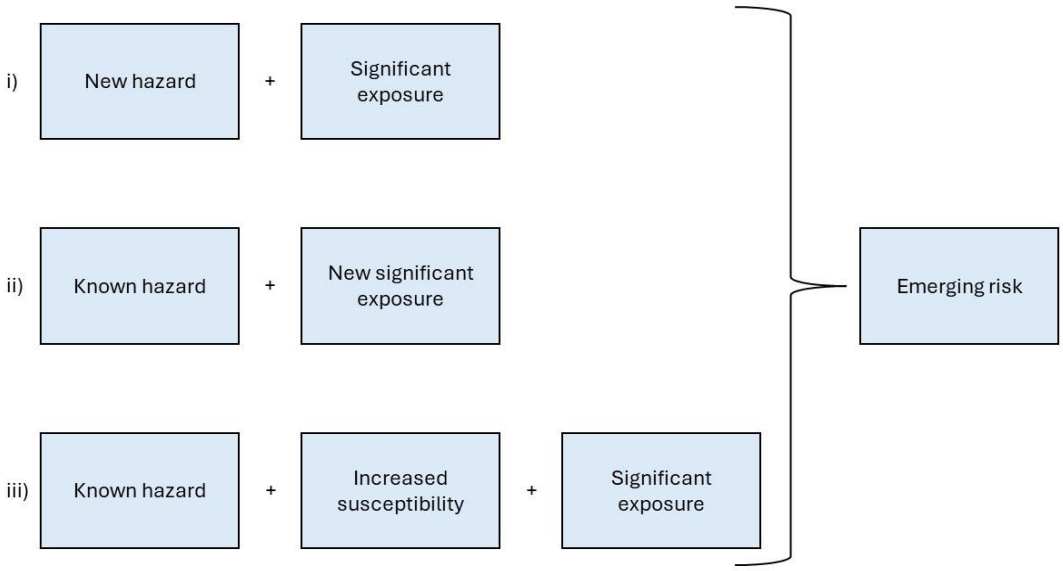

Figure 1 The threefold definition of emerging risks according to EFSA. (EFSA,2012)

Hazards in this context are defined as microbiological agents with the potential of causing adverse health effects to human through consumption of food, while **risks** are the likelihood of those hazards actually causing harm. These microbiological agents could be bacteria, for example Salmonella spp., viruses, such as Norovirus, parasites, like nematodes, and prions (WHO, n.d.). Risks are defined as a function of both the possibility of adverse health effects occurring and the severity of those effects caused by the relevant hazard. These definitions are laid out in EU Regulation 178/2002. According to this regulation, the Food Business Operator (FBO) has the end responsibility to assure food safety, for which **food safety** can be defined as the food not being injurious to human health or unfit for human consumption. FBO's thus have to deal with these microbiological hazards, as well as with food fraud and physical and chemical hazards, and reducing associated risks in their end product to ensure food safety. The way a company goes about this is called food safety management. The scope of this thesis is specifically **microbiological food safety management,** which focuses on the management of human pathogens as hazards and related risks.

Context changes, like the drivers described in this thesis, are often analysed using a **STEEP** analysis. To do this, the macro-environment that a business operates in can be split up into five domains of external factors: **Social, Technological, Environmental, Economic & Political.** This kind of analysis is often used in strategic management to gain insights in upcoming trends to be able to anticipate them (Hunger & Wheelen, 2014). A list of the drivers to consider in light of microbiological hazards has been compiled as part of the Horizon Europe FoodSafeR project. Table 1 shows an overview of all drivers and subdrivers organized in the STEEP framework.

Table 1 Drivers and subdrivers defined in the context of microbiological food safety, organized according to the STEEP framework. This list was compiled as part of the Horizon Europe FoodSafeR project.

STEEP	Drivers	Subdrivers
Social	Consumer behaviour	Dietary choice
		Consumer awareness and attitude
		Consumer knowledge
		Public awareness
	Demographic development	Population (size)
		Prevalence of vulnerable groups
		Urbanisation
		Migration and travel
	Human health and wellbeing	Human health conditions
		Resistant pests and diseases
Technological	Technology in food production	Plant-derived food production
		Animal-derived food production
		Novel food sources
		Products for food production
	Technology in food processing	Processing techniques and scale
		Upcycling for food
		New digital technologies
		Food formulation
		Food packaging
Environmental	Environmental contamination	Agricultural pollution
		Sewage treatment
	Management of natural resources	Recycling
		Use of side streams
		Water and soil management
	Geographic region	
	Seasonality and weather	
	Climate change	
Economic	Distribution	Global trade
		Distribution channels
Political	Legislation, policies and governance	Official controls and communication
		Good practices and standards
		Food legislation
	Geopolitical instability	War and conflict
		Fragmentation between nations

1.1.2 Drivers

From a **social** standpoint, the three major drivers of emerging microbiological hazards in food are *consumer behaviour, demographic development* and *human health and wellbeing*. *Dietary choices* such as consumers leaning towards more minimally processed foods can be related to higher initial contamination and with this higher food safety requirements for the production and processing industry. The combination of higher demand for ready-to-eat meals as a dietary choice and lack of *consumer knowledge* concerning food safety and hygiene results in threats towards human health. Improving knowledge on food safety and hygiene depends on the accessibility of food safety information. *Public awareness* on issues like food waste and depletion of natural resources shifts the attitude and requirements from consumers, which leads to new innovations in the industry, in which food safety should always be kept in mind. This public awareness can also ignite more personal *consumer awareness and attitude* in which certain consumers go for more extreme behaviour around food, such as eating only plant-based foods or watching out for only clean labels. These specific consumer groups also need to be catered to by the food industry (FAO, 2022; Marvin et al., 2019). In terms of demographic development, the growth of the global *population* leads to increased food demand and decreased food security. Rapidly growing food demand can destabilize the food industry, but is also drives innovation. The *prevalence of vulnerable groups* in this growing population is also a factor to consider, as products can have different health effects on different groups of people. Specifically ageing plays an important role in this, as older people are more vulnerable to adverse health effects. *Urbanisation* is the process of people more and more moving to urban areas, which increases in its turn the surface area that is urbanized. This calls for new food production systems in urban settings, or urban agriculture. However, the soil, water and air quality in urban areas and their contamination with specific pathogens is a concern. With *migration and travel* eating habits and dietary patterns spread globally, introducing foods that weren't consumed at all or in lesser amounts to other regions of the world (Buscaroli, 2021; FCEC, 2013; Mylona et al., 2016; Wentholt et al., 2010). Similar to the prevalence of vulnerable groups, *human health conditions* can make an individual more susceptible to a certain hazard. This also depends on the health protection that is in place. When however too much antimicrobial medicine is used, for humas or in rearing of animals, this can result in *resistant pests and diseases*. The more resistance is built up against these antimicrobial drugs, the less protective they are and the less human health can be protected. This also can lead to innovations in new drug development (Engering et al., 2013; Wentholt et al., 2010)

Two drivers can be categorized under the **technological** domain: *technology in food production* and *technology in food production*. Innovations driven by increased scientific knowledge and by other drivers constantly impact technology used in *plant*-and *animal-based food production*. New technological solutions for production problems constantly arise. Next to that, through global travel and the search for more sustainable production solutions, *novel food sources* gain more and more terrain. Novel foods is defined by the European Union (EU) as food not eaten to a significant degree in the EU before 1997 according to EU Regulation 2015/2283. Examples of more recent novel food sources are insects and seaweed. *Products for food production* refers to products like feed for the production of animal-based food and fertilizers for production of plant-based food. Innovations in the use of these products have an indirect effect on the final food product. *Processing techniques and scale* refers to the techniques used for food processing and the scale in which this happens. Smaller companies that use more innovative techniques often result in higher context risk. In the light of sustainability and circular economies, *upcycling for food* of waste streams, for example using whey protein from cheese production as protein powder, can lead to new upcoming companies. Using these waste streams is a reason for concern for microbiological food safety. On the other hand, *new digital technologies* can lead to improvements in food safety management, with for example the rise of blockchains as a tool for trustworthy documentation and record-keeping. Artificial Intelligence (AI) can also play a role in finding solutions to emerging issues, as they are often used for predictive modelling. AI can help in tracking the current situation and correcting operational mistakes, as well as predicting future issues and foreseeing the right solution for handling them. *Food formulation* refers to the composition

of the product and its intrinsic, extrinsic and implicit factors. Intrinsic factors are specific to the product, like pH or aw. Extrinsic factors are environmental factors such as storage temperature or relative humidity. Implicit factors are related to the influence micro-organisms present in the product have on each other, they can compete with each other for resources or help create an ideal environment for each other. Technology in *food packaging* has been striving towards more recyclability, reusing and reducing of packaging materials, while also maintaining good barrier properties to influence food safety. New technologies can thus provide a solution for emerging issues, but can also create them (FAO, 2022; Marvin et al., 2019; Marvin et al., 2022; Mylona et al., 2016).

Environmental drivers are *environmental contamination, management of natural resources, geographic region, seasonality and weather* and *climate change.* Leaching out of pollutants in groundwater leads to *agricultural pollution*. This is mainly the case with inorganic agent from fertilizer, but can also spread microbial contaminants throughout the food chain. Higher pollution levels also lead to water scarcity, which causes issues for food security. This is also related to *sewage treatment* : water that is used in the food chain should be of potable quality and treated well. Sewage treatment plants often result in highly contaminated areas, which should be considered in primary production (FAO, 2022; FCEC, 2013; Kendall et al., 2018; Mylona et al., 2016). The concept of *recycling* as a form of circular economy implementation in the packaging industry raises concerns towards contamination of the contamination from initial use of the reused materials. Whereas recycling refers to the reuse of the end product of the main production stream, *use of side streams* raises similar concerns. Reusing waste streams or side streams can be about reusing process water but also upcycling of waste products that are created in the production of the end products. Reusing process water demands sufficient treatment to safe levels. Upcycling means that further attention needs to be paid to the food safety of what are otherwise waste or side streams. In light of sustainability *water and soil management* become increasingly important the amount of and how these two are used should be managed in a more sustainable way. Water scarcity can pose a real threat to food security, which can be linked to emerging food safety issues. Soilless cultivation becomes more popular, especially in urban agriculture, but also requires attention to food safety (Buscaroli, 2021; FAO, 2022; Kendall et al., 2018). The impact of *geographic region, seasonality and weather* and *climate change* are all linked to each other: the climate of the region where food is produced is related to the changing climate, which also impacts more extreme weather events in different regions. Temperature, precipitation, relative humidity, soil salinity and pH, and exposure to light can create an environment that is more suitable for pathogens to grow in. Temperature also influences the cold chain, as it is harder to maintain when travelling through different regions with varying climate conditions. Heavy rainfall can lead to flooding, which redistributes contaminated water which can end up in food production or processing. Drought leads to water scarcity, which is linked to emerging issues in food safety (Duchenne-Moutien & Neetoo, 2021; Kendall et al., 2018)

For the **economic** domain, *distribution* is the only major driver of change which was retained. *Global trade* can lead to an improved economy of the export country, which can lead to more investments in the food production and processing industry. Due to differing requirements in each country, export can also lead to advancement of food safety management in the exporting companies if food safety requirements are harder to meet in the importing country or region. On the other hand, globalisation of food distribution also makes distribution more complex, which makes it harder to maintain the cold chain, for example. Pathogens are also redistributed to new regions where the specific form of that pathogen might not be known, which can lead to severe foodborne illness outbreaks (Engering et al., 2013; FCEC, 2013; Kirezieva, Luning et al., 2015; Wentholt et al., 2010). *Distribution channels* are also more complex, with the rise towards shorter supply chains, alternative food chains and last-mile delivery. Distribution channels can also pose varying requirements for the food safety output of a company. The way in which the product is distributed needs to be taken into account with regards to food safety at the time of consumption (FCEC, 2013).

Politically, the drivers of change are considered to be *legislation, policies and governance* and *geopolitical instability. Official controls and communication* are important in enforcing *food legislation* and the implementation of *good practices and standards*. Decision making in food legislation should always be based on the most recent scientific knowledge and updated regularly when new information arises and the environment around the food industry shifts (Fernandez & Paoletti, 2021; Wentholt et al., 2010). *War and conflict* and *fragmentation between nations* can lead to political instability and thus impact the way legislation and controls are made. When war occurs in an important country for export, this can lead to food scarcity, as has happened recently with the war in Ukraine, and this can lead to several emerging food safety issues. When a large supplier is located in a conflict area, the need for alternative sourcing can arise, and the quality of materials of new suppliers can be hard to predict (Kendall et al., 2018; Wentholt et al., 2010).

1.2 Assessment of food safety management systems

1.2.1 Food Safety Management Systems

In 1962, the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) of the United Nations (UN) created the Codex Alimentarius (CA). It forms the benchmark for policy making around food legislation all over the world. With the aim of protecting human health and serving as a basis for balanced international trade, the CA sets certain standards for e.g. food hygiene, pesticide residues, contaminants, pathogen analysis, etc. Based on the standards and guidelines set by the CA, the European Union implemented the hygiene requirements for FBO's in EU Regulation (EC) No. 852/2004 on the hygiene of foodstuffs. It includes prerequisite programs or PRPs, Hazard Analysis Critical Control Points or HACCP principles, the need for setting requirements based on scientific evidence, the importance of traceability throughout the whole food chain and the responsibility of the FBO to ensure safety of the end product (Trienekens & Zuurbier, 2008). Regulation (EC) No. 853/2004 is an additional legislation for FBO's working with raw, unprocessed products from animal origin.

An FBO's **Food Safety Management System (FSMS)** is the company's own set of procedures aimed at ensuring that the produced end products are safe for human consumption. It is part of the overall Quality Management System that ensures high and consistent quality throughout the production process. Implementation of the legislation in this FSMS is personal to the company and can often be a challenge. Commission Notice 2022/C 355/01, as a revision of Commission Notice 2016/C 278/01, lays down the basics of how to translate this legislation and set up the FSMS for different types of food businesses. Generic standards such as Good Agricultural Practices or GAP standards, the HACCP principle and International Standardisation Organization or ISO standards are based on the aforementioned regulation, and are meant to achieve international uniformity. *GAP standards* are guidelines for the production and storage of food in the agricultural sector. It describes standards for sanitation, pest management, water quality, but also documentation, recall procedures etc. They are based on the PRP's as described in Commission Notice 2022/C 355/01. *HACCP principles* lay down a systematic approach for identification, evaluation and control of critical steps in food processing. *Good Manufacturing Practices* (GMP) are set up similar to GAP but for processing, and serve as a prerequisite for the implementation of HACCP principles. *ISO standards* are more focused on the managerial approach to food safety management and focus on writing down activities into specific procedures. Audits are performed by stakeholders to verify if guidelines and standards are well implemented. Certain private standards exist that are aimed at improving supplier and customer relationships and eliminating the need for multiple audits through certification. These standards often apply to the entire Quality Management Systems and are based on GAP, GMP, HACCP and ISO principles. Examples are Global GAP, British Retail Consortium (BRC) and Safe Quality Food (SQF) (Jacxsens et al, 2011; Luning et al, 2009; Trienekens & Zuurbier, 2008).

The FSMS is usually a combination of **Quality Control (QC)** and **Quality Assurance (QA)** activities, as described in Commission Notice 2022/C 355/01. QC activities or control measures are aimed at keeping product and process characteristics in an acceptable range, while QA activities are aimed at setting system requirements, evaluating system performance and organizing necessary changes Control measures have the goal of preventing, reducing or eliminating pathogens in food to result in safe end products. It includes preventive measures, interventions, and monitoring of product and process characteristics. Assurance activities include system set-up, validation, verification, documentation and record-keeping. They support the implementation of control measures (Commission Notice 2022/C 355/01; Luning et al, 2008; Luning, Marcelis et al, 2009).

1.2.2 The food safety management system diagnostic instrument

1.2.2.1 History of the diagnostic instrument

In light of the European FP6 Pathogen Combat project (2005-2009), a diagnostic instrument to assess performance of a company's FSMS was developed in 2009. The FSMS Diagnostic Instrument (FSMS-DI) is designed to assess the maturity of a company's FSMS as a form of self-checking. An inspection like this is done to assess the current state of a company in a more informal way, and to improve microbial food safety control and identify strengths and weaknesses towards ensuring food safety. For a company, implementing requirements of different stakeholders can be complicated, so a diagnostic instrument like this can help to define the gaps in the existing FSMS. The FSMS-DI is based on indicators evaluating the most important processes and activities for food safety management. These were defined through literature review and all indicators were validated through expert elicitation. It concerns context factors such as product and process characteristics, organisational characteristics and chain characteristics; control and assurance activities as explained in Chapter 1.2.1, and internal and external food safety performance evaluation. The higher the context riskiness, the more advanced the control and assurance activities should be to get the same level of food safety of the output. Food safety performance as evaluated through a diagnostic tool handles internal and external audits and customer complaints (Jacxsens et al., 2011; Luning et al., 2008; Luning et al., 2009; Luning, Marcelis et al., 2011).

In 2013, the diagnostic tool was further developed to include processing, production and trade of fresh produce in light of the European FP7 Veg-I-Trade project (2010-2014). In primary production, the safety management system is called the Horticulture Safety Management System (HSMS). Through literature review and an expert elicitation following the Delphi approach, the existing tool was re-evaluated. Indicators that were deemed less relevant were scrapped, and new indicators were added specifically related to fresh produce. Examples and definitions were adapted to the case of fresh produce handling. The final diagnostic tool was validated through expert elicitation (Kirezieva, Nanyunja et al., 2013; Kirezieva, Jacxsens et al., 2013).

1.2.2.2 Structure of the diagnostic instrument

The tool works as a checklist for which indicators are evaluated based on their presence and advancement level. These indicators are the key activities that establish the maturity of the FSMS. The original tool contains 58 indicators: 17 on context riskiness, 25 on control activities, 9 on assurance activities and 7 on performance evaluation. For each indicator the impact on food safety of the end product is described. Three levels are also defined: grids are set up to identify the descriptions for each level (Luning et al., 2008). An overview of the indicators of the original tool and the changes made for the fresh produce tool is given in Figure 2.

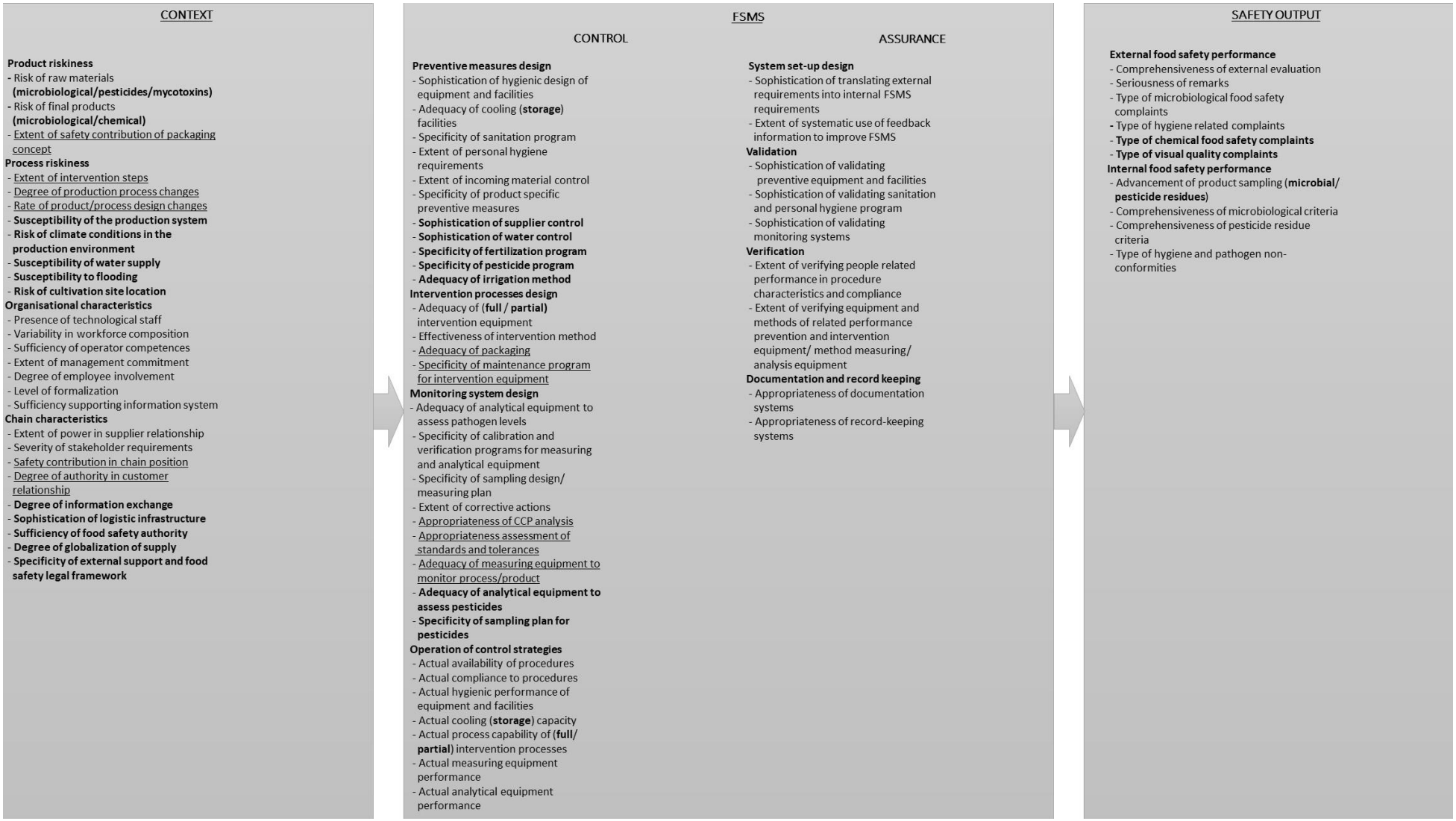

Figure 2 Indicators of the diagnostic instrument. Indicators shown underlined are only present in the original FSMS-DI and not in the HSMS-DI. Changes made for the HSMS-DI are indicated in bold (Jacxsens et al., 2010; Luning et al., 2009; Luning, Marcelis et al., 2011; Kirezieva, Jacxsens et al, 2013; Kirizieva, Nanyunja et al., 2013)

Context indicators are split up into product, process, organizational and chain characteristics. They are used to define the riskiness of the context in which the company operates. For product and process characteristics, low, medium and high risks represent respectively low, potential and high chance of contamination, growth or survival of pathogens. For organisational characteristics, low, moderate and high level represent respectively supportive, constrained and lack of administrative conditions for decision-making. For chain characteristics, the levels represent low, moderate and high dependence on other chain actors (Luning, Marcelis et al.,2011). For the HSMS diagnostic instrument a few changes were made to the context indicators. For product characteristics, the indicator for packaging concepts was scrapped as packaging is often less relevant in the fresh produce chain. The risk of raw materials was split up into microbial risk, risk due to pesticides and risk due to mycotoxins. Risk of final products was split into microbial and chemical risk. All production characteristics were left out and replaced by indicators for the susceptibility of the production system, the risk of climate conditions in the production environment and the susceptibility of the water supply. Only for primary production an indicator for susceptibility to flooding and risk of the cultivation site location was added. Organisation characteristics were all kept the same. Some extra indicators were added for chain characteristics: the degree of information exchange, sophistication of logistic infrastructure, sufficiency of the food safety authority, the degree of globalization of the supply, the specificity of external support and of the food safety legal framework were added. Safety contribution in the chain position was omitted as a separate tool exists for each position in the fresh produce chain. The indicator for degree of authority in customer relationships was also omitted (Kirizieva, Nanyunja et al., 2013).

Indicators for **control activities** concern preventive measures design, intervention processes design, monitoring system design and operation of control strategies. Grids were made to define at what level the company's activities are designed and operated. If the activity described in the indicator is not present in the company's FSMS, the lowest level is attributed for this indicator. If the activity is present, a low, medium and high level of advancement in its design are evaluated as follows. Low levels represent lack of scientific evidence, lack of predictability and design based on company experience and common equipment that is neither specific nor adapted to the company's own production system. Medium levels relate to best practice knowledge and equipment that is not always predictable, and design based on generic information. High levels correspond to scientifically underpinned design that is adapted to the own production process and that is stable and predictable. *Preventive measures* are aimed at preventing cross contamination and growth of pathogens within the production process. *Intervention* activities have the goal of reducing or inactivating pathogens to an acceptable level. *Monitoring* design refers to the present measuring and analytical equipment that is used to check if product and process parameters are kept in an acceptable range. *Operation* levels are defined to assess how the preventive measures, intervention processes and monitoring systems occur in practice (Luning et al., 2008). For the fresh produce chain, the following changes were made. Adequacy of cooling facilities was broadened to include all storage facilities. Extra indicators were added for sophistication of supplier control, sophistication of water control, specificity of the fertilization program, specificity of the pesticide program and adequacy of the irrigation method. Indicators for intervention processes are aimed at the adequacy of full, partial and chemical interventions. Indicators that are aimed at the implementation of HACCP principles are omitted as HACCP principles are not used for primary production. Indicators on adequacy of analytical equipment and specificity of sampling plans are split up into microbiological analysis and pesticide analysis. Indicators for operation levels follow these changes, as the indicator for actual capability of intervention processes is split into the capability of the full and the capability of the partial intervention processes, and actual cooling capacity is changed into actual storage capacity (Kirezieva, Jacxsens et al, 2013).

Indicators for **assurance activities** include indicators for systems set-up, validation, verification and documentation and record keeping. Criteria to differentiate between the different levels of advancement are as follows. High levels correspond to specific information based on scientific knowledge, with a criticising, procedure driven, systematic and full independent structure. Medium levels represent standard information based on expert knowledge, in a analysing,

feedback driven and partly independent structure. Low levels are based on general information obtained from historical data, within a checking, problem driven and not independent structure. If the activity described in the indicator is not present in the company's FSMS, a zero-level is attributed for this indicator. *System set-up* refers to how the FSMS is set-up, and how it is changed over time. *Validation* concerns the obtaining of scientific evidence about the effectiveness of the designed control activities. This means specifically that it has been checked in advance how effective the steps in the HACCP plan can be in assuring food safety. *Verification* is aimed at ensuring that the implemented control activities succeed in assuring food safety. Performance of the designed control activities in reality is checked here after implementation of the HACCP plan. *Documentation & record-keeping* is essential for the implementation of hygiene principles as it concerns documenting and keeping record of all procedures, implementation of HACCP principles, corrective actions, obtained scientific evidence from validation and verification, etc (Luning et al., 2009). The diagnostic instruments for the fresh produce chain keep all the same indicators for assurance activities and no new indicators are added.

System output indicators can be split into indicators for external and internal food safety performance. If no indication of food safety performance is present, a zero-level is attributed. If the specific food safety performance information is known, three levels of food safety performance are defined. The lowest level corresponds to poor performance and is associated with ad-hoc sampling, minimal used criteria for FSMS evaluation and various food safety problems due to different issues in the FSMS. Medium levels is defined as moderate performance and contains regular sampling, several used criteria and a restricted number of food safety problems all due to one specific type of problem occurring in the FSMS. The highest level means good performance and refers to systematic evaluation, specific criteria and no food safety problems. (Jacxsens et al., 2010). In the fresh produce diagnostic instruments two types of complaints are added as indicators: chemical food safety complaints and visual quality complaints. Advancement of sampling for pesticide residues and comprehensiveness of judgement criteria for pesticide residues are also added, in line with the control indicators on pesticide analysis (Kirezieva, Jacxsens et al., 2013).

1.2.2.3 Use of the diagnostic instrument in research

The FSMS-DI has already been used in numerous studies, as shown in Table 2. The original tool was aimed at companies producing animal-based products, and it was thus originally used in meat, fish and dairy processing businesses. After the development of the tool for fresh produce production by Kirezieva et al. (2013), the tool has been used in several studies concerning fresh produce such as leafy greens, strawberries, raspberries, mushrooms, etc. Next to production and processing companies, the tool had also been used in food services. Some studies investigate the FSMS of one specific company, while others make assessments for a bigger number of companies to perform cluster analysis and locate issues in food safety management for a whole sector.

Table 2 An overview of studies using the FSMS-DI to assess maturity and performance of food safety management systems is given. The investigated food sector and countries and the reached conclusions are listed.

Food Sector	Country	Conclusion	Reference
Animal based food products	Belgium, Spain, The Netherlands, Greece, Italy, Hungary	Small and medium enterprises need more tailored support from government and/or branch organizations to develop more advanced FSMSs	Luning et al. (2015)
Dairy	Japan	Companies with national HACCP approval have more advanced FSMSs and less context riskiness. Vertical legislation leads to more hazard- or legislation based FSMSs	Sampers et al. (2012)
	Tanzania	A two stage intervention would enable long term commitment and improvement to increase food safety levels	Kussaga et al. (2015)
	Kenya	Small sized company's often lack in their FSMS which decreases their ability for high microbial safety output	Njage et al. (2018)
Fish	Vietnam	A lack of data and knowledge on microbial contamination results in higher microbial risk of end products	Noseda et al. (2012)
		Following multiple food safety standards, and the presence of physical interventions have a positive effect on FSMS maturity	Van Durme et al. (2024)
	Kenya	An FSMS should be based on scientific information, historical results and own experimental trials to enhance food safety performance	Onjong et al. (2014)
	Tanzania	Reduction of context riskiness through automation of the production process is needed to move towards more effective FSMSs	Kussaga et al. (2014)
		Hygienic design needs to be improved and context riskiness reduced to guarantee safe output	Kussaga et al. (2017)
Meat	Belgium, The Netherlands, Spain	Combination of FSMS-DI and actual microbiological output measurement can provide insight in specific causes of safety problems	Luning, Jacxsens et al. (2011)
	Spain	Combined assessment with the FSMS-DI and microbiological output measurement is useful in determining specific points of improvement for better food safety performance	Oses et al. (2012)
Poultry	Belgium	The level of core FSMS activities differs between different companies in the same country. An advanced FSMS does not mean a pathogen-free product if effective interventions are not in place.	Sampers et al. (2010)
Fresh produce	Brazil	More awareness and training of farmers for implementing good agricultural practices is needed	de Quadros Rodrigues et al. (2014)

	Kenya	Due to the high context riskiness in fresh produce production, moderate FSMS activity levels are not enough to improve food safety levels	Sawe et al. (2014)
Fresh produce	Belgium, The Netherlands, Spain, Norway, Brazil, China, Egypt, India, Serbia, Kenya, South Africa, Uganda	Need for stratified measures and policies to support fresh produce companies in designing their FSMS	Kirezieva, Luning et al. (2015)
	Kenya & Uganda	Food safety standard certification play a major role in increasing maturity of FSMSs in developing countries	Nanyunja et al. (2015)
	South Africa	Small farms often lack effective HSMS implementation, which results in poor to moderate levels of food safety performance	Dzingirayi & Korsten (2016)
	Belgium & The Netherlands	Farmers in cooperatives with more hierarchical relationships score better in assessment of their FSMS, but large cooperatives with complex business systems have lower FSMS performance at farms	Kirezieva et al. (2016)
	Serbia	Global GAP certification results in better food safety outputs in primary production	Rajkovic et al. (2017)
Edible oil	China	Although food safety output is good, advancements in assurance activities can lead to a more robust FSMS	Ren et al. (2016)
Apple packhouses	Australia	Even though high FSMS performance is measured, the FSMS-DI better examined the details of the FSMS to enable continuous improvement	Frankish et al. (2022)
Powdered beverages	Malaysia	A more stringent FSMS certification contributes to better microbiological safety performance	Cheah et al. (2021)
Ready-to-eat meals	Belgium	For a high level context, a high advancement of control and assurance activities are needed, for which in this case control activities are lacking.	Spagnoli et al. (2023)
Various FBO's	Belgium	Certification systems based on audits can increase robustness of FSMSs	Jacxsens et al. (2015)
	China	An unbalance in current food laws emphasis on control over assurance activities is reflected clearly in FSMS assessments. Organizational characteristics should be improved	Ren et al. (2022)
Food service	Spain	Food service establishments with insufficient organizational conditions show both a risky context and low activity levels, which increases food safety risks	Luning et al. (2013)
Hospital food service	Belgium	Possibilities for improvement of hygienic design, sampling plans, validation and verification activities can be defined	Lahou et al. (2015)

The tool is often used in combination with microbiological output measurement such as a Microbiological Assessment Scheme (MAS). This type of combined assessment, as used by Oses et al. (2012) for example gives the opportunity to locate more precisely where the issues lie within the FSMS by microbiological analysis and what causes poor food safety performance. Like Ren et al. (2016) shows, even if good performance is found by measurement of the output microbiological food safety, the FSMS-DI can define which activities still should be improved to create a more robust FSMS. This is necessary to keep performance levels stable, even if, for example, context riskiness would increase. Spagnoli et al. (2023) uses the tool in combination with tools to assess organizational food safety culture and individual participation and motivation towards food safety, in order to make an assessment of the food safety culture in a company.

In several studies shown in Table 2, the FSMS diagnostic instrument is used to compare companies that are certified for certain food safety standards to non-certified companies. In all of these studies, it was concluded that the implementation and certification of these standards leads to more mature and more robust FSMSs (Cheah et al., 2021; Jacxsens et al., 2015; Nanyunja et al., 2015; Rajkovic et al. 2017; Sampers et al., 2012; Van Durme et al., 2024). This seems reasonable as certification bodies require implementation of certain activities into the FSMS and regularly perform audits to check compliance to the standards. These standards are set-up to try and guarantee food safety of the outcome. Maturity of the FSMS is an important part of this.

In Table 2 it is also clear that the diagnostic tool is used globally. For example, Kirezieva, Luning et al. (2015) compares the situation in countries from the EU with non-EU countries. The countries from outside the EU that were investigated are crucial in international trading relationships with the EU. It is therefore important to know whether or not FSMSs in these countries are mature and robust enough to guarantee food safety of the exported products similar to products produced in the EU. Ren et al. (2022) focuses on FBOs in China, where food law focuses more on the importance of control activities over assurance activities. This unbalance is reflected when performing FSMS assessment with the diagnostic instrument: control activities were way more advanced than assurance activities. This is often the case as quality control activities are developed first.

1.3 Impact of drivers on food safety management

Regulations on food safety and food safety standards are made up in line with the scientific knowledge that is present at the time of their development. However, this knowledge and the decisions made based on this knowledge are also subject to the cultural and political environment at that time, as Fernandez & Paoletti state (2021). It is thus important to consider the changing environment in which FBOs operate over time when making food safety management decisions. This idea has also been investigated by Baert et al. (2012), who described this process as a so called Pressure-State-Response or PSR system. The “Pressures” in this context are the drivers of change that are explained in chapter 1.1.2. These societal, technological, economic, environmental and political factors in their turn influence the “State”, which is the microbiological food safety status at the time. This then solicits a “Response” from the FBOs to deal with this new situation in their FSMS. This framework has also been expanded on to the “DPSIR framework” that Kirezieva , Jacxsens et al. (2015) uses to investigate the influence of climate change on food safety in the fresh produce chain. It exists of the “Driving force” that exerts “Pressure” and accordingly results in a certain “State” of the system. This has an "Impact" on the environment of the system and elicits a “Response”.

In Figure 3 we can see how pressures from the drivers as explained in Section 1.1.2 can impact food safety management through the structure of the diagnostic tool from Section 1.2.2.2. On the one hand, drivers can elicit a change in internal context of the company through innovation. If this internal context changes, the FSMS had to change accordingly to

preserve food safety of the output. On the other hand, drivers can also impact the way QC and QA activities are performed, and the way food safety performance is scored through food safety shocks. The company needs to build up resilience in their FSMS to combat these food safety shocks from the external environment to make sure the output always meets the needs of food safety.

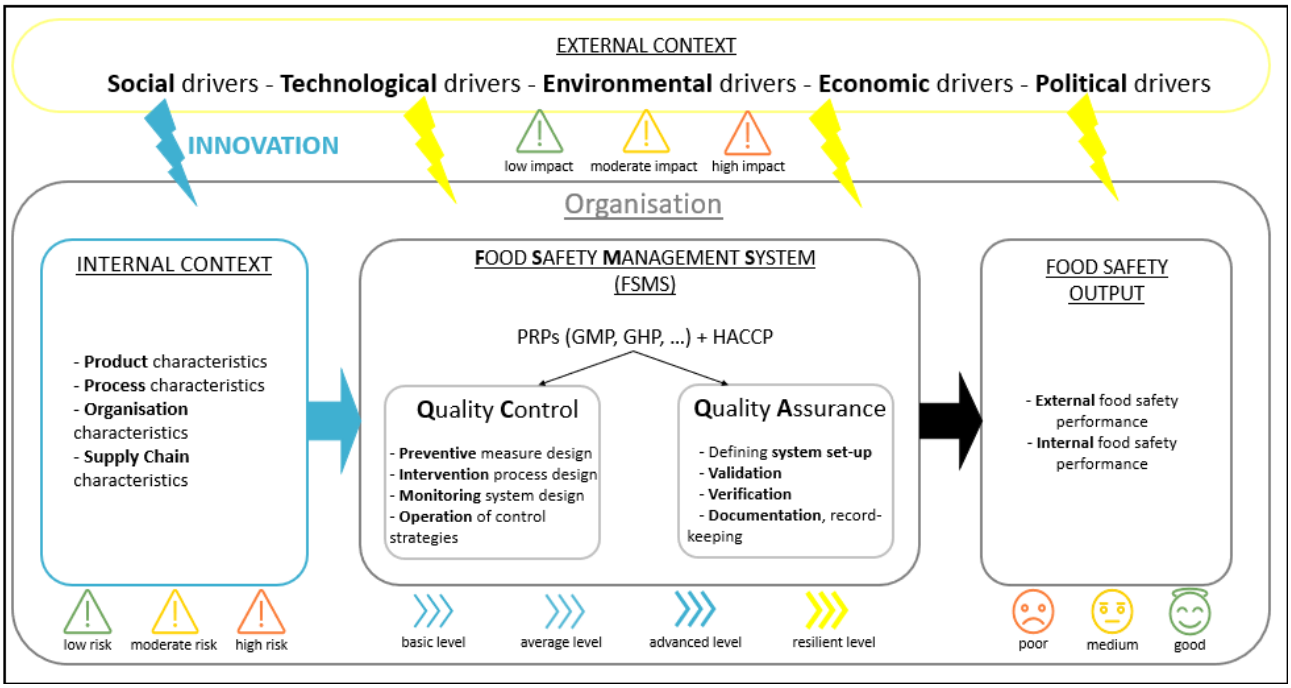

Figure 3 Impact of the drivers from the external context on the internal context via an innovation pathway (indicated with blue lightning bolt), and on the food safety management system via food safety shocks (indicated by yellow lightning bolts) eliciting the need for resilience (Vermeersch, 2024)

1.3.1 Innovation pathway

When the pressures that come from drivers change the state of the external context in which a food business operates, an FBO can choose to take a rather drastic approach by changing aspects of its internal context, as shown by the blue lightning bolt in Figure 3. An example of this could be a meat company coming on the market with plant-based alternatives and having to make up an entirely new FSMS. Another example of innovation could be the development of alternative food systems, like aquaponics as explained in Box 1. This is not the scope of this research as innovation evokes the set-up of an entirely new FSMS.

Box 1: Aquaponics

Aquaponics is an example of an alternative food system, that is influenced by the drivers of management of natural resources, climate change and urbanisation. It is based on the pairing of fish farming or aquaculture and soilless cultivation of fresh produce or hydroponics. Fish waste water goes through a set of filtration steps before being used for the cultivation of herbs and vegetables. The fish excrements still present in this water serve as a fertilizer for growing the plants. Zero-waste strategies and the principles of a circular economy are the basis of this concept. Aquaponics also fit into urban settings where surface area for agricultural activities is limited (Nenciu et al., 2022). Because there are two coupled production systems present here, one focused on animal based products and one plant based, food safety management is more complicated. Reusing the aquaculture water for the hydroponics system also calls for specific food safety measures. Integrating such a system in an urban environment can also bring with it certain pathogens that can end up in the produced end products (Buscaroli et al., 2021). Alternative systems like aquaponics should be considered in FSMS assessment as they bring with them emerging issues that should be addressed.

1.3.2 Food safety shocks

1.3.2.1 Reacting to food safety shocks

When a food safety shock occurs, the impact of it on microbiological food safety will be felt in the food safety of a food company's output, as indicated by the yellow lightning bolts in Figure 3. It is possible that there is no option to intervene with this issue or prevent it from impacting food safety of the product, and that the company has to undergo the consequences (e.g. a recall). However, there are multiple ways in which a company can react to try to combat this food safety shock. **Coping** can be described as a short-term solution that uses the available knowledge and equipment to preserve the current systems as much as possible while dealing with the influence of the drivers. **Adaptation** can then be seen as a long-term evolution of the FSMS where learning and experimentation are key (Paloviita et al., 2017). Possible responses for FBOs that were listed by Baert et al. (2012) are communication as a form of coping, and training as a form of adaptation. Communication here includes informing and sensitizing, dialogue and consultation. Training refers to capacity building in comprehending and providing clarity on drivers and their impact on food safety.

1.3.2.2 Resilient food safety management

Multiple definitions exist of what it means to be 'resilient'. When used in the context of business management, resilience is often defined in terms of the capacity to recover from future disturbances of any possible form. Different from the definition of "robustness", which is a system's ability to resist the impact of shocks and maintain a stable situation, resilience includes the flexibility to adapt to the situation and recover to a "new normal". A resilient system can be vulnerable in case of disturbances, but has the capacity to recover from these shocks (Antunes et al., 2011; Mu et al., 2021). When an unforeseen disturbance, albeit known or unknown, occurs, a resilient system has the robustness to not immediately feel the impact, but when the disturbance does trigger a response, the system can be adapted to rebound as quickly as possible. This is illustrated by the resilience triangle theory shown in Figure 4. System A in this graph lacks resilience as the operational level drops immediately when confronted with a disturbance and recovers slowly. System C is too robust, and lacks flexibility: the system stays stable through the disruptions at first, but long-term pressure leaves the system with a significant drop in operational level from which it cannot recover. System B is the most resilient: the response is small and postponed, and the recovery is quick. The smaller the resilience triangle is, the more resilient the system (Rød et al., 2020).

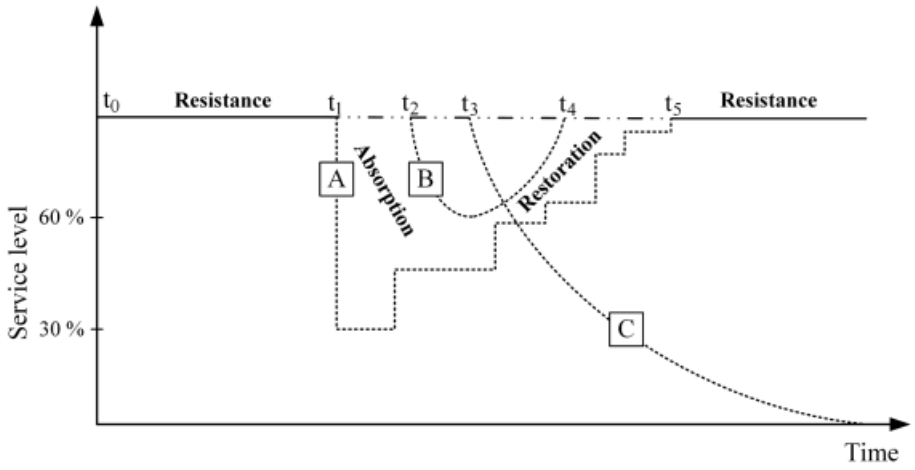

Figure 4 The resilience triangle: how different systems react to unforeseen disturbances. (Rød et al., 2020)

Mu et al. (2021) defines resilient food safety management specifically as "the recovery and adaptation capacity of the food supply chain to food safety shocks to allow the delivery of safe food over a reasonable lead time". In this situation, the desired state of the food system is that of sufficient food safety. While robust food safety management aims at the idea of zero food safety risks, resilient food safety management is more practical by adapting to emerging hazards and returning to a reasonable food safety state as quickly as possible. The same definition can be used on the level of FBO's.

Frameworks on how this resilience can be achieved practically, often start from the Skill-Rule-Knowledge model set up by Rasmussen (1982). According to this study, the human mind can react to a problem in three different ways: a skill-based reaction relies entirely on automatic control and happens almost unconsciously. It is the result of long-term experience and good training. On the other hand, a knowledge-based approach concerns situations where active problem-solving and improvisation come into play. A rule-based reaction forms the middle ground between the two: this occurs when the situation consists of known or prescribed problems, for which a right way to handle them has already been determined. The used reactions in these situations are different from day-to-day activities, but improvisation is not needed as the rules are already written down. Resilience is then the capability to successfully solve novel problems in a knowledge-based way, translate this into new rules and eventually be able to react to similar problems in a skill-based way. Bracco et al. (2014) used this idea to create a Resilience Framework Matrix, shown in Figure 5.

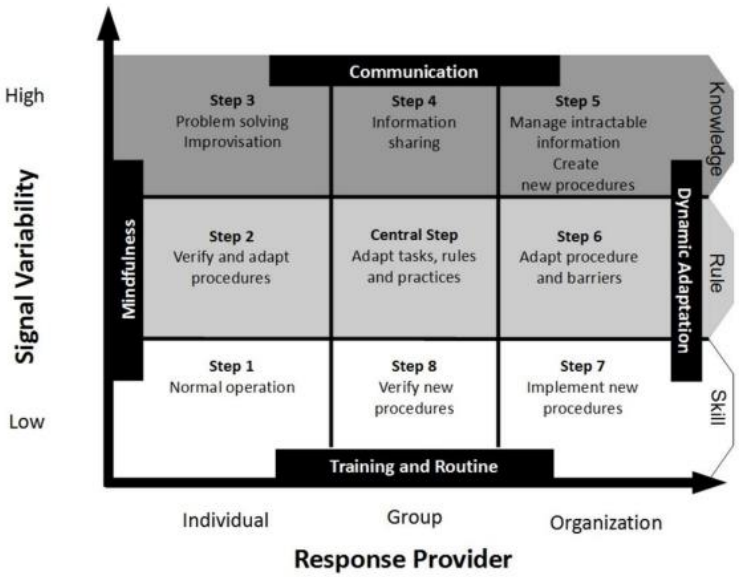

Figure 5 Resilience Framework Matrix (Bracco et al., 2014)

This framework can be applied to businesses to show how should be reacted to inconsistencies and works as a cyclic information system. Variability in operations are normal to a certain extent, and can be dealt with as part of normal operations on a skill-based level to that extent. With larger variability, it can be necessary for the production workers to verify or adapt procedures in a rule-based way, or even to proceed to problem solving and improvisation. Production workers should be able to recognize these inconsistencies and what could be the source of them, and then communicate to the group what they observed. The group could decide to adapt certain tasks, rules and practices in order to deal with these inconsistencies better in the future, but if this is out of there hand, they should inform the organization. On the organizational level, the received information should be used to look at the bigger picture and figure out the root cause of the problems. The new information can be used to clear up parts of the intractable system in which a business operates. New procedures are created based on the new insights, and can then be translated into new rules and day-to-day operations. This information needs to be relayed back to the group and the individual workers through training. New procedures can then be verified for how well they deal with the incoming disturbances and resulting inconsistencies (Bracco et al., 2014). Adini et al. (2017) also highlight the importance of collaboration, planning, procedures and training is resilient management. Good communication is key to make this cycle run smoothly.

A high level of resilience in a company's food safety management system is thus characterized by how quickly they can turn an adverse situation around to be able to provide safe food again after a disturbance has occurred. This was highlighted by the resilience triangle as seen in Figure 4, as well as in the Resilience Framework Matrix, where the cycle should be run through in a smooth way. At the basis of this are various trade-offs. The system should be robust enough to be stable through disturbances, but also flexible enough to actually absorb the disturbance and adapt to it, in order to stay stable if this disturbance becomes more prominent. Procedures should be strict enough to be able to mainly work in a skill-based or rule-based way, but there should be room for adaptation of procedures and improvisation on a knowledge-based level when needed. Inconsistencies should be monitored and analyzed, but should only be translated into new procedures when there is a significant root cause that should be dealt with now and in the future. For this all to work, communication and training are necessary (Adini et al., 2017 ; Antunes et al., 2011 ; Bracco et al., 2014). Rød et al. (2020) measured this in different companies through indicators, where the highest level of resilience was described as having continuous re-evaluation or monitoring, and ongoing preventive maintenance. This can be incorporated into the Food Safety Management System Diagnostic Instrument by adding a new level to the indicators for quality control and quality assurance where evaluation and monitoring occur routinely or continuously, and the possibility for adaptation is present.

2 MATERIALS AND METHODS

2.1 Diagnosis of an alternative food system using the current diagnostic instrument

To get familiar with the diagnostic instrument, the current tool was tested in an alternative food system. To do this, an in depth interview was conducted with the manager of an aquaponics company. Results of this interview could also highlight any weaknesses of the current tool in assessing the maturity of a Food Safety Management System in a more innovative food business. Indicators from the original tool as well as the tool for primary production were used to allow for comparison between the two. Indicators related to the HACCP principles were left out as the focus was on their primary production, where HACCP principles are not legally obliged to be used. These were the indicators for *Appropriateness of CCP analysis, Appropriateness assessment of standards and tolerances* and *Sophistication of validating monitoring systems* . Firstly, the diagnostic instrument was introduced and some important definitions that come back regularly in the indicators were explained. The company characteristics that are questioned at the start of the tool were defined. A representative production unit or RPU was chosen following the instructions provided in the tool. Then, all 74 indicators were gone over and the appropriate level was indicated. To differentiate between the levels, the descriptions in the grids and the provided "if, then" statements were used. Where needed, discussion was possible between the company managers and the interviewers to define the right level based on provided examples. Results were translated into spider diagrams for both the original tool and the tool for primary production. For the context indicators, the bigger the coloured surface area on the spider chart, the higher the context riskiness. For the other indicator categories, the bigger the coloured surface area, the more mature the company's Food Safety Management System is for this category. Average scores per category were calculated based on the indicated levels for each indicator: the lowest level corresponds to a score of 1, and the highest level corresponds to a score of 3 for context indicators and a score of 4 for the other indicator categories. Based on the conversion shown in Table 3, these averages were translated into an attributed score.

Table 3 Score conversion for the interpretation of the results for an interview with the current diagnostic instrument

Category	Average score	Attributed score
Context	1 - 1.2	1
	1.3 - 1.7	1_2
	1.8 – 2.2	2
	2.3 – 2.7	2_3
	2.8 – 3.0	3
Control / Assurance / Performance	1 – 1.2	1
	1.3 – 2.2	2
	2.3 – 2.7	2_3
	2.8 – 3.2	3
	3.3 – 3.7	3_4
	3.8 – 4	4

The results of this interview are meant to shed light on how the current diagnostic instrument assesses an alternative food business, where innovation was influenced by specific drivers and subdrivers such as urbanisation and management of natural resources. A comparison between the original tool and the tool for primary production, constructed by Kirezieva et al. (2013) can also be made. When the tool is updated to include the influence of drivers and subdrivers, for which this thesis forms the basis, this result can be used as a baseline measurement to compare the new results to.

2.2 Updating the existing diagnostic instrument

The goal of this research is to contribute to an update of the diagnostic instrument by incorporating the influence of the drivers and subdrivers on a company's FSMS. The approach is shown graphically in Figure 6. A first literature review, which can be found in the literature study of this thesis, was used to set the scene. This led to the determination of two pathways in which this takes place, the innovation pathway and the resilience pathway. The focus of this thesis will be on the latter, and thus the influence of food safety shocks leading to the need for resilient food safety management. These food safety shocks have specific implications for the way FSMS activities are executed, so this impact needs to be taking into account in the FSMS-DI as well as the resilience of the FSMS activities. Therefore, the next step is to figure out which drivers have impact and which are most important to consider. An expert elicitation, as well as a structured literature study, are used for data collection. The results of this are found in the results section of this thesis. The collected data is then analysed to couple the drivers and subdrivers to the FSMS activities and indicators of the FSMS-DI. This coupling is also found in the results section. These results, as well as the results of the first literature review, are used to propose how the indicators of the current diagnostic instrument can be updated to include a resilience level for QC and QA activities, and to include indicators on the impact of external context factors. The definition of the resilience level is established in the results section. Suggestions for external context indicators are given in the discussion section.

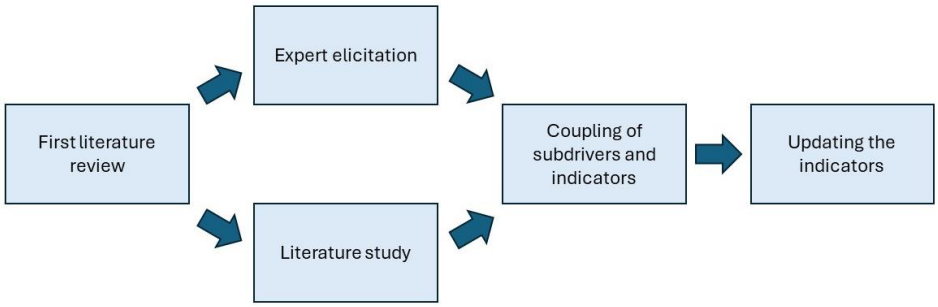

Figure 6 Approach to update the diagnostic instrument

2.2.1 Expert elicitation

2.2.1.1 Goal and methodology of the expert elicitation

To understand how drivers and subdrivers impact the external context of a food business, experts from the field are consulted. An answer is sought to the question of which drivers are relevant to consider and if/how an FBO can deal with these drivers. Based on the guidance document of EFSA (2014b) concerning expert elicitations in food safety risk assessment and the study of Rowe et al. (2016) on ranking food safety priorities, a Delphi study was selected as the method for this expert evaluation. A Delphi study consists of iterative individual questionnaires, conducted in person or online, with feedback moments between the different rounds where answers from the previous rounds are provided to include controlled and anonymous interaction. The goal is to gain consensus among experts. The first round is usually mostly qualitative, asking open questions to get a wide variety of input, whereas the following rounds aim at quantitatively assessing the input from the first round through iterative surveys using scores, rankings, etc. Rationales are often requested, so that these can be used as feedback for a next round. In this study however, a list of drivers to go over is already provided, so there is no need for an open ended first round question. This approach is called a modified Delphi method (Johnston et al., 2014). The question to ask would be to score the different subdrivers on relevance and on feasibility using a 5-point Likert scale. Relevance is understood as the extent to which it is important to consider the subdriver in a business's FSMS, whereas feasibility is about whether an FBO can anticipate and deal with the impact of this subdriver. Additionally, a top 3 including rationales behind the selection of the 3 most important subdrivers would

be asked for. Average scores for relevance and feasibility and ranking results as well as the rationales could be provided as feedback for a second round.
However, when discussing this approach with an expert in the field, a point was made about the importance of understanding how FBO's see the way in which subdrivers impact their food safety management. This resulted in a shift of approach where the focus now lies on finding the mechanisms at play between food safety shocks caused by drivers/subdrivers, and changes in microbiological food safety management in a food business. The first suggestion to reach this goal was to organize an in person focus group discussion, where FBO's are first asked to think about which drivers are important to consider individually and which FSMS they think are affected by the driver, followed by a division in groups where the mechanisms that are present are analyzed. These mechanisms could then be presented to the other groups, which allows for feedback and open discussion between the groups. This approach was then revised and further refined, keeping in mind how the results of these discussions would be collected in a uniform manner. A second suggestion, inspired by the concept of a modified Delphi approach included a first and third round asking for a ranking of subdrivers that are important to consider as well as the mechanisms with which these drivers impact certain FSMS activities, with the second round being a group discussion focused on the specific impact of these drivers they foresee and how a business could deal with this impact. The mechanisms in the first and third round would be constructed in the form of "For subdriver X, the considered impact is …, affecting the FSMS activity Y". This sentence would need to be provided for the 10 subdrivers that are considered most important according to the participant. A list of all 34 subdrivers would be given, and FSMS activities would be split up into preventive measures, interventions, monitoring and operation for QC, system set-up, validation, verification and documentation & record-keeping for QA, and external and internal food safety performance for food safety of the ouput, following the structure of the diagnostic tool as explained in Section 1.2.2.2. All subdrivers and FSMS activities would be explained in the introduction of the session. The second round would consist of 4 groups, with one discussing all subdrivers in the social category, one discussing the subdrivers of the technological category, a third group going over the environmental category, and the last group talking about economic and political subdrivers. A presentation from each group would conclude the second round. To spare time however, the need for a group discussion was questioned. As no real consensus is needed, as much as getting the individual input of each FBO, this element was scrapped.

2.2.1.2 Set-up of the workshop

A workshop was conducted in two sessions of about 2 hours each, on the 27th and the 28th of March 2024. The workshop followed a simple questionnaire set up with Qualtrics, and was held online through a Teams meeting. This was decided on so that participants can follow the workshop from their own workplace. Participants were selected based on voluntary participation, by sending an e-mail to as many contacts in the field as possible. Employees working in quality management in food businesses throughout Flanders were targeted for this thought experiment. An informed consent, which can be found in Appendix 1, was obtained from all participants. Participants were encouraged to ask questions where needed throughout the sessions. In this workshop, the goal is to gather information on how FBO's felt subdrivers could impact their FSMS activities, focusing on microbiological food safety, as well as making a ranking of the most important subdrivers to consider in a food business's FSMS.

The introduction of the sessions included a personal introduction of all participants present in the meeting, an introduction of the Horizon Europe FoodSafeR project, an explanation of Food Safety Management Systems as described in Commission Notice 2016/C278 and the diagnostic instrument, as well as the goal of this research and the workshops. In this the 10 FSMS activities that are incorporated in the questionnaire were explained as shown in Appendix 2. The participants were then given the URL for the Qualtrics survey, and asked to fill out the questions on company characteristics. The questions included in this were based on the list of company characteristics questioned in the research of Spagnoli, Vlerick et al. (2023) for the department of Food Technology, Safety and Health last year. Some

extra questions based on the company characteristics asked about in the diagnostic instrument are added to this. The whole list of company characteristics questions is given in Appendix 3. Then, the first set of subdrivers were explained. The subdrivers were split into 4 groups: the social (n=10), technological (n=9), environmental (n=8) and economic & political (n=2+5) categories. Per group, an explanation of each driver and its subdrivers was given orally as well as presented on screen. The explanations for each subdriver are given in Appendix 2. For each group, an example of a subdriver impacting a FSMS activity in a fictitious company was provided to help the participants along. These examples are given in Appendix 4. The first question about these subdrivers is "Can these social subdrivers have a direct impact on the Food Safety Management System of your organisation?", followed by a list of these subdrivers for which the participant had to check "Yes" or "No". Then, for all subdrivers where the answer "Yes" was checked, two follow-up questions were given: "What food safety management system activity does the subdriver **"..."** directly impact?" and "Provide an example of how the subdriver "..." affects this FSMS activity in your organisation.". The former is a multiple choice question where one of the 10 FSMS activities has to be indicated, the latter being an open-ended question. Per subdriver, this could be filled in for a maximum of three FSMS activities. This was done by asking the question "Does the subdriver "..." affect other FSMS activities?" where the answer options were "Yes" or "No". If the participant checks "Yes", the two questions on the impact of the subdriver are asked again in the same way, followed again by the question of if there are any other FSMS activities affected. If the participant checks "Yes" again, the two questions are asked yet again, without asking if there are any more. When completing this set of questions for all subdrivers in one group, the participants were asked to wait for the explanation of the next group of subdrivers before continuing the survey. When most participants reached this point, the next group was introduced and a new round of the same questions were gone through. A break was inserted between the technological and the environmental group. After the questions for the last group of subdrivers were completed, the participants were asked to rank the subdrivers with the question "What are the most important subdrivers that have a direct impact on your food safety management system? Provide your top 5 by dragging the subdrivers in the box and ranking them.". A list of all subdrivers that the participant previously indicated in the first question per group was provided, as well as a box named "Top 5" where they could drag the subdrivers to in the correct order according to them.

2.2.1.3 Conduct of the workshop sessions

For the first session, 16 people were registered to attend, of which 15 people actually attended. One person chose to not complete the survey because their company solely focuses on distribution and they felt this exercise was less applicable to them. One person had to leave due to urgent work commitments. In the end, only eight full responses were recorded for this first session. At the end of the session, participants were asked to orally give their remarks on the workshop. Multiple participants mentioned the lack of a "back" button, to go back to the previous question, bothering them. Most participants did say that they found this thought exercise quite hard, especially with the focus purely being on microbiological food safety. They also noted that they were often confused on the specific definition of the subdrivers and FSMS activities, despite the encouragement to ask those questions during the workshop.

For the second session, nine people were registered to attend. One person immediately excused themselves as their company had an unannounced audit at the time of the workshop. Of the eight responses recorded at the end of the workshop, one participant missed the introductory explanation due to being late, and one participant missed the explanation of the economic and political subdrivers. It is not known which responses belong to these participants. One participant had technical difficulties at the end of the survey which meant they were unable to fill out the question on ranking of the subdrivers. The participant did send in their top 5 through email one month after the workshop due to being in leave in between. Following the reactions of the participants from session 1, a "back" button was added to the survey, and more attention was given to the explanation of the FSMS activities and the subdrivers.

Table 4 Company characteristics from the respondents. These questions are based on the company characteristics questioned in Spagnoli, Vlerick et al. (2023)

Participant	Session	Larger company	Family owned	#FTE	Chain position	Plant/animal based	Export	Premium/private label
1	1	No	Yes	>249	Trans + distr	Plant	Yes	Private
2	1	No	Yes	10-49	Trans + distr	Plant	Yes	Premium
3	1	No	Yes	10-49	Trans + distr	Plant	Yes	Both
4	1	Yes	Yes	10-49	Trans	Plant	Yes	Both
5	1	Yes	Yes	>249	Trans + distr	Plant	Yes	Both
6	1	No	No	<10	Trans	Animal	Yes	Both
7	1	No	Yes	50-249	Trans + distr	Both	Yes	Private
8	1	No	Yes	10-49	Trans + distr	Animal	Yes	Both
9	2	No	Yes	50-249	Trans + distr	Plant	No	Both
10	2	Yes	Yes	>249	Trans + distr	Both	Yes	Both
11	2	Yes	Yes	>249	Trans + distr	Animal	No	Premium
12	2	Yes	Yes	50-249	Trans + distr	Plant	Yes	Both
13	2	No	Yes	10-49	Trans + distr	Both	No	Both
14	2	Yes	Yes	>249	Trans	Both	Yes	Both
15	2	Yes	No	>249	Trans	Plant	Yes	Both

The company characteristics that were recorded according to the questions in Appendix 3 are provided for all 15 participants in Table 4 and Table 5. Participant 6 is an employee in a sector organisation concerning animal products. This is also the only participating company that has no QA manager or department. Participant 15 is the person that had to sent in their top 5 through email at a later date due to technical difficulties. Out of the 15 participants, 13 work for a family-owned business, which is representative of the situation in Belgium, and most (n=12) companies do export outside of the European Union. All companies are certified for at least one QA standard.

Figure 6 shows a screenshot of the workshop as it took place on Microsoft Teams. The introduction was given by both the writer, tutor and promotor of this thesis. Explanations of a specific part were done by the same person over the two sessions. In session 1 all three were present at the same place, in session 2 only the writer and the tutor of this thesis. All participants were encouraged to put on their camera during the introduction, disconnect the camera while filling in the survey, and put it on again when they were finished filling in all questions of a group. When a new group of subdrivers was explained, they were encouraged to all reconnect their camera, despite of if they were finished with the previous group, to make sure everyone was attentive to these explanations. Question could be put in the meeting chat or posed orally.

Table 5 Company characteristics of the 15 workshop participants. These questions are based on the company characteristics questioned in the FSMS diagnostic instrument.

Participant	Session	QA standards implemented	QA standards certified	QA manager	QA department	# QA employees
1	1	PRP, HACCP, ISO9001, ISO22000, BRC, IFS	ISO9001, ISO22000, BRC, IFS	Yes	Yes	30
2	1	HACCP, IFS	IFS	Yes	Yes	4
3	1	PRP, HACCP, IFS	IFS	Yes	Yes	4
4	1	HACCP, IFS	IFS	Yes	Yes	4
5	1	PRP, HACCP, IFS, National standard: ACS	IFS, National standard: ACS	Yes	Yes	9
6	1		BRC, IFS, Others: Febev +, Belpork, Belbeef	No	No	/
7	1	BRC, IFS, National standard: ACS	BRC, IFS, National standard: ACS	Yes	Yes	3
8	1	PRP, HACCP, IFS, National standard: ACS	IFS, National standard: ACS	Yes	Yes	4
9	2	PRP, HACCP, IFS, National standard: ACS	IFS, National standard: ACS	Yes	Yes	4
10	2	HACCP, ISO9001, ISO22000, National standard: FSSC 22000	ISO9001, ISO22000	Yes	Yes	>100
11	2	PRP, HACCP, National standard: ACS	National standard: ACS	Yes	Yes	6
12	2	HACCP, BRC, IFS	BRC	Yes	Yes	12
13	2	PRP, HACCP, ISO22000	ISO22000, Other: MSC, ASC, BIO	Yes	Yes	2
14	2	BRC, IFS, National standard: ACS, Other: RSPO, BIO, glutenfree, customer specific QA standards	BRC, IFS, National standard: ACS, Other: RSPO, BIO, glutenfree	Yes	Yes	20
15	2	PRP, HACCP, ISO22000, National standard: Depending on the country, in Belgium - Zelf controle	ISO22000, National standard: As above	Yes	Yes	~1000

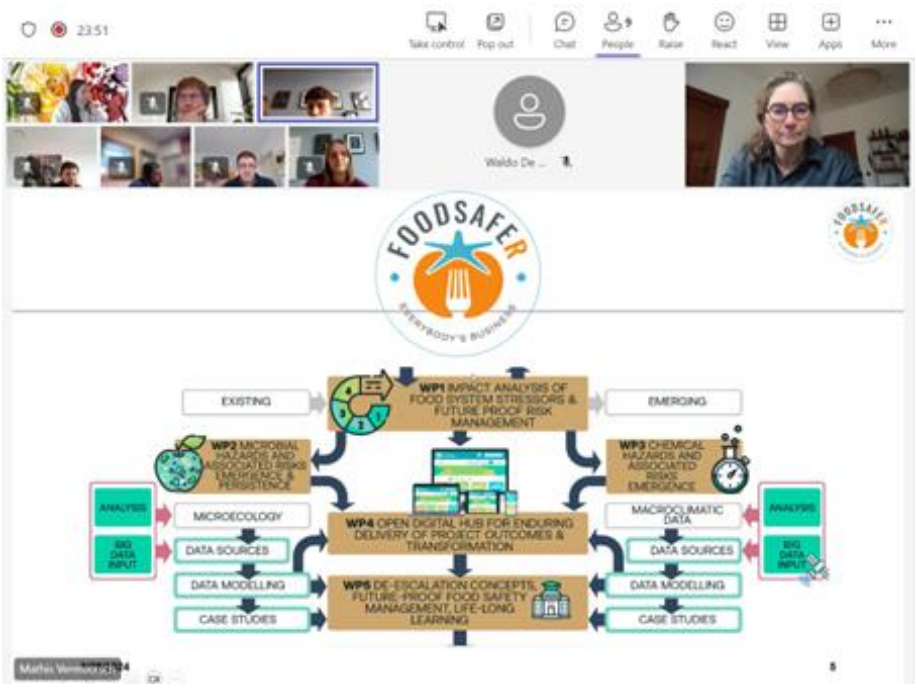

Figure 6 Screenshot taken during the introduction of session 2 of the workshop

2.2.1.4 Data processing of workshop results

Data was obtained from Qualtrics in the form of excel files. Participant were given the option to answer either in Dutch or English. The first steps of the data processing uses the both languages as used by the participants. Where given, translations are made with DeepL Translate. Company characteristics were not further processed. Results of this are mostly provided to give an idea of the constitution of the group of participants. Answers on the question "Can these social subdrivers have a direct impact on the Food Safety Management System of your organisation?" are processed quantitatively to see which drivers are most indicated as having a direct impact on a company's FSMS. To do this, firstly the provided examples given for each subdriver are also considered to allow for interpretation and related data cleaning. If the example refers specifically to a mechanism for chemical food safety issues or allergen issues, instead of microbiological food safety issues, the answer is not considered in counting the indicated drivers. Examples mentioning no actual impact is considered are also not considered. Examples that clearly indicate misinterpretation of the subdriver definition are either not considered if the example does not fall under any other subdrivers, or added to the count of another subdriver if it does refer to that subdriver. Based on the final count, a top 3 can be established for each category of subdrivers. As there are only 2 economic subdrivers, here only the most indicated subdriver is chosen.

The provided examples, as answers to the question "Provide an example of how the subdriver **"..."** affects this FSMS activity in your organisation.", are processed quantitatively. This is done for all subdrivers that are part of the top 3 of their respective category. The way in which this will be done is based on the principles of grounded theory to inductively generate an understanding of the impact mechanisms of subdrivers on FSMS activities. To do this, coding of the given answers is used to find relationships and theories in the various provided examples. Based on the guidelines of Charmaz (2006) the data analysis starts with initial coding. The intention here is to stick as closely to the initial data as possible and keep an open mind on interpretation of the words. Codes can be adapted throughout this first phase when different examples use different wordings to say the same thing, without steering too much away from the original phrase. In this research, initial coding will be used to simplify the examples to get a mechanism in the form of "subdriver effect" -> "FSMS activity impact". A code is thus formed to represent the effect the FBO sees at the subdriver side, as well as the specific impact it has on the FSMS activity. If no information is given on one of the two sides (e.g. only the specific impact on the FSMS activity is mentioned without giving a reason for this at the subdriver side), the name of the indicated subdriver or FSMS activity is used as a code to complete the mechanism. If the participant gives no example

or an example where no clear mechanism can be described, no coding is done. This coding also reveals if the participant understood the meaning of the subdrivers correctly. Where needed, the indicated FSMS activity is replaced by one that more closely relates to the given example. For the answers where no (clear) mechanism is described, it is assumed that the participant understood the meaning of the FSMS activity correctly. The answers for the question "What food safety management system activity does the subdriver **"..."** directly impact?" are cleaned up in this way. For the top 3 of each category (for the economic category only the highest ranked driver is considered in further processing), a heat map is made up of the links between the subdrivers and the FSMS activities. Then a second phase of coding is started: focused coding. Here codes from both the subdriver and the FSMS activity side are grouped together to form categories of effects and their impacts. Interpretation of the answers to form these categories are based on analysis of the different answers that are given as well as on scientific knowledge. More detailed heatmaps can then be made showing the mechanisms at play between the subdrivers and FSMS activities.

2.2.2 Coupling of subdrivers and indicators through literature review

Literature can be used to either support the qualitative analysis, but also to be processed and coded in the same way as the workshop results. This is done to give a comparison of the most important mechanisms according to scientific literature. A second way in which literature is used here is to find out where the drivers could impact the existing context indicators (McCalin, 2003).

In a first stage, an attempt was made to couple drivers and indicators through internal discussions amongst student, tutor and promotor. The thought process behind the links that were made could then be supported through a targeted literature search. However, to make the methodology more robust and reproducible, another approach was chosen where a scoping literature review is at the basis of the coupling. The results of this coupling and the papers that are found can then be used to support the results of the workshop, and to reflect on what mechanisms are highlighted most in literature.

The bibliographic database of Clarivate Web of Science was consulted for this literature review. In order to find the relevant literature search strings are constructed as follows. The abstract of the paper should contain the words "safe" or "safety" (coded together as "safe*"), "microbiological" or any variations on it (coded as microb*) and food. To find a link between drivers and indicators, a list of search terms is compiled for all subdrivers and indicators, shown in Table 6 for the subdrivers, Table 7 for the context indicators and in Table 8 for the FSMS activities. This list was compiled based on the explanations of the subdrivers as described in Chapter 1.1.2 of this thesis and on the full content of the indicators in the current diagnostic instrument. In a first draft of these search terms, it seemed that some subdrivers were not sufficiently characterized by these terms and that they often appeared in a different context then intended. For the subdrivers of "Dietary choice" and "Consumer awareness & attitude", at first the used search terms were based upon the explanations given in Chapter 1.1.2, including terms for "Ready-to-eat" and "Fresh food" for dietary choice and "Plant-based" and "Clean label" for consumer awareness & attitude, which led to the majority of the papers highlighting these specific topics. However, in the workshop, different definitions were used for these subdrivers, so using these search terms would complicate comparison between the results of the workshop and the literature review. Therefore these search terms were left out and were exchanged for "Dietary preference" and "Dietary choice", and for "Consumer preference", "Consumer awareness" and "Consumer attitude" to reflect the definitions given in the workshop more closely. For the subdriver on Urbanisation, the initial search term "Urban*" was intended to encompass urbanisation and variations on the word written with an s or a z, as well as concepts like urban agriculture. However, the use of urban as an adjective in papers often did not fit the context of growing urbanisation, so the search term was changed for "Urbani*" to still include both spellings, and "Urban agriculture" was included as a second search term. "Migration" as a search term for migration & travel led to papers talking about migration from chemical components in packaging to

the packaged food, so this search term was changed to “Immigration”. For “Resistant pests & diseases”, the search term “Diseas*” was scrapped, as most papers that were found were only included in the search because there was mention of “foodborne diseases” as a result of lacking food safety, which is too broad for the intent of this literature review. It was replaced by “Antimicrobial resistance”. For “Products for food production, “Feed” was used as a third search term, but this often led to studies that focused on “food and feed” or feed in general, instead of finding results on how the used feed for animal production could impact microbiological quality of a food product using the meat or other products from these animals. The search terms of “Formulation” and “Composition” were changed to “Food formulation” and “Food composition” as too often papers talking about formulation or composition of other elements such as packaging materials were included in the search. For the FSMS activity of monitoring, the search terms that were used in the first place were “Monitor*”, “Analys*” and “Measur*” to include all forms of this activity, however, a lot of irrelevant results turned up because they included other types of analysis (data analysis, analysis of other components, analysis of other papers, …) and measurements of other aspects performed in the reported research. No usable results were found for the search term “Measur*” Therefore, the search terms were changed to “Monitoring” and “Microbiological analysis” to find more accurate results.

These terms from Table 6, 7 & 8 are added to the search string separated by the Boolean operator “AND” between the terms for subdrivers and indicators, and the Boolean operator “OR” between the different search terms for either the subdriver or indicator. An example of how the search string looks like for the indicator of “Information systems” and the subdriver “New digital technologies” is as follows: AB=(safe* AND food AND microb* AND ("information system") AND ("digital technology" OR "blockchain" OR “artificial intelligence”)). An exemption is made for the drivers of “Plant-derived food production” and “Animal-derived food production”, that both pertain to primary production. Here, the search string for the driver will look like this: (“agriculture* technolog*” OR “primary production” AND “plant”), with “plant” being replaced by “animal” for the latter. The words “plant” and “animal” in Table 4 are indicated in bold to signify that they are preceded by the Boolean operator AND. The results are further refined by excluding all articles older then 2017, all articles in another language then English and all articles where no full text was available through the University of Ghent. When no results are found, it is assumed that no link can be found through this method.

Table 6 Search terms for the subdrivers in the scoping review

Subdriver	Search term 1	Search term 2	Search term 3
Dietary choice	Dietary choice	Dietary preference	Diet*
Consumer awareness and attitude	Consumer awareness	Consumer attitude*	Consumer preference*
Consumer knowledge	Consumer knowledge	Hygiene knowledge	Consumer information
Public awareness	Public awareness		
Population (size)	Population growth	Population size	Food demand increas*
Prevalence of vulnerable groups	Vulnerable group*	Consumer vulnerab*	YOPI
Urbanisation	Urbani*	Urban agriculture	
Migration and travel	Immigrat*	Travel	Traditional food
Human health conditions	Consumer health	Consumer susceptib*	Health condition
Resistant pests and diseases	Resistan* pest*	Resistan* pathogen	Antimicrobial resistance
Plant-derived food production	Agricultur* technolog*	Primary production	**Plant**
Animal-derived food production	Agricultur* technolog*	Primary production	**Animal**
Novel food sources	Novel food*	Insect*	Seaweed
Products for food production	Fertiliz*	Pesticide	
Processing techniques and scale	Processing scale	Processing technique*	
Upcycling for food	Upcycl*		
New digital technologies	Digital technology	Blockchain	Artificial intelligence
Food formulation	Food formulation	Food composition	
Food packaging	Packaging technology		
Agricultural pollution	Agricultur* pollut*	Groundwater pollut*	
Sewage treatment	Sewage treatment		
Recycling	Recycl*		
Use of side streams	Sidestream	Process water	
Water and soil management	Water management	Soil management	
Geographic region	Geographic region		
Seasonality & weather	Season*	Weather	
Climate change	Climate change	Global warming	
Global trade	Global trade	Globali*	
Distribution channels	Distribution channel	Supply chain	
Official controls and communication	Official control*	Official communication	
Good practices and standards	Good practices	Standards	
Food legislation	Food legislation	Food law	
War and conflict	War	International conflict	
Fragmentation between nations	International fragmentation		

Table 7 Search terms for the context indicators in the scoping review

Indicator	Search term 1	Search term 2	Search term 3
Contamination initial materials	Contaminat* ingredient*	Initial contamin*	
Contamination final product	Product contaminat*		
Packaging concept	Packaging		
Interventions	Intervention strategies	Pathogen reduc*	Pathogen inactivat*
Changes in the production process	Product chang*	Process chang*	
Rate of changes	Product change rate	Process change rate	
Technological staff	Technological staff		
Variability of workforce composition	Staff variability	Workforce variability	Workforce composition
Operator competences	Operator competence		
Management commitment	Management commitment		
Employee involvement	Employee involvement		
Formalization	Formali*ation		
Information systems	Information system		
Role in the safety of the chain	Supply chain position		
Supplier relationship	Supplier relationship		
Customer relationship	Customer relationship		
Requirements of stakeholders	Stakeholder require*		

Table 8 Search terms for control and assurance activities and performance indicators in the scoping review

	Search term 1	Search term 2	Search term 3
Preventive measures	Preventive measure*	Hygiene	Material control
Intervention	Intervention strategies	Pathogen reduc*	Pathogen inactivat*
Monitoring	Monitoring	Microbiological analysis	
Operation	Operation*	Procedure compl*	Equipment capacity
System set-up	System set-up	System modification	
Validation	Validation		
Verification	Verification		
Documentation & record-keeping	Documentation	Record keeping	
External food safety performance	Audit*	External inspection	Complaint*
Internal food safety performance	Non-conformities	Internal inspection	

This selection of papers was scanned further by reading through the article abstract. If the search terms that lead to this article were present in another context or with another meaning, the articles were excluded. Examples of this are seasoning for "Season*", gut microbiota for "microb*", novel or traditional food processing or packaging for "Novel food*" or "Traditional food". Articles talking mainly about chemical risks, allergens, production of animal food or animal diets, and production of non-food products were also excluded. Figure 7 shows the PRISMA flow diagrams of the literature review, based on the PRISMA flow diagram of Page et al. (2021), but adapted for the order of steps taken in this review. The remaining articles were used to define a mechanism with which the subdriver influences the specific Food Safety Management System activity. This is done in the same way of processing as the examples given in the workshops. Parts of the papers that talk about the trend that follows from this subdriver, and the way in which this impacts an FSMS are highlighted, an initial and focusing coding is done, and a schematic overview as well as a heatmap of the found mechanisms is made. The results of this can then be compared to the results of the workshop.

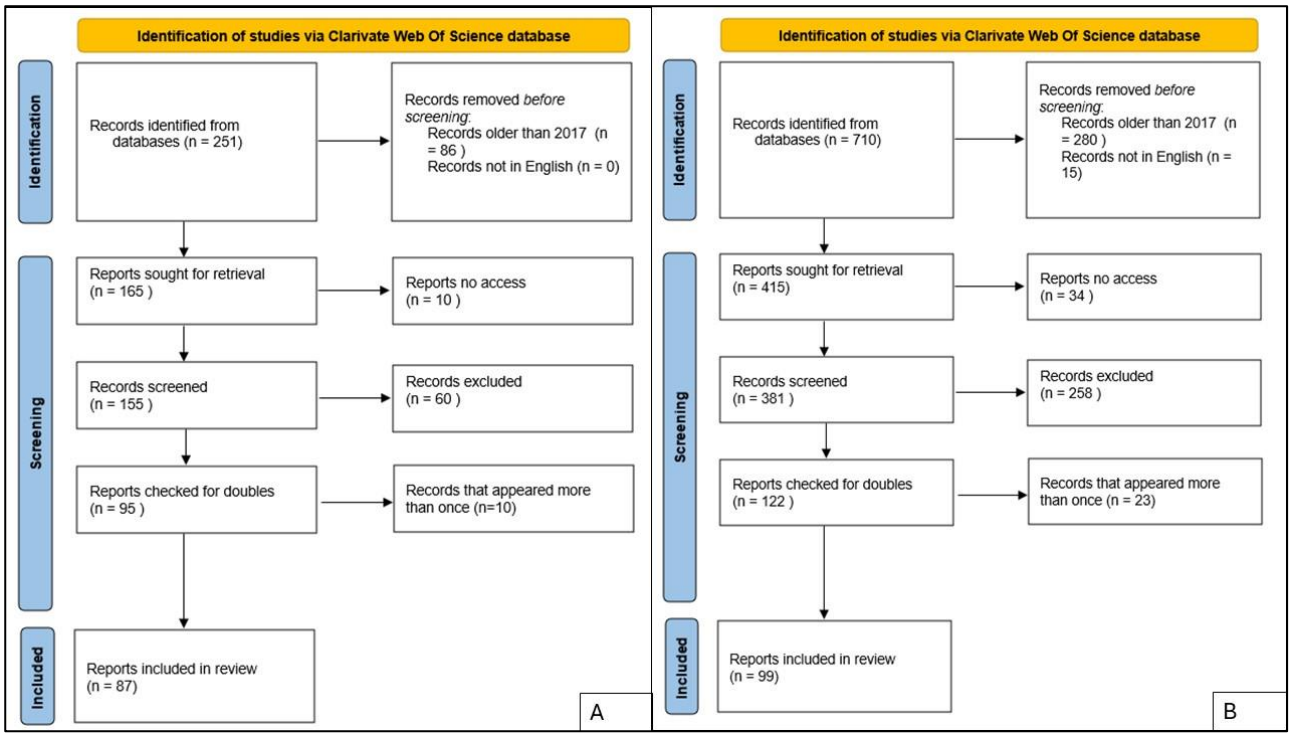

Figure 7 PRISMA flow diagram of the conducted literature study, adapted for the order of steps taken in this review (Page et al., 2021). (A) shows the flow diagram for the coupling of subdrivers and context indicators through literature, (B) shows the coupling of subdrivers and FSMS activities through literature

2.2.3 Adding a resilience level to existing indicators

An important part of this research is the assessment of resilience in a company's FSMS. As explained in Section 1.4, resilience comes down to adaptability, continuous monitoring and re-evaluation, and preventive maintenance. To incorporate this idea into the diagnostic instrument, a fourth level of advancement of FSMS activities will be added where resilient food safety management is seen as the most advanced level. This resilience is needed to cope with a multitude of food safety shocks that a company gets to deal with in its everyday operation. Based on the framework for resilience set out through literature study in Section 1.4, and through internal discussions, a definition of this fourth level is sought for Quality Control and Quality Assurance indicators. The structure of the grids from the current diagnostic tool is used to compile a complete definition. This new grid can then be used to make up the new grids for each individual indicator. An example will be given for an indicator of each subsection, but the development of grids for all indicators is outside the scope of this thesis.

2.2.4 Formulating new external context indicators

Based on the results from the workshop and literature study, a prompt is given for the development of new context indicators. These indicators will try to capture the extent of the impact of external context factors on the FSMS of a company.

3 RESULTS

3.1 Diagnosis of an alternative food system using the current diagnostic instrument

In depth interviews using the FSMS and HSMS diagnostic instrument were conducted with the Belgian aquaponics company BIGH. The interview starts with some introduction questions from the HSMS-DI on company characteristics, followed by some questions on the Representative Production Unit or RPU that will be used. The RPU should be a recognizable product that is most susceptible to microbiological contamination and is a good representation of the company's food safety issues. The company is a small scale farm with about 8 employees at the farm and 2 additional employees, producing about 10 varieties of herbs and 20 varieties of microgreens under a "société anonyme". The products are not organic, and there is a combined production with animal products. No QA standards are implemented, let alone certified for, and the owner has had no training on food safety or quality management. The RPU that is used in the interview is basil, which is sold in retail stores in and around Brussels. The initial materials that are used are substrate, seeds and water, which are supplied from multiple countries, and the product is packaged in plastic pots, sleeves from reusable paper and per six in cardboard boxes. The major activities involved in the cultivation of this RPU are seeding (with a machine), germination (in a germination chamber), growing under light (in a greenhouse), tide tables (in another greenhouse), packaging (in a packing zone) and distribution.

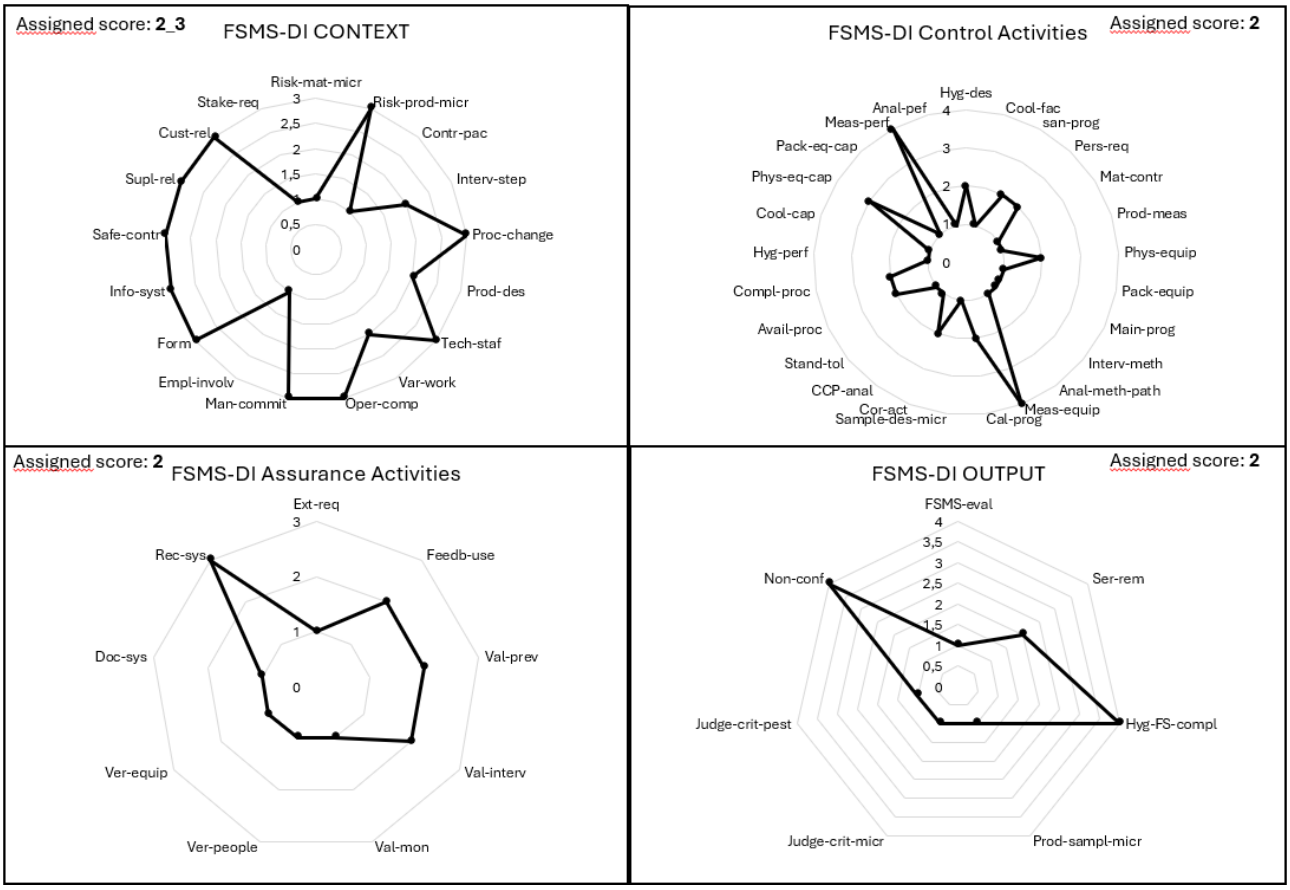

Figure 8 Results of the diagnosis performed with the original FSMS-DI. Spider charts are used to present the indicated levels of context riskiness, advancement of control and assurance activities, and performance, for each indicator. An overall score for each category is also attributed based on the average level.

Figure 8 shows the results of the interview for the indicators of the original FSMS-DI. The levels of context riskiness, advancement of control and assurance activities, and performance are shown in spider charts. An overall score for each of these categories is also shown. This attributed score is given based on the average level over all indicators from this category. The higher the overall context riskiness, the higher the advancement of the FSMS activities should be to get a

high level of food safety performance of the output. The maximum score for context is 3, while the maximum score for QC, QA and system output is 4. The company thus has a rather high context riskiness, combined with low advancement of FSMS activities leading to poor performance. Basil is quite a high risk product, and it is also often eaten without any further processing at the customer side, and it is produced here by people not knowledgeable in the field of food quality and safety in a fast changing company that has a rather weak position in the chain. This all leads to a high context riskiness, which is then not sufficiently compensated for by QC and QC activities. Most activities asked about in the indicators are not present or only performed when issues occur. Only measurement activities happen regularly as environment parameters like temperature and humidity are also important to measure to follow up the growth process of the plant. The performance score is mainly this low because no microbiological tests are performed (which leads to a score of 1 for indicators related to this, meaning absence of this activity), while there are no hygienic complaints from customers and non-conformities are not detected.

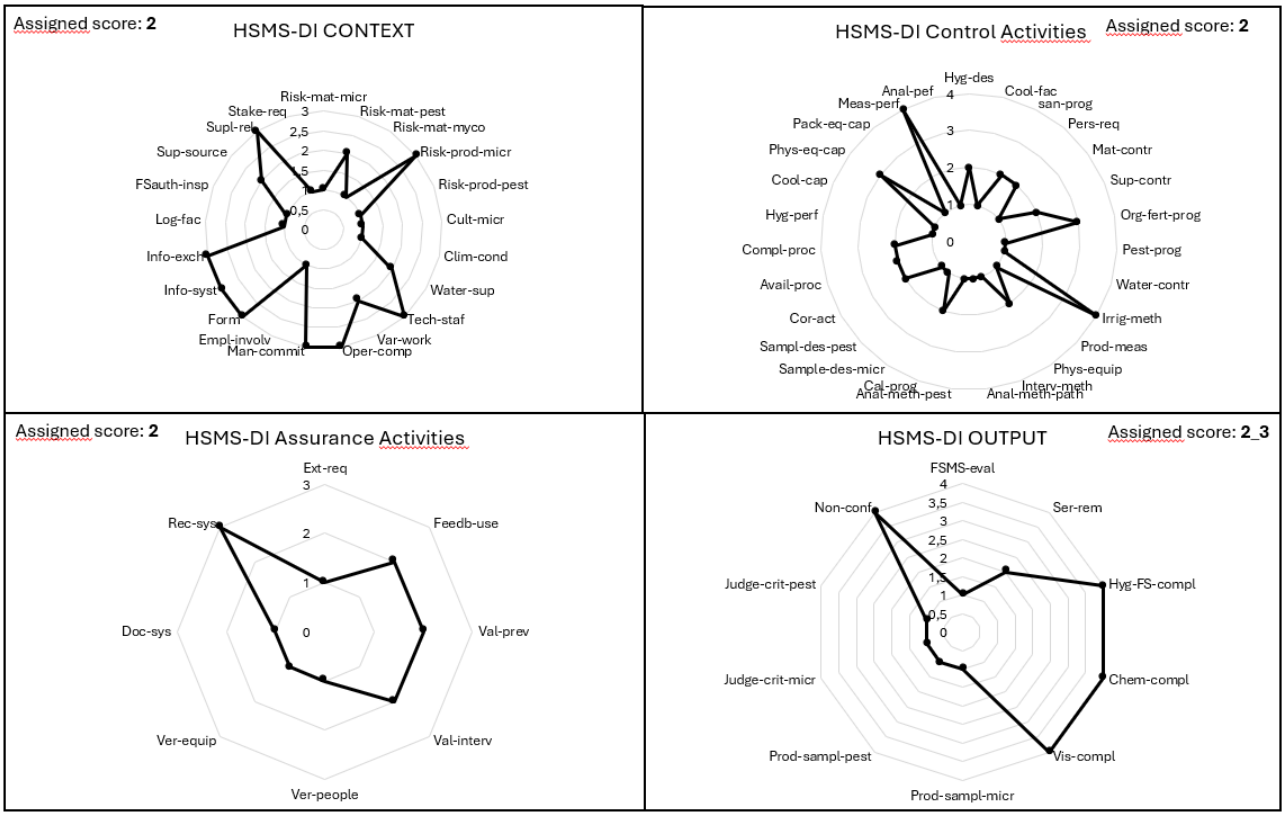

Figure 9 Results of the diagnosis performed with the adapted HSMS-DI for primary production. Spider charts are used to present the indicated levels of context riskiness, advancement of control and assurance activities, and performance, for each indicator. An overall score for each category is also attributed based on the average level.

Figure 9 shows the results of the interview for the indicators of the adapted HSMS-DI. Results are presented in the same way as with the results of the FSMS-DI. With this set of indicators, context riskiness is now medium high, and performance also leans more towards the medium score. The company scores rather well for the context indicators that are added such as microbiological contamination of the cultivation system (soilless), climate conditions (controlled) and pesticide risk of the product (no risk), as well as for the added performance indicators of chemical and physical complaints (no complaints). However, FSMS activities are still mostly not present or only ad hoc.

During the interview with the manager of this company, it was often mentioned that this long list of indicators is rather hard to go through for someone with no knowledge on quality and food safety. It's a small company that works off of the issues that present themselves when they happen, and until now, they have not seen a lot of reason to change this. This interview is mostly done to get a feel for how this diagnostic instrument performs in alternative food system like aquaponics, because it was set up mainly for more traditional systems, as also shown in Table 2 in Section 1.2.2.3

3.2 Results of the expert elicitation

3.2.1 Subdrivers that have an impact on food safety management

Appendix 5 show all answers as they were given by the respondents of the workshop around considered impacts of subdrivers on FSMS activities, divided per category of subdrivers, including the provided examples. Examples that clearly mention the impact being on allergens or chemical food safety issues are indicated in italics, as well as the answers stating clearly that no impact is considered. These answers and links are not considered in further data-analysis. When an example clearly references an effect that is not related to the subdrivers, the name of the subdriver is put in italics. Excerpts will be shown to give an explanation for these choices.

Table 10 Excerpt of Table A5.1 in Appendix 5. This excerpt contains all answers where the example mentions allergens or chemical food safety issues, as well as where it is clearly stated no impact is observed.

Participant	Subdriver	FSMS activity	Example
1	Dietary choice	System set-up	Allergen management, plant-based solutions
3	Dietary choice	Internal food safety performance	The presence of allergens or vegan products implicate directly impact on preventive measures, validation, verifications, etc
7	Dietary choice	System set-up	Dit antwoord mag je negeren maar ik kon geen tabblad terug gaan *Translation: You may ignore this answer but I couldn't go back a tab*
12	Migration & travel	Operation	Innovating products to different cultures → change of lines + buying products and ingredients from countries outside EU → can give some challenges regarding pesticide residues etc → monitoring plan per product per region (low risk vs high risk)
14	Population size	External food safety performance	It will have no impact
	Prevalence of vulnerable groups	Internal food safety performance	This factor has no impact on the FSMS since this already build to protect this type of consumers
	Urbanisation	External food safety performance	This factor has no impact
	Migration & travel	Internal food safety performance	No impact
	Human health condition	External food safety performance	No impact

In the section of social subdrivers, shown in Table A5.1 of the appendix, two examples mention allergen management (Dietary choice -> Preventive measures for participant 1 and Dietary choice -> Internal food safety performance for participant 3). Allergen management does not fit into the scope of this research, being microbiological food safety management. Participant 12 mentions pesticide monitoring as an example of Migration -> Operation, which is a chemical food safety hazard. The answer of participant 7 and five of the answers of participant 14 clearly state that they see no impact for this subdriver, despite checking "Yes" when they were asked if these subdrivers impacted food safety management.

Table 11 Excerpt of Table A5.1 in Appendix 5. This excerpt shows all examples that reference an impact either related to a different subdriver, or not related to any subdrivers in particular

Participant	Subdriver	FSMS activity	Example
1	*Migration & travel* -> /	Operation	Different regulatory frameworks with special impact on food safety
	Human health condition -> /	Operation	Sick people is strictly forbidden to work at the facilities due to the food safety impact
2	*Consumer knowledge* -> Consumer awareness & attitude	Internal food safety performance	Knowledge causes additional requests towards nutritional value
4	*Consumer knowledge* -> Consumer awareness & attitude	Internal food safety performance	Minder E-nummers gewenst -> andere alternatieven zoeken (HPP – stap ipv bewaarmiddel) *Translation: Fewer E numbers desired -> seek other alternatives (HPP - step instead of preservative)*
5	*Consumer awareness & attitude* -> Consumer knowledge	Preventive measures	Wrong usage of goods
	Public awareness -> Consumer knowledge	Preventive measures	Cold chain
10	*Consumer awareness & attitude* -> Consumer knowledge	Preventive measures	Optimale bewaaromstandigheden worden verbroken -> uitgroei van microbiologie mogelijk maar consumenten klagen liever *Translation: Optimal storage conditions are broken -> outgrowth of microbiology possible but consumers prefer to complain*
		External food safety performance	Impact vanuit de thuissituatie wordt onvoldoende meegenomen als een risico door externe partijen zoals auditbureaus en FAVV -> risico naar de eindconsument blijft onze verantwoordelijkheid terwijl we geen zicht hebben op wat de klant thuis doet *Translation: Impact from the home situation is insufficiently taken into account as a risk by external parties such as audit agencies and FASFC -> risk to the end consumer remains our responsibility while we have no insight into what the customer does at home*
13	Consumer awareness & attitude	Verification	Meer ready to eat producten (geen afdoding meer van pathogenen door consumer) / of meer (korte of onvolledige) opwarming in een microgolf door tijdsgebrek (ipv door verhitting of langdurige verhitting in oven of friteuse bv) / in welke mate is consument zich bewust van gevaren als bv koudeketen onderbroken is (of bv niet op tijd geconsumeerd is of tijdelijk bij een hogere temperatuur) *Translation: More ready-to-eat products (no more killing of pathogens by consumers) / or more (short or incomplete) heating in a microwave oven due to lack of time (instead of by heating or prolonged heating in an oven or deep-fryer, for example) / to what extent is the consumer aware of the dangers, for example, if the cold chain is interrupted (or e.g. not consumed on time or temporarily at a higher temperature)*
15	*Consumer knowledge* -> Consumer awareness & attitude	Preventive measures	Dietary knowledge might impact product design e.g. no preservatives

The example given by participant 1 on impact of the subdriver Human health conditions is about sick people being denied access to the workplace, but this subdriver is explained to be about non communicable diseases. Their example on Migration & travel also seems to be off context, talking about regulatory frameworks in other countries. Participant 2, 4 and 15 gave examples regarding the subdriver of Consumer knowledge that point to a misunderstanding of this subdriver, with all three answers pointing towards the subdriver of Consumer awareness & attitude. Participant 5 gave the same example to link both Consumer awareness & attitude and Consumer knowledge to Preventive measures, while the answer references only the definition Consumer knowledge, so the other answer is disregarded. This participants example for Public awareness probably references keeping up the cold chain at the customer side, which falls under Consumer knowledge too. The examples given by participant 10 on Consumer awareness & attitude also reference Consumer knowledge more. For participant 13, a similar point can be made, however, the given examples reference both subdrivers, and because Consumer knowledge is also indicated as having an impact, with a fitting example, no data cleaning actions are taken for this in this step.

Table 12 Excerpt of Table A5.2 in Appendix 5. This excerpt contains all examples related to chemical food safety issues or referencing no observed food safety impact of a subdriver.

Participant	Subdriver	FSMS activity	Example
2	Food packaging	External food safety performance	DoC & migration
3	Plant-derived food production	Operation	The presence of endogeneous plant material must be prevented
		Internal food safety performance	Presence of endogenous material must be monitored and registered
11	Plant-derived food production	Validation	Residu-analyses, bij overschrijding, recall *Translation: Residue analyses, if exceeded, recall*
	Animal-derived food production	Verification	Geneesmiddelen residu's, bij overschrijding, recall *Translation: Drug residues, if exceeded, recall*
	Food packaging	Validation	Verpakkingstechnologie ifv commerciële aspecten (kleurbehoud) eerder dan voedselveiligheid *Translation: Packaging technology ifv commercial aspects (colour retention) rather than food safety*
14	Upcycling for food	Operation	No impact

Moving on to Table A5.2 on technological subdrivers, participant 14 mentions no impact for Upcycling for food so this answer can be neglected. The answers of participant 2 about Food packaging, of participant 3 on Plant-derived food production and of participant 11 on Plant-derived and Animal-derived food production mention chemical food safety impact rather than microbiological food safety, so they are also disregarded. The example of participant 11 on Food packaging mentions commercial impact rather than food safety impact so this answer is also neglected. To determine the top indicated technological drivers, Plant- and Animal-derived food production are added together because the choice between these two mainly depends on the type of product the company uses.

Table 13 Excerpt from Table A5.3 in Appendix 5. This excerpt shows all answers related to chemical food safety issues or other impacts then microbiological food safety issues.

Participant	Subdriver	FSMS activity	Example
1	Recycling	Internal food safety performance	Several chemical contaminants are known to come from recycling (i.e. mineral oil hydrocarbons from recycled packaging, allergen cross-contamination)
2	Seasonality & weather	External food safety performance	Avocado grown in southern countries, variability of fat content and viscosity
3	Agricultural pollution	Monitoring	Pesticide monitoring
	Geographic region	Monitoring	Cadmium is more presence in some regions
6	Geographic region	Monitoring	Naar microbiologische impact heb ik hier niet onmiddellijk een idee, maar naar chemische verontreiniging kan dit wel een impact hebben op het FSMS (vb PFAS en regio's die gekend zijn als vervuilde zones) *Translation: In terms of microbiological impact, I do not have an immediate idea here, but in terms of chemical contamination, this could have an impact on the FSMS (e.g. PFAS and regions known to be contaminated zones)*
11	Agricultural pollution	Documentation & record-keeping	Steeds meer forever chemicals in het milieu = in het voedingsproduct, vaak dure analyses voor organisatie en/of overheid *Translation: More and more forever chemicals in the environment = in the food product, often expensive analyses for organisation and/or government*
		Monitoring	Teveel N = minder biodiversiteit, meer pesticiden nodig Translation: Too much N = less biodiversity, more pesticides needed
	Recycling	Monitoring	Migratie van chemische componenten (Mosh/Moah) vanuit verpakking naar voeding *Translation: Migration of chemical components (Mosh/Moah) from packaging to food*
12	Agricultural pollution	Preventive measures	Pollution → more attention to preventive measures; more samples; drift is an important one; drift is hugh problem → but more related to chemicals than microbiological

In the case of the environmental subdriver, found in Table A5.3, multiple answers talk about chemical food safety issues, so they are disregarded for further processing. These are the answer of participant 1 on Recycling, participant 3's answers on Agricultural pollution and Geographic region, participant 6 on Geographic region, all answers of participant 11 and participant 12 on Agricultural pollution. Participant 2 gives an example of physical quality of the ingredients when talking about Seasonality & weather, so this answer is also not taken further for processing.

Table 14 Excerpt from Table A5.4 in Appendix 5. This excerpt shows the answer related to economic impact instead of microbiological food safety.

Participant	Subdriver	FSMS activity	Example
1	Distribution channels	Operation	The economic impact when selling to the artisan market is different when we talk about retailers. The latter has a larger distribution/impact

From the economic and political subdrivers in Table A5.4, the only answer that is not used for further processing from is participant 1's answer for impact of Distribution channels, as it talks about economic impact rather than food safety.

When all of these examples that were just discussed are omitted or replaced to another subdriver, top 3 rankings of the most indicated subdrivers per category can be made. For economic drivers, it is a top 1 that is established, as there are only 2 economic subdrivers. The top social subdriver having an impact on food safety management are Resistant pests & diseases (n=14), with Dietary choice (n=11) taking the second spot, and in third place Consumer awareness & attitude (n=9). The top technological subdrivers having an impact on food safety management according to these FBO's are Food packaging (n=12), products for food production (n=11) and processing techniques & scale (n=11). From the eight environmental drivers, the subdrivers that were indicated most for having an impact on food safety management are Climate change (n=9), Seasonality & weather (n=8), and a shared third place for Agricultural pollution (n=6) and Geographic region (n=6).From the two economic subdrivers, Global trade (n=10) is indicated most as having an impact on food safety management in a company. For the political subdrivers, the top 3 consists of Food legislation (n=13), Official controls & communication (n=11) and War & conflict (n=11). To get an idea of the category that participants see the most impact of, the average amount of participants that indicated a subdriver from each category can be calculated by adding up the amount of times one of the subdrivers was indicated and dividing that number by the amount of subdrivers in this category. The most popular category is then political subdrivers (x=10.8), followed by economic (x=8.5) and social (x=7.6) subdrivers. Environmental (x=5.6) subdrivers are averagely the least indicated.

3.2.2 Activities in food safety management impacted by changes in subdrivers

For these top indicated subdrivers, a closer look is taken at the examples of impact mechanisms provided by the participants. This time, the focus is on the correctness of the indicated FSMS activity that the subdriver impacts. All examples referencing material control, supplier control and hygiene management are attributed to the FSMS activity of preventive measures. Where reduction of pathogens and the methods to do this are mentioned, the FSMS activity is interventions. Monitoring includes all aspects of sampling and monitoring plans. Operation includes changes in operational activity and proper working of people and machinery. Where the whole FSMS set-up is taken under the loop, the FSMS activity is system set-up. Examples where validation and verification are indicated are assumed to represent actions where new validation needs to be done, and are often explicitly mentioned in the examples. Documentation & record-keeping envelop all statements regarding management of documents and using documentation to analyse the situation. External food safety performance handles all audits and inspections done by external entities, as well as customer complaints. Internal food safety performance is about internal inspections and own test results. Where the example was unclear in its meaning or specific mechanism, other examples of the same participant or other examples attributed to the same link were taken into account to decide if the FSMS activity was indicated correctly. Where it still was not clear, or where no actual examples were given, it was assumed that the participant understood the meaning of the FSMS activity well. The examples with their attributed FSMS activities can be found in Appendix 6. These changes lead us to a clear image of the type of FSMS activities that each of these subdrivers impacts most.

Figure 10 shows a heat map of the impacted FSMS activities for each of the most indicated subdrivers, according to the results of the workshop. The impact of the social subdrivers is given a dark blue color, technological subdrivers are indicated in orange, environmental subdrivers in green, economic in light blue and the impact of the political subdrivers is shown in purple. The diameter of the circles represents the amount of times the given link is made by the participants. The ovals show the impact of each subdriver on the category of FSMS activities, namely QC, QA or PI. Here the smallest diameter is representative of the amount of times a link inside this category was made.

From this figure, it can be seen that the social subdrivers impact the whole FSMS, and for Dietary choice and Consumer awareness & attitude also the food safety performance. This means that when changes in social subdrivers are at play, the FBO's need to re-evaluate the whole FSMS, and issues can occur along the entire system. The technological subdrivers mostly impact QA activities, especially validation, meaning that revalidation needs to happen when these subdrivers are at play. On the other hand, environmental subdrivers show their influence mostly in QC activities: importance of supply chain analysis and material control, and follow up in the monitoring system are highlighted here. The economic subdriver shows a scattered impact on all FSMS activities, which is also true for the subdriver of Food Legislation. Official controls and communication impact mostly external food safety performance as it has to do with auditing, while War & conflict influences mostly QC activities.

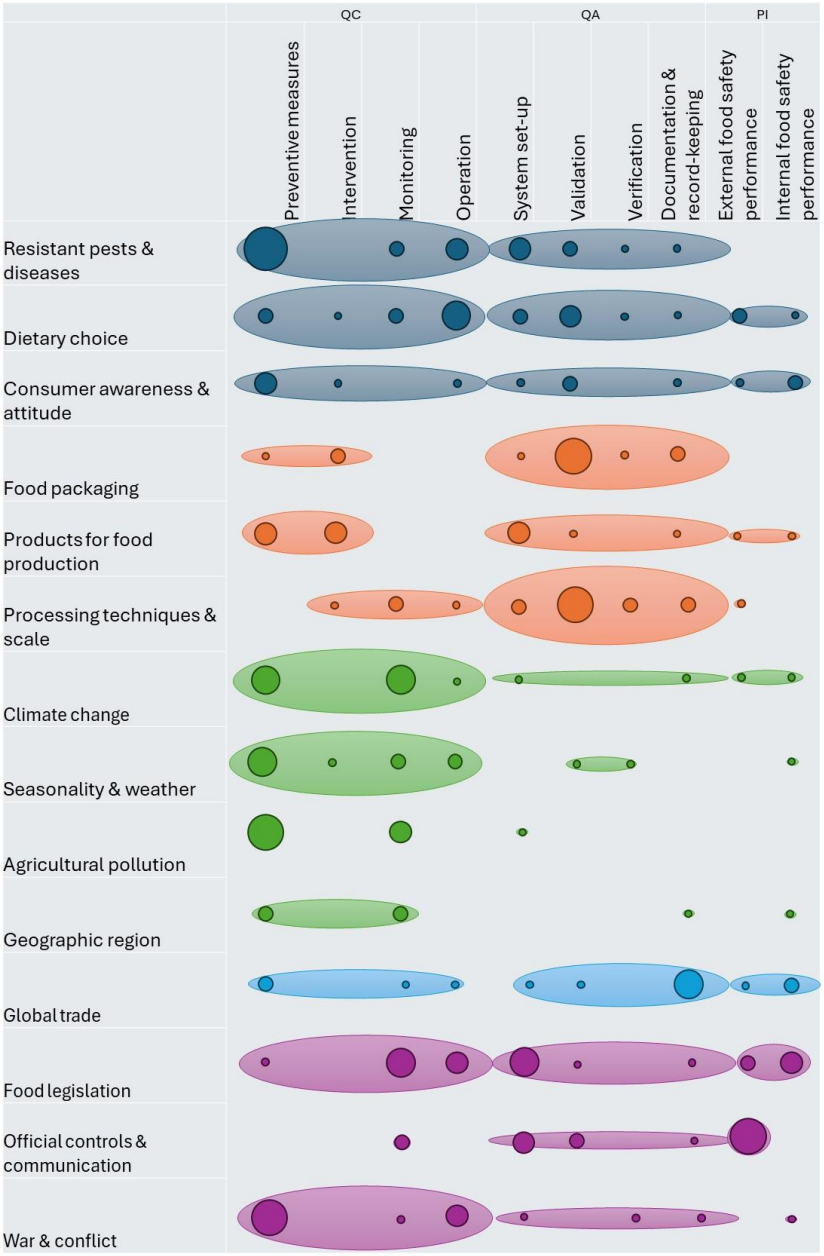

Figure 10 Heatmap showing the top subdrivers per category (dark blue = social, orange = technological, green = environmental, light blue = economic, purple = political) and the FSMS activities that they impact, according to the participants of the workshop. The diameter of the circles is representative of the amount of participants indicating this link. The ovals represent the impact per group of activities (QA, QC, PI), and here the smallest diameter is representative of the amount of participants indicating this link.

3.2.3 Mechanisms of impact between subdrivers and FSMS activities

To really understand the mechanisms of impact that FBO's deal with, the examples provided by the participants were converted into the form of "subdriver effect" -> "FSMS activity impact". This was done by the principles of initial and focused coding found in grounded theory by Charmaz (2006). These codings for each of the provided examples are shown in Appendix 6. In initial coding, the codes match as closely as possible the wording of the original answer, while filtering out the effect on the subdriver side and the impact on the FSMS side. Where one of the two is not clearly stated, other answers from the same participant are consulted. If this brings no clarity, the name of the FSMS activity or subdriver is used as an initial code. When neither sides of the mechanisms are clearly formulated, and no link is found when looking at the other answers of this participant, or when no example is given, no coding is done. In focused coding, initial codes that resemble each other are grouped into categories. For the subdrivers, this is done taken into consideration all initial codes of this subdrivers side, for the FSMS activities, all examples given for this FSMS activity are taken into account to set up these categories.

For preventive measures, five categories could be distinguished: improvement of pest control, increase or improvement of incoming material control, having to change suppliers and the management that comes with this, hygiene management, and control of multiple suppliers, often from multiple regions of the world. For intervention, the inclusion of additional intervention steps in the production process, and the need for new machinery are the two impacts that are considered. For monitoring, the modification of the entirety of the monitoring plans could be needed, or more specifically, it might be crucial to take more samples, or include new criteria. For the activity of operation, it might be needed to pay more attention to actual hygienic working on the production floor, operational activities might need to be adapted in general, or attention must be paid to the cold chain. The system set-up might need to be revised as a whole, or incorporation of specific stakeholder requirements can be important. Validation is mostly indicated when new validation is necessary, and this is sometimes specified to be validation of the shelf life or technologies due to the impact of the subdrivers. Improvement of verification of effectiveness is about the improvement of verification activities to follow up on the effectiveness of all taken measures to ensure a safe end product. Documentation & Record-keeping includes four categories, namely the correct documentation of changes in product and process parameters to be used for re-evaluation, the management of supplier documentation, challenges with traceability, and modification of documents and the documentation system. External food safety performance is impacted through additional audits, more customer complaints, differing auditing results depending on the auditing body and the auditor, and one category showing a positive impact, namely that a resource of info is provided. In internal food safety performance disturbed lab results, high risks of non-compliance and the consideration of different regulations are noticed.

Table 15 shows a heat map of the mechanisms as indicated by the participants and focused coding of their answers for the social subdrivers top 3. It can be seen that no mechanisms are included for impact on internal food safety performance, despite this impact being indicated in Figure 10. This is because all examples given for this link were unclear or did not actually mention a mechanism. For Resistant pests & diseases, when the occurrence of both was listed in initial coding, both were seen as a separate mechanism in focused coding. Resistance against treatments includes heat treatments as well as preventive measures. For Dietary choice, using less sugar and less salt are grouped together in focused coding as the issue for both is listed as the influence of these components on water activity. The most notable mechanisms at play here, as they were indicated by multiple participants, are the occurrence of more resistant pests and micro-organisms or MO impacting the preventive measures of pests and incoming material control, increased sickness of the working staff leading to need for higher attention of their hygienic working, and using less sugar or salt leading to new validation of the shelf life.

Table 16 shows a similar heat map for the technological subdrivers. For Food packaging, all packaging innovations that are related to sustainability are grouped together. This includes using less packaging, using monomaterials and using recycled packaging. Three people gave examples saying that switching to these more sustainable packaging solutions instigates the need for validation of the shelf life as barrier properties change. Implementing new and innovative techniques also leads to the need for revalidation. Five participants mentioned this impact , of which two specified this being about the validation of the technology. Two participants mentioned that products for food production could impact the quality and contamination of the raw materials, which calls for increased material control.

Table 15 Mechanisms at play when social subdrivers impact FSMS activities. Based on focused coding of the answers from the participants of the workshop. The number of times each specific link was made is indicated with the exact number, and is also shown through the darkness of the coloring.

		Quality Control													Quality Assurance										Performance Indicators						
	FSMS activity	Preventive measures					Intervention		Monitoring			Operation			System set-up		Validation			Verification	Documentation & record-keeping				External food safety performance				Internal food safety performance		
Subdriver	FSMS activity impact / Subdriver effect	Improve pest control	Improve material control	Change suppliers	Hygiene management	Multiple supplier control	Additional intervention steps	New machines	Modification monitoring plan	More sampling	New criteria	More attention to hygienic working	Adapt operational activities	Failing cold chain	Revise system set-up	Incorporate stakeholder requirements	Validate technology	Validate shelf life	New validation	Improve verification of effectiveness	Documentation of changes	Supplier document management	Traceability	Modification documentation	Additional audits	More complaints	Differing audit results	Resource of info	Disturbed lab results	High risk of non-compliance	Different regulations
Resistant pests & diseases	More pests	3	2																1											
	More resistant MO		3									1			1					1											
	New diseases								1						1																
	MO/Pests resistant to treatments								1								1				1										
	Sickness staff											2																			
Dietary choice	Bio-products		1																												
	Less sugar/salt						1			1			1					2													
	Claims								1			1	1						1	1											
	New retailer demands														1																
	New products														1									1							
Consumer awareness & attitude	Negative publicity			1											1																
	Specific region sourcing			1																											
	Less additives						1																								
	More plant-based																		1											
	More ready-to-eat																		1		1										
	Consumer awareness																								1						

Table 16 Mechanisms at play when technological subdrivers impact FSMS activities. Based on focused coding of the answers from the participants of the workshop. The number of times each specific link was made is indicated with the exact number, and is also shown through the darkness of the coloring.

		Quality Control													Quality Assurance										Performance Indicators						
	FSMS activity	Preventive measures					Intervention		Monitoring			Operation			System set-up		Validation			Verification	Documentation & record-keeping				External food safety performance				Internal food safety performance		
Subdriver	FSMS activity impact / Subdriver effect	Improve pest control	Improve material control	Change suppliers	Hygiene management	Multiple supplier control	Additional intervention steps	New machines	Modification monitoring plan	More sampling	New criteria	More attention to hygienic working	Adapt operational activities	Failing cold chain	Revise system set-up	Incorporate stakeholder requirements	Validate technology	Validate shelf life	New validation	Improve verification of effectiveness	Documentation of changes	Supplier document management	Traceability	Modification documentation	Additional audits	More complaints	Differing audit results	Resource of info	Disturbed lab results	High risk of non-compliance	Different regulations
Food packaging	New packaging							1								1		1						1							
	MAP gassing						1																								
	Sustainable packaging																	3		1		1									
Products for food production	Water quality		1						1						1																
	Quality raw materials		2																												
	New products								1						2							1									
	Regulation change									1																					
	Specification sheets																		1												
	Use of biological products																												1		
Processing techniques & scale	New techniques							1	1						1		2		3	1	1			1							
	Export										1														1						
	Upscaling														1											1					

Table 17 shows the heat map for the top 3 environmental subdrivers, in which there is a tie for third place. Both for Climate change and Seasonality & weather low availability of ingredients, variable quality of ingredients and changing weather are categories in effects of these subdrivers. Changing weather could mean hotter temperatures or dry weather. This is not surprising as climate change does impact the weather, and can thus impact the FSMS activities in the same way. Low availability calls for a change in suppliers and managing these new suppliers. This is mentioned when talking about both subdrivers. When weather events lead to variable quality of ingredients, multiple suppliers need to be balanced to guarantee sufficient quality materials to come in. It also sets up that

material control needs to be increased and monitoring plans might need modification, which were mentioned as mechanisms for both subdrivers. Changing weather, especially higher temperatures, can lead to failing of the cold chain. This can happen along each step of the supply chain and should be followed up closely. This phenomenon was also mentioned in the example giving in the workshop, as shown in Appendix 4. Agricultural pollution results mostly in contamination of raw materials, which calls for increased material control. It can also impact water quality in primary production or in processing, so monitoring of both water quality and material quality throughout the production process will be important.

Table 17 Mechanisms at play when environmental subdrivers impact FSMS activities. Based on focused coding of the answers from the participants of the workshop. The number of times each specific link was made is indicated with the exact number, and is also shown through the darkness of the coloring.

		Quality Control													Quality Assurance										Performance Indicators						
	FSMS activity	Preventive measures					Intervention		Monitoring			Operation			System set-up		Validation			Verification	Documentation & record-keeping				External food safety performance				Internal food safety performance		
Subdriver	FSMS activity impact / Subdriver effect	Improve pest control	Increase material control	Change suppliers	Hygiene management	Multiple supplier control	Additional intervention steps	New machines	Modification monitoring plan	More sampling	New criteria	More attention to hygienic working	Adapt operational activities	Failing cold chain	Revise system set-up	Incorporate stakeholder requirements	Validate technology	Validate shelf life	New validation	Improve verification of effectiveness	Documentation of changes	Supplier document management	Traceability	Modification documentation	Additional audits	More complaints	Differing audit results	Resource of info	Disturbed lab results	High risk of non-compliance	Different regulations
Climate change	Low availability ingredients			2																			1				1				
	Reduce water use				1																										
	Variable quality ingredients		1						1						1											1					
	Regions of sourcing										1																				
	Changing weather								1					1															1		
Seasonality & weather	Variable quality ingredients		1			2	1		1	1																					
	Low availability ingredients			1		1																									
	Changing weather		1											2																	
	Microbiological environment																												1		
Agricultural pollution	Contamination raw materials		5							1																					
	Water quality								2						1																
Geographic region	Different sourcing regions								1	1														1							1

Table 18 Mechanisms at play when economic and political subdrivers impact FSMS activities. Based on focused coding of the answers from the participants of the workshop. The number of times each specific link was made is indicated with the exact number, and is also shown through the darkness of the coloring.

		Quality Control													Quality Assurance										Performance Indicators						
	FSMS activity	Preventive measures					Intervention		Monitoring			Operation			System set-up		Validation			Verification	Documentation & record-keeping				External food safety performance				Internal food safety performance		
Subdriver	FSMS activity impact / Subdriver effect	Improve pest control	Improve material control	Change suppliers	Hygiene management	Multiple supplier control	Additional intervention steps	New machines	Modification monitoring plan	More sampling	New criteria	More attention to hygienic working	Adapt operational activities	Failing cold chain	Revise system set-up	Incorporate stakeholder requirements	Validate technology	Validate shelf life	New validation	Improve verification of effectiveness	Documentation of changes	Supplier document management	Traceability	Modification documentation	Additional audits	More complaints	Differing audit results	Resource of info	Disturbed lab results	High risk of non-compliance	Different regulations
Global trade	Export										1							1						1							
	Multiple country sourcing											1											1								1
	More stakeholders															1										1					
	New region sourcing																					1		1						1	
Food legislation	Differing regulatory requirements			1							1					1			1						1						
	New legislation								1	1			2		1	2								2								1
Official controls & communication	Interpretation of legislation								1		1																2				
	Official controls								1										1									2				
	Authority expectations														1									1								
	High degree of control														1																	
War & conflict	New sourcing areas			1		2										1													1		
	Low availability of ingredients			2											1																	
	Higher costs								1				1											1								

The heatmap for economic (in light blue) and political (in purple) subdrivers is given in Table 18. The impact of the economic subdriver Global trade is scattered across the FSMS activities, as was also mentioned when looking at Figure 10. The implementation of new legislation, which includes new regulations and stricter regulations, can result in necessary adaptations of operational activities, the need for incorporation of new stakeholder requirements in the system set-up and need for modification of documents and documentation systems. For Official controls and communication, it is mentioned that different interpretations of legislation can lead to different auditing results when confronted with different auditing bodies or auditors. A positive impact of Official controls and communication could be that they are a resource of info about external food safety performance, which can help identify weaknesses and improve the FSMS. War & conflict as a third political subdriver can instigate the need for new sourcing areas when conflict in sourcing regions results in restricted import. This will result in having to manage multiple suppliers from these new sourcing areas. The low availability of ingredients also leads to looking for new suppliers to compensate.

3.2.4 Most important subdrivers to consider

At the end of the workshop, participants were asked to give their top 5 of all subdrivers that they had indicated, ranking the most important subdrivers to consider in their FSMS. The results of this are given in Tabel A5.5 in Appendix 5. Based on their position in each ranking, the subdrivers were given scores: 5 points when the subdriver ranked highest in a participant's ranking, 1 when it ranked lowest. 26 of the 34 subdrivers were included in at least one top 5 ranking. The top 10 highest ranked subdrivers are given below, with corresponding colors to the ones in Figure 10 and Table 15-18.

1.Food legislation	5.Products for food production	8b.Food packaging
2.Climate change	6.Consumer awareness & attitude	9a.Dietary choice
3.Good practices & standards	7.Resistant pests & diseases	9b.Water & soil management
4.Processing techniques & scale	8a.Global trade	10.Novel food sources

The top 3 contains two political subdrivers. FBO's thus feel the most pressure coming from these subdrivers. Good practices & standards shows up in third place in this overall ranking, while it was not in the top 3 most indicated subdrivers from the political category. FBO's who encounter the pressures from this, also rank it very high, while the other FBO's didn't even indicate it as having an impact. Official controls & communication and War & conflict were indicated by more separate FBO's, but did not rank high enough to even be in the overall top 10. The ranking is completed with 4 technological subdrivers and 3 social subdrivers that do correspond to their most indicated subdrivers. The top indicated economic subdriver is in a shared 8th place. Climate change as the most indicated environmental subdriver, scores high in the overall ranking as well. Water & soil management was not part of the environmental subdrivers but was ranked quite high by the FBO's who did indicate its impact. The other subdrivers that were included in the participants ranking were, in order for their scores, New digital technologies, Plant-derived food production, Seasonality & weather, Human health conditions, Distribution channels, Animal-derived food production, Fragmentation between nations, Official controls & communication, War & conflict, Food formulation, Agricultural pollution, Use of sidestreams, Consumer knowledge and Sewage treatment. The average score when looking at all subdrivers of a category (with subdrivers that were not included in any ranking having a score of 0) for political subdrivers is highest, followed by technological subdrivers, economic subdrivers, then environmental subdrivers and lastly social subdrivers. If only the scores of the subdrivers included in at least one top 5 are averaged out, social subdrivers fall in third place, while economic subdrivers end last. The other 3 categories remain in the same spot.

3.3 Coupling of drivers and indicators through literature review

3.3.1 Coupling of subdrivers and context indicators through literature review

In a first stage of this research, a coupling of drivers, subdrivers and indicators was made through internal discussions where the goal was to find where drivers were already incorporated or could be further incorporated in existing indicators. The results of this can be found in Appendix 7. Mostly influences of the innovation pathway and thus impact on context indicators were incorporated in this. A structured literature review is conducted as described in Section 2.2.2. When a paper is found when using a search term from the subdriver side and a search term from the context indicator side, and this paper was deemed relevant after screening of the abstract, it shows that the two are linked and have an influence on each other. Most links that were made are related to the indicator of packaging concept, and to a lesser extent, intervention strategies and final product contamination. For all other context indicators, no relevant papers could be found when conducting the literature review in this way. This could be related to the chosen search terms for the other indicators. The amount of links that are found in this way per subdriver can be added up and used to find the top 3 subdrivers per category for which a link to context indicators can be found in literature For the economic category, only one subdriver will be selected. For the social category, Consumer awareness & attitude (n=9) is linked to context indicators the most, followed by Dietary choice (n=5) and Resistant pests & diseases (n=3). For technological subdrivers, the top 3 consists of Food packaging (n=11), Processing techniques & scale (n=7) and Novel food sources (n=5). From the environmental subdrivers, the highest amounts of relevant papers were found for Seasonality & weather (n=8), Recycling (n=6) and in a shared third place Use of sidestreams (n=2) and Climate change (n=2). The top economic subdriver is Distribution channels (n=13), and for political subdrivers, the only subdriver generating relevant papers is Good practices & standards (n=18). Relevant passages of the papers found for these top subdrivers that give an idea of the link between the subdrivers and these indicators are shown in Appendix 8 and then coded through initial and focused coding in the same way as for the workshop results. As already mentioned, most innovations mentioned in these papers have to do with packaging concept. The importance of packaging for shelf life is highlighted in light of Dietary choice of ready-to-eat meals and traditional foods (Dzikunoo et al., 2021; Lapikadis & Frangkiadakis, 2022; Makinde et al., 2020), Consumer awareness & attitude towards preservatives and minimal processing (Khade et al., 2023; Mei et al., 2019), the rise of Resistant pests and pathogens (Sequino et al., 2024), Novel food sources such as edible insects and seaweed (Blikra et al., 2021; Hyun et al., 2018; Moreira-Leite et al., 2023; Ojha et al., 2021), contamination of food related to Seasonality & weather (Bai et al., 2019), handling of products in Distribution channels (Ahmed et al., 2023; Gomez et al., 2023; Lopez-Galvez et al., 2021; Peng et al., 2022; Zhang et al., 2023), and keeping up compliance with microbiological Standards (Abrokwah et al., 2020; Bandyopadhyay et al., 2020; Esposito et al., 2021; Gutierrez-Rodriguez & Adhakari, 2018; Pushparaj et al., 2022). New Processing techniques, innovation in Recycling can result in better protection of the food product (Dzikunoo et al., 2021; Ferri et al., 2023; Stanley et al., 2023) , so that requirements set in Standards can be met (Aiyar & Pingali, 2020; Ferri et al., 2023; Hernandez-Garcia et al., 2022; Manikandan & Min., 2023; Zaidi et al., 2022). Consumer awareness towards sustainability gives rise to the construction of biodegradable and biobased packaging. Active and smart packaging are developed as new Food packaging technologies (Alizadeh-Sani et al., 2020; Ibrahim et al., 2021; Pou et al., 2022; Rangaraj et al., 2021; Suvarna et al., 2022, Zhang et al., 2023), and used to simplify control in Distribution channels and provide more information to consumers (Ahmed et al., 2018; Chisenga et al., 2020; Fang et al., 2017; Liu et al., 2019; Pou et al., 2022. The indicator for final product contamination was linked to Dietary choice through the rise of consumption of products with high risk of contamination (Cano et al., 2019), Resistant pests & diseases leading to high risk of contamination (Aragao et al., 2021), and Good practices & standards laying out guidelines for product contamination(Aragao et al., 2021). Effectiveness of interventions can be impacted by overuse of refrigeration in Distribution channels (Hingston et al., 2019). Use of sidestreams, specifically reuse of water elicits the need for extra intervention steps (Gadelha et al., 2019; Koutsoumanis et al., 2023).

3.3.2 Coupling of subdrivers and FSMS activities through literature review

When looking at the impact of subdrivers on FSMS activities, as was done in the workshop, the top saturated subdrivers per category in literature concerning their impact on FSMS activities can be calculated in the same way. In the social category, the top subdrivers Resistant pests & diseases (n=16) and Dietary choice (n=10). For all other social subdrivers, only 1 or no papers were found indicating a link to FSMS activities, so no third place is attributed. In the technological category, Novel food sources (n=6) takes the top spot, followed by Processing techniques & scale (n=4), and New digital technologies (n=3). The top 3 for environmental subdrivers are Seasonality & weather (n=13), Use of sidestreams (n=7) and Water & soil management (n=5). For the latter two, there are only 2 papers but they cover multiple links. The top economic subdriver is Distribution channels (n=10). From the political subcategory, the top 3 consists of Good practices & standards (n=22), Official controls & communication (n=2) and Food legislation (n=2). A heatmap showing the links that can be made between these top subdrivers and FSMS activities is shown in Figure 11. Relevant passages from these papers that give an idea of the mechanisms between the two are shown in Appendix 9 and coded through initial and focused coding in the same way as for the workshop results. Table 19 and 20 show the results of this coding

From the heatmap in Figure 11 it is clear that most papers that were found concern QA activities, especially preventive measures and monitoring. The search terms that led to the most papers for these two activities were “Hygiene” and “Monitoring”. For the technological subdrivers, no relevant papers were even found linking the impact of these subdrivers to QC activities, while the workshop results suggested that these subdrivers do impact QC activities the most. No papers were found linking any subdrivers to system set-up or internal food safety performance.

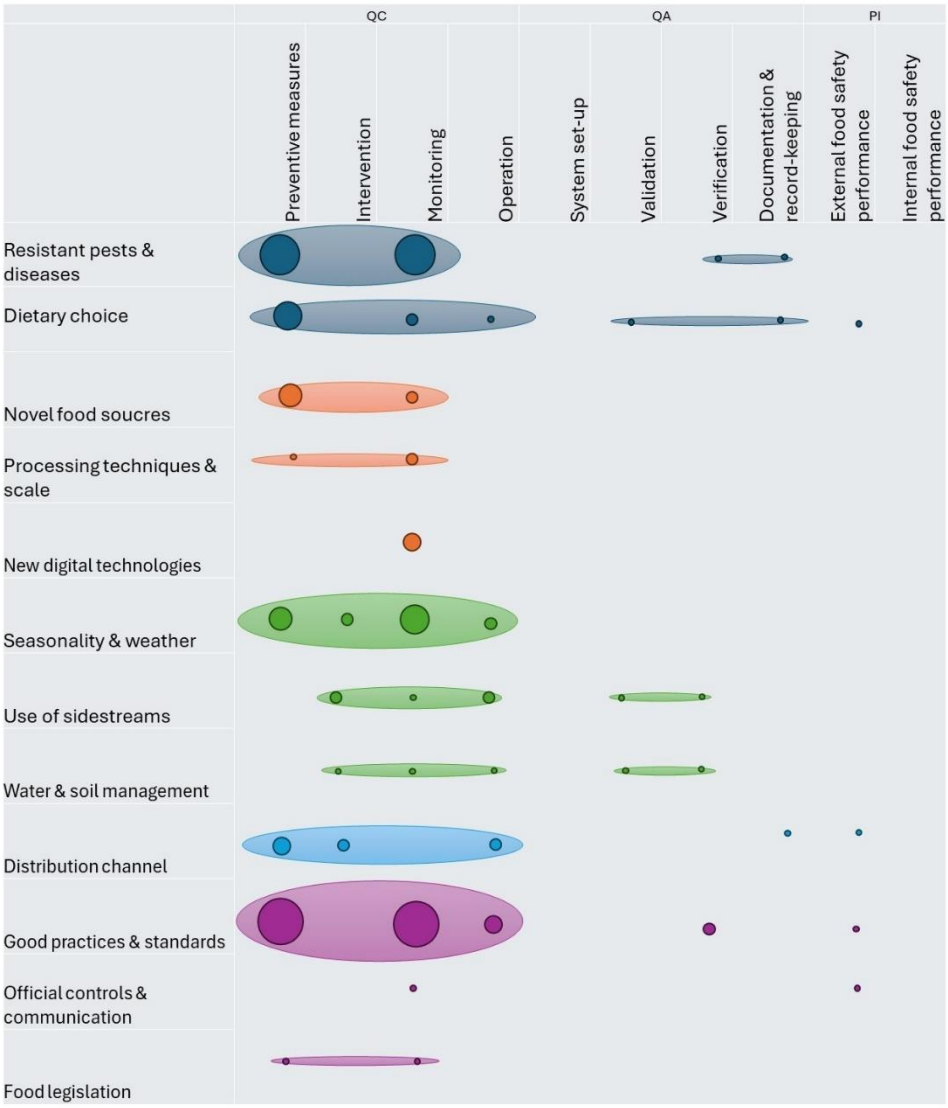

Figure 11 Heatmap showing the top subdrivers per category (dark blue = social, orange = technological, green = environmental, light blue = economic, purple = political) and the FSMS activities that they impact, according to the literature study. The diameter of the circles is representative of the amount of papers indicating this link. The ovals represent the impact per group of activities (QA, QC, PI), and here the smallest diameter is representative of the amount of parpers indicating this link.

Table 19 Mechanisms at play when social and technological subdrivers impact FSMS activities, based on literature review. The number of times each specific link was made is indicated with the exact number, and is also shown through the darkness of the coloring. Dark blue = Social, Orange = technological

		Quality Control											Quality Assurance					Performance	
	FSMS activity	Preventive measures	Interventions		Monitoring					Operation			Vali-dation	Verification		Documentation & record-keeping		External food safety performance	
Subdriver	FSMS activity / Subdriver effect	Hygiene management	Effective intervention techniques	Effectiveness of intervention	Continuous monitoring	Improve microbiological analysis	New monitoring technologies	Specific monitoring	Modification monitoring plans	Ease of operation	Adapat operations	Knowledge of personnel	Need for validation	Verification of strains	Verification of strategies	Modifciation of documentation	Documentation for follow-up	Additional audits	Less complaints
Resistant pests & diseases	Antimicrobial resistance	7			4	1	2							1			1		
Dietary choice	Diet staples	4			1				1	1			1					1	
	Ready -to-eat food	1																	
	New products															1			
Novel food sources	Edible insects	4							1										
	Algae					1													
Processing techniques & scale	New technology		1							1		1							
New digital technologies	Digital technology					1	2												

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Table 20 Mechanisms at play when environmental, economic & politcal subdrivers impact FSMS activities, based on literature review. The number of times each specific link was made is indicated with the exact number, and is also shown through the darkness of the coloring. Green = environmental, light blue = economic, purple = political

		Quality assurance											Quality assurance					Performance	
		Preventive measures	Interventions		Monitoring					Operation			Validation	Verification		Documentation & record-keeping		External food safety performance	
Subdriver	FSMS activity / Subdriver effect	Hygiene management	Effective intervention techniques	Effectiveness of intervention	Continuous monitoring	Improve microbiological analysis	New monitoring technologies	Specific monitoring	Modification monitoring plans	Ease of operation	Adapat operations	Knowledge of personnel	Need for validation	Verification of strains	Verification of strategies	Modification of documentation	Documentation for follow-up	Additional audits	Less complaints
Seasonality & weather	Seasonal variation in contamination	4	1	1	2			1	1		1								
	Microbiological environment							1			1								
Use of sidestreams	Reuse of water		2		1						1	1	1		1				
Water & soil management	Reuse of water		1									1							
	Good water management							1					1		1				
Distribution channels	Transport to distribution	2																	
	Cold chain	1	1	1						1	1								
	Information for retailer																1		1
Good practices & standards	Standards	8			5	3				2	1				2			1	
Official controls & communication	Official controls					1													
	Different countries of control																	1	
Food legislation	Food legislation requirements	1			1														

Table 19 and 20 show the mechanisms of social and technological, and environmental, economic and political subdrivers respecetively, impacting FSMS activities according to literature. The social subdriver of Resistant pests & diseases has the most impact on preventive measures, especially hygiene management. The idea here is mainly to prevent resistant pathogens from coming in (Aleksic et al., 2024; Aragao et al., 2021; Fernandes et al., 2018; Koutsoumanis et al., 2021; Rubiola et al., 2022; Rugna et al.,2021; Yang et al. ,2024). Antimicrobial resistance also elicits continuous monitoring and the development of new monitoring technologies, specifically to follow up on resistance (Allard et al., 2018; Alvarez-Molina et al., 2023; Bahramianfard et al., 2021; Brunn et al., 2022; Elafify et al., 2022; Saksena et al., 2019). For Dietary choice, most papers talked about the production of a few diet staples in different countries, for example different types of meat and herbs. As these are eaten in abundance, albeit in a specific region, hygiene management is important to prevent pathogens from entering the supply chain (Ngo et al., 2021; Oliveira et al., 2018). Edible insects as a Novel food source can be passive carriers for human pathogens, and their gut microbiota are often related to hygiene indicators (Egonyu et al., 2021; Garofalo et al., 2019; Grabowski et al., 2017; Wynants et al., 2017). Hygiene management in production and processing is thus of utmost concern to produce safe end products. The use of New digital technologies can aid especially in monitoring, via the implementation of new monitoring technologies based on artificial intelligence or geographical information systems (Varyvoda et al., 2021; Wu et al., 2022).

The biggest reason of concern for Seasonality & weather seems to be seasonal variation in contamination. Hot and wet weather often favors the growth and trasmission of pathogens, so hygiene is extra important in the summer (Amaiach et al., 2023; Dzudor et al., 2024; Hull-Jackson & Adesiyun., 2019; Lim et al., 2021). It also elicits the need for continuous monitoring to detect variation (Bogdanovicova et al., 2019; Srisamran et al., 2022). When process water is reused, implementation of effective intervention steps, e.g. chemical disinfection is required (Gadelha et al., 2019; Koutsoumanis et al., 2023). In transport to Distribution channels, hygiene management is required, because time-temperature combinations are often not favorable for food safety (Lopez-Galvez et al., 2021; Ortuzar et al., 2020). The difference between effective intervention techniques and effectiveness of intervention for the impact of the cold chain, lies in that effective intervention techniques are required to inactivate pathogens before the cold chain, where they can't grow further, to provide food safety (Dogan et al., 2019), and effectiveness of interventions is impacted through the overuse of the cold chain, which results in adaptation of pathogen which can render interventions ineffective (Hingston et al., 2019). Established standards, stringent standard criteria, legally defined standards, ... all require proper hygiene management to meet the criteria. This is achieved through good hygiene practices (Achinas et al., 2019; Berge & Baars, 2020; Constanzo et al., 2018; Firmo et al., 2023; Nalbone et al., 2022; Sab et al., 2024; Sobolik et al., 2021; Zwietering et al., 2023) and continuous monitoring (Jacxsens et al., 2017; Kharbach et al., 2023; Mario et al., 2024; Saksena et al., 2019; Vallinayagam et al., 2022). Improved microbiological analysis is used to provide more information on the microbiological status and performance (Bahuguna et al., 2023; da Silva et al., 2023; Sab et al., 2024). This is important for the verification of effectiveness of the intervention strategies (da Silva et al., 2023; Vallinayagam et al., 2022). Standards can also give rise to innovations optimizing and streamlining food processing operations (du Plessis et al., 2023; Wu et al., 2024)

3.4 Adding a resilience level to existing indicators

Based on the literature review on resilient food safety management as described in Section 1.2.3.2 and expert discussions, a definition of the resilience level is formulated for QC and QA activities. These definitions are shown in Table 19 and 20, based on the structure of the definitions of the existing levels of advancement. To achieve resilience, a company needs to take into account scientific knowledge on not only the activity, but also on drivers and subdrivers, and their possible impact. This is based on food system knowledge: to know what impacts can be expected, all steps of the food system need to be known and observed. Variability in product and process parameters, which QC activities should keep in an acceptable range, is expected due to the impact of drivers and subdrivers, and can be unpredictable, but the company needs to strive to limit uncertainty in these situations and combat this variability as quickly as possible

and bring product and process characteristics to a new normal. The implemented activities should be adapted to the production system, and adaptable following impacts of external factors.

Table 19 Definition of the various levels of advancement of QC activities from the current diagnostic tool as explained in Luning et al. (2008), expanded to include the resilience level, defined in this research based on literature study and expert discussions.

QC activities	Knowledge base	Variability	Specificity
0 - absence	Absence of activity		
1 – basic level	Lack of scientific evidence, using historical company data	Variable, unknown, unpredictable	Based on common materials / practices, neither specific nor adapted
2 – average level	Best practice knowledge / equipment	Sometimes variable, not always predictable	Based on generic information for the product sector
3 – advanced level	Scientifically underpinned	Stable, predictable	Tailored for the specific production system
4 – resilience level	*Scientific knowledge & food system knowledge*	*Expected variable, sometimes unpredictable, limited uncertainty*	*Adaptable to production system*

Table 20 Definition of the various levels of advancement of QA activities from the current diagnostic tool as explained in Luning et al. (2009), expanded to include the resilience level, defined in this research based on literature study and expert discussions.

QA activities	Content of activities		Structure of activities	
	Specificity of information	Knowledge base	Method	Controllability
0 - absence	Absence of activity			
1 – basic level	General information	Historical data	Checking, problem driven	Ad hoc, not independent
2 – average level	Standard information	Expert knowledge	Analysing, feedback driven	Regular, partly independent
3 – advanced level	Specific information	Scientific knowledge	Criticizing, procedure driven	Systematic, fully independent
4 – resilience level	*Research & Innovation information*	*Scientific knowledge & food system knowledge*	*Re-evaluating, future driven*	*Adaptable, various ranges of independency*

QA activities should be based on research and information and focused on constant re-evaluation of the system. A pro-active and future driven approach is crucial in resilient food safety management. There should always be a plan B and activities should be adaptable to the situation. To do this, the company needs to record as much information as possible themselves, but information coming from other links in the food supply chain should be consulted as well to get as good of an image as possible on what mechanisms are at play. This means that the company is not always fully independent in the controlling of QA activities. An example is given for both a QC activity and a QA activity of how this resilience level can be translated into specific indicators of the current FSMS diagnostic instrument. For QC, the indicator for incoming material control is shown in Table 21, for QA the indicator for validation of preventive measures is shown in Table 22.

Table 21 Example of the implementation of the resilience level definition in the QC indicator for incoming material control

Situation 0	Situation 1	Situation 2	Situation 3	*Situation 4*
No control of food safety level of incoming material	Incoming material control on food safety level is ad hoc and is mainly based on historical experience with suppliers	Incoming material control on food safety level is based on guidelines, or legislative requirements or guidance document for sector and is implemented in daily practice	Incoming material control on food safety level is based on use of statistical underpinned acceptance sampling (i.e. sampling frequency, location, analysis, rejection criteria, etc.) using actual historical data of suppliers, and is implemented in daily practice	*Incoming material control on food safety level is based on scientific knowledge as well as all information available in the food system, and is constantly re-evaluated to adapt when variability exceeds limits*
Systematic and adequate incoming material control will prevent (high and variable initial) acceptance of contaminated incoming materials, which will reduce chance on (cross) contamination of the production process which will positively contribute to food safety.				

Table 22 Example of the implementation of the resilience level definition in the QA indicator for validation of preventive measures

Situation 0	Situation 1	Situation 2	Situation 3	Situation 4
Effectiveness of preventive measures have (yet) never been validated	Effectiveness of preventive measures is validated based on historical knowledge only judged by own people	Effectiveness of preventive measures is validated based on opinion of independent expert, using expert knowledge, regulatory documents and historical results	Effectiveness of preventive measures is systematically validated, by independent experts, based upon specific scientific sources (like scientific data/literature on validation studies, predictive modeling), historical results, and own experimental trials;	*Effectiveness of preventive measures is validated and re-evaluated regularly, based upon scientific sources as well as knowledge gathered from other links in the food supply chain, and adapted through research and innovation*
	On ad-hoc basis	On regular basis and after system modifications	On regular basis and after system modifications	*On regular basis following continuous monitoring and re-evaluation*
	Findings scarcely (not) described.	Findings described in reports	Activities and results well documented	*Activities and results well documented*
Systematic and adequate incoming material control will prevent (high and variable initial) acceptance of contaminated incoming materials, which will reduce chance on (cross) contamination of the production process which will positively contribute to food safety.				

4 DISCUSSION

4.1 Diagnosis of an alternative food system using the current diagnostic instrument

Aquaponics as a food production system are an example of an innovation led by the impact of certain drivers and subdrivers, as explained in Box 1 of Section 1.3.1. The system consists of a combination of primary production of vegetables, herbs and microgreens, and the primary production of fish. The latter falls under Regulation (EG) 853/2004 when it comes to hygiene regulation, as it concerns food production of animal origin. HACCP principles need to be in place along with the specific hygiene requirements for fishery products. In the interview, it was discussed that these regulations are followed by the company in their fish farming section. However, for primary production of plants, no HACCP implementation is required, as stated in Regulation (EG) 852/2004. Indicators related to HACCP principles are also not present in the HSMS-DI that is specifically set up for primary production. The company is however still responsible for producing a safe end product, and possible food safety hazards should be identified and controlled. It is stated in this regulation that in the case of production of small quantities directly sold to local retail markets, the regulation does not necessarily apply and national law should be followed to protect human health. The company that was interviewed for this only sells through retail markets in and around Brussels, so this might be the case for them.

There are some important aspects here concerning food safety that should be considered when setting up a food safety management system for an aquaponics farm. The water that is used for fish production, is then reused to grow plants. This water could potentially be contaminated with pathogens coming from the fish or fish handling. The fish excrements present in the water are useful as an organic fertilizer for the primary production of the plants, but could also be contaminated. These microbiological risks are often unknown or uncertain, especially in small companies like this where limited food safety knowledge is present, like the one interviewed here (Ljubojevic et al., 2017). The water is filtered before application in plant primary production, but monitoring, validation and verification activities are limited. The implementation of this filtration step is based on best practices and guidelines, as was also established through the indicator concerning the organic fertilizer program of the HSMS-DI. However, for the indicator on water control, it was mentioned that water control is not in place. The products are sold as fresh produce for ready-to-eat consumption, so the aquaponics farm is the most important link in the supply chain when it comes to ensuring food safety. As it is a fresh product, the only intervention step that occurs is the removal of visibly contaminated or wilted parts of the plant. This was started as a reaction to customer complaints. The manager of the company mentioned that this was not well controlled nor documented and based entirely on the knowledge and action of the workers. The same goes for hygiene requirements: the supervisor is instructed to make sure the employees pay attention to hygiene, but besides the encouragement to keep hands and equipment clean, no structural sanitation program is in place. Especially when working with seasonal workers, that are often not knowledgeable and not trained in food safety, this might be a reason for concern (Labovic et al., 2023). The only FSMS activity that is well established and documented is the measuring of environmental parameters in the production environment, although this is mostly done to support the growth of the plants rather than for food safety. Food safety effects of these measured parameters are also not really considered or followed up.

Overall, the HSMS for primary production in this company is not well structured, although fresh produce has a significant risk for contamination and no further processing or handling by the customer is expected before consumption. As this is a small company where the manager has no food safety training and no QA manager is present, this lack of knowledge is represented in the lack of implemented FSMS activities and follow up of the product's food safety. They act solely on complaints and ad hoc issues, and hygiene and physical intervention are fully in the hands of a staff with variable composition. Through this interview, it also became clear that the exhaustive list of indicators as presented in the

diagnostic instrument is quite hard to get through when interviewing someone with limited to no food safety knowledge. Specific terms often needed extra explanation and it was often up to the interviewer to decide which level should be attributed, based on the explanations of the manager. Paying attention to the given answers was also important to guide the manager through the interview, by adapting examples that were given to the specific situations in the company. This does show the importance of having conducting interviews to go through the diagnostic instrument, with interviewers that are knowledgeable on the subject. Some answers that were given in the beginning, e.g. that no pesticides are used in the company, made other indicators useless, e.g. pesticide analysis. However, these indicators were still gone through, albeit with less attention spent on these follow up indicators. This gives rise to the question of if this diagnostic instrument should be adapted to the specific situation of the company: if no pesticides are used for example, the indicators on follow up and control of pesticides will render low scores, although this does not affect the product safety.

The diagnostic instrument could also be adapted to the size of the company and their consumer market. However, the current form is quite established and has been used in a multitude of sectors and FBO's already, as was shown in Section 1.2.2.3. Luning et al. (2015), Njage et al. (2018) and Dzingirayi & Korsten (2016) use the diagnostic to compare companies and farms of different sizes. The conclusion is that smaller companies often lack advancement of QC and QA activities, and don't have the same range of implemented activities as larger companies, resulting in lower food safety performance. The reason for the lack of FSMS activities could be that the cost of the implementation is too high for a company of that size, and they cannot cover this investment in food safety. If the expectation however is that less advanced activities will be installed, going through that long list of indicators, could be unnecessary. When adapting the diagnostic instrument to a small business situation, the list of FSMS indicators could be reduced to activities that are more often present in these companies, but correcting in scoring for the fact that the risk in small business is often higher. This adaptation is however outside the scope of this research.

4.2 Updating the existing diagnostic instrument

4.2.1 Mechanisms of impact of subdrivers on internal context indicators

Through the literature review, mostly links were made between subdrivers and the internal context indicator packaging concept, as seen in Section 3.3.1. In early internal discussions concerning the update of the diagnostic instrument, the context indicator of packaging concept was already considered as an example of an indicator that should be updated under the influence of the drivers and subdrivers. Especially the drive towards more sustainable packaging options, such as biodegradable packaging and design for recyclability, are not considered in the current formulation of the indicator. The balance between good barrier properties and protection of the food product, and sustainability is delicate and should be thought about. Multi-layer plastic packaging is often used because of its excellent product protection, but isn't recyclable. Monomaterial packaging on the other hand is more recyclable but doesn't offer as good of a barrier, which has implications for food safety. Guttierez et al. (2017) even proved that sometimes using non-recycled materials has a smaller environmental impact because it reduces food waste. However, the European strategy for circular economy states that in 2030, all plastic packaging should either be reusable or recyclable (Matthews et al., 2021). The evolution towards packaging that is recyclable or biodegradable and has better barrier properties is still ongoing, but with the pressure of changing regulations around single use plastics, FBO's already feel the need to incorporate more sustainable packaging materials. This can be seen in the rather high amount of participants in the workshop highlighting sustainable packaging as a trend with impact on their FSMS, especially on the shelf life. This is not reflected in the current indicator for packaging concept. An update of this indicator that includes this trend towards sustainability might be beneficial to asses maturity of the business better. The indicator for packaging concept is set up following the rationale that a packaging concept that is meant to influence the shelf life poses higher requirements for QA and QC

activities. Using recyclable or recycled packaging, or biobased packaging, intended to have the same barrier properties as multilayer packaging also poses high requirements for the FSMS, especially through the need for validation of this impact on shelf life. Implementation of hygienic standards, combined with extra intervention and a recyclable packaging option could even come close to protection of classic packaging (Ferri et al., 2023)

Some of the trends stemming from the influence of drivers that are highlighted by FBO's in the workshop could also be seen as innovations, impacting context indicators. New technologies, new products, new packaging, more plant-based and ready-to-eat products, minimal processing and use of additives,… these trends can already be measured in the current context indicators. For example, the indicator for rate of changes of products and processes. A high impact of these drivers for implementation of new products or technologies will result in a high score for this indicator. Minimal processing and use of additives is discussed in the indicator for intervention strategies. Ready-to-eat products are an end of line product where no further handling or processing is expected from the customer, as assessed by the indicator for position in the supply chain. When FBO's follow these trends and often change their product portfolio, this will be reflected in a high score for their context riskiness and so a more robust FSMS is needed. A similar thought process can be followed for the indicator of contamination of initial materials. When the risk of contamination goes up for their incoming materials, following the impact of drivers and subdrivers, or when more contaminated materials are chosen, this context indicator will already reflect that.

These internal context indicators go over product, process, organisational and chain characteristics. As mentioned in Section 1.3, these internal contest indicators are under the pressure of the drivers and subdrivers via the innovation pathway. The variability of these impacts and the pressure to follow these trends is rooted in the impact level of the external business context. This external context consists of the drivers and subdrivers. Therefore, the inclusion of new indicators for external context, can form a good addition to these internal context indicators, to assess how mature the FSMS activities should be. Stoyanova (2019) describes a similar research linking internal and external context factors to impact on food safety management, and concludes that both can have significant impact on food safety output. The dynamic character of the external factors can lead to inconsistencies in output performance and present adverse effects. The more dynamic the external factors are, the higher the impact, which should be considered in the FSMS-DI.

4.2.2 Mechanisms of impact of subdrivers on FSMS activities

For all the subdrivers, there was at least one workshop participant that indicated that this subdriver has an impact on their food safety management system. This shows that these FBO's really feel the pressure of the drivers and subdrivers that were established in the Horizon Europe FoodSafeR project. In the workshop, only a limited number of FBO's participated, all located in Belgium. This does implicate uncertainty about the results and if this applies for a larger number of FBO's all over Europe in the same way. Although the scope of the workshop was microbiological food safety management, multiple answers included examples for chemical food safety management, and even overall product quality. The participants mentioned struggling with this restriction for microbiological food safety, as they usually have to keep an overview of all consequences on food safety and quality. These examples were not further analysed, but it is noteworthy that drivers and subdrivers do not only impact microbiological food safety. The literature study did not result in papers linking subdrivers to FSMS activities for all subdrivers. This review is however limited by the search terms that were chosen. The search for papers was also limited to containing the search terms, as well as some variations of the words "food", "microbiological" and "safety", in the abstract. This was done to simplify initial screening of the papers, but the search terms might appear in the full text of a paper, without all appearing in the abstract too. In the literature review, a multitude of papers were also not used for further analysis because of their focus on chemical food safety.

The category of drivers that was on average indicated by the most participants was the political category. The three subdrivers that were indicated most for this category are Food legislation, Official controls & communication and War & conflict. This category also scores best in the overall ranking of subdrivers to consider, with Food legislation taking first place and Good practices and standards in third. These political subdrivers impact all parts of the FSMS and also of the performance indicators.

For Food legislation, the impact is scattered over all FSMS activities, through the influence of changing legislation and lack of harmonisation in legislation between different import and export regions. For Official controls & communication, the impact is mostly on external food safety performance, as different interpretation of legislation by different auditing bodies results in different auditing results. The high degree of controls and authority expectations put pressure on the QA team and the development of the FSMS. These findings are however not supported by the literature review. Very few papers were found discussing the impact of legislation and official controls on microbiological food safety, while the FBO's consider this as one of the most important subdrivers. Scientific research deviates here from the issues that occur in real-life situations.

War & conflict mostly impact QC activities, especially preventive measures, because restricted import and low availability of materials from conflict regions result in the need to look for other suppliers and manage multiple suppliers when products were originally sourced from suppliers in conflict regions. This impact was already suggested in Section 1.1.2 based on Kendall et al. (2018) and Wentholt et al., (2010) This subdriver scoring this high in the workshop might be related to the recent occurrence of wars in important export countries, mainly Ukraine. FBO's working with grains or other materials from Ukraine will have definitely felt the impact of the restricted export due to the ongoing war (EUCO, 2024).

Good practices & standards was not indicated by as many participants, but the ones who did feel the impact, ranked it quite high. In the literature study it did appear in multiple papers highlighting its impact on multiple FSMS activities, especially preventive measures and monitoring. When putting the results of this literature review next to the examples provided by the participants that did indicate this impact, it can be seen that the implementation of good practices and the follow up of microbiological standards does put pressure on the implementation of preventive measures such as hygiene management (Achinas et al., 2019; Berge & Baars, 2020; Constanzo et al., 2018; Firmo et al., 2023; Nalbone et al., 2022; Sab et al., 2024; Sobolik et al., 2021; Zwietering et al., 2023) , monitoring of process and product parameters to stay in between the acceptable ranges set by standards (Jacxsens et al., 2017; Kharbach et al., 2023; Mario et al., 2024; Saksena et al., 2019; Vallinayagam et al., 2022), and the implementation of changing standards in the system set-up, which was mostly mentioned by the workshop participants.

The economic subdriver of Global trade was indicated by two thirds of the participants and ranked 8th in the overall subdriver ranking. The impact of it on food safety management is rather scattered over different activities. Globalisation leads to export to new countries, as well as import from suppliers all over the world. The whole FSMS, both QC and QA activities, is subject to changes caused by new sourcing regions, new export countries and the increase of stakeholders that need to be considered. In the literature review, more papers were found on the impact of Distribution channels than for Global trade. The mechanisms described in these papers talk about the influence of time, temperature and handling in transport to the Distribution channels on food safety. If any of these aspects are not favourable for the food safety of the product, a higher pressure is put on hygiene, interventions and optimised operations, to prevent pathogens from entering or growing throughout the supply chain (Lopez-Galvez et al., 2021; Ortuzar et al., 2020).

Dietary choice and Resistant pests & diseases are the top subdrivers with an impact on food safety in both the workshop and the literature review, with Consumer awareness & attitude coming in third in the workshop results. All three also show up in the top 10 of the overall ranking of subdrivers to consider. They impact all parts of the FSMS. Resistant pests diseases especially have an impact on preventive measures: when resistance of pests and diseases to interventions increases, it becomes more important to keep them out of the workplace. Increased incoming material control, pest

control and hygienic working are most important to achieve this, according to the participants in the workshop. This is confirmed by the literature (Aleksic et al., 2024; Aragao et al., 2021; Fernandes et al., 2018; Koutsoumanis et al., 2021; Rubiola et al., 2022; Rugna et al.,2021; Yang et al. ,2024). Dietary choice and Consumer awareness & attitude mostly have an impact through rising demand for new or different products, leading to a revision of the whole FSMS to accommodate for these new products. For the subdriver of Dietary choice, FBO's also highlighted the demand for products with a different formulation and production, like containing less salt or sugar, and adapting to the requirements for claims. When production is adapted like this, validation of the food safety of this adapted product and production process are required. Two different participants also mentioned the impact of allergen free diets, as this is also managed in the FSMS. The scope of this thesis is on microbiological food safety, so these results were not taken into account in further processing, but it is worth mentioning that this is also a possible impact of Dietary choice. In the literature review, the main focus concerning Dietary choice is on dietary staples in different countries. Large demand for these products put pressure on FBO's, and also results in large exposure of contaminations on this product. This calls for good hygiene management in production facilities of such diet staples (Bahuguna et al., 2023; Cortes-Sanchez et al., 2023; Ngo et al., 2021; Oliveira et al., 2018) For Consumer awareness & attitude, it was also mentioned that negative publicity and demand for new sourcing regions, e.g. local sourcing, could lead to a necessary change in suppliers.

The technological subdrivers of Food packaging and Processing techniques & scale mainly implicate that new and sustainable packaging solutions, and new technologies, should always be validated before implementation. Literature shows that new processing techniques could make operation easier and be used as effective intervention techniques, but they do require good knowledge and understanding of the operating personnel. Products for food production have an impact on the quality of the raw materials, and when new products are used, this should be taken into account in system set-up. When regulation on products like pesticides change and pesticide use is reduced, microbiological quality of the incoming materials might decrease, and more sampling might be necessary. On the other hand, as shown in the literature study, the administration of pesticides using contaminated water might also result in higher microbial loads of the incoming materials (Gomba et al., 2017). The same is true for fertilizes, as they provide a favourable environment for growth of plants, they can also facilitate growth of micro-organisms (Amkor et al., 2024). The literature review highlighted the impact of Novel food sources on food safety management (Egonyu et al., 2021; Garofalo et al., 2019; Grabowski et al., 2017; Wu et al., 2022; Vandeweyer et al., 2021; Wynants et al., 2017) , but this is only relevant when a company actually introduces these materials for new food products. New digital technologies, such as artificial intelligence, can help in facilitating monitoring activities according to literature (Ma et al., 2023; Varyvoda et al., 2021; Wu et al., 2021).

For the environmental drivers, Seasonality & weather and Climate change are the most indicated by participants. Both subdrivers are explained through similar impacts by the participants of the workshop: changes in weather, especially due to climate change, resulting in lower availability of ingredients, and these ingredients often vary in quality and food safety. Literature however mostly highlights the seasonal variation is pathogen contamination. Warm and wet weather can stimulate the growth and transmission of pathogens (Amaiach et al., 2023; Beckiewicz & Kowalcyk, 2021; Bogdanovicova et al., 2019; du Plessis et al., 2023; Dzudzor et al., 2024; Hull-Jackson & Adesiyun, 2019; Ilic et al., 2017; Jeon et al., 2020; Lim et al., 2021; Sabillon et al., 2020; Srisamran et al., 2022). This phenomenon is not mentioned by the FBO's in the workshop. This could mean that FBO's do not observe these variations in their production, or that they are not attentive to these variations. Participants of the workshop also highlighted the effect of agricultural pollution on contamination of ingredients and water quality. A few of the examples for this were not considered in further analysis because they specifically mentioned chemical issues. Other examples did not specifically mention if they considered microbiological or chemical contamination. The geographic region of sourcing can impact multiple facets of food safety management, but none of these mechanisms were mentioned by more than participant. This influence was also not supported by the literature review. Reuse of water was considered in literature as a Use of sidestreams and as

part of good Water management. To be able to repurpose process water safely, interventions, validation of these interventions, monitoring and verification of the process parameters are required (Gadelha et al., 2019; Koutsoumanis et al., 2023)

4.2.3 Formulation of new external context indicators

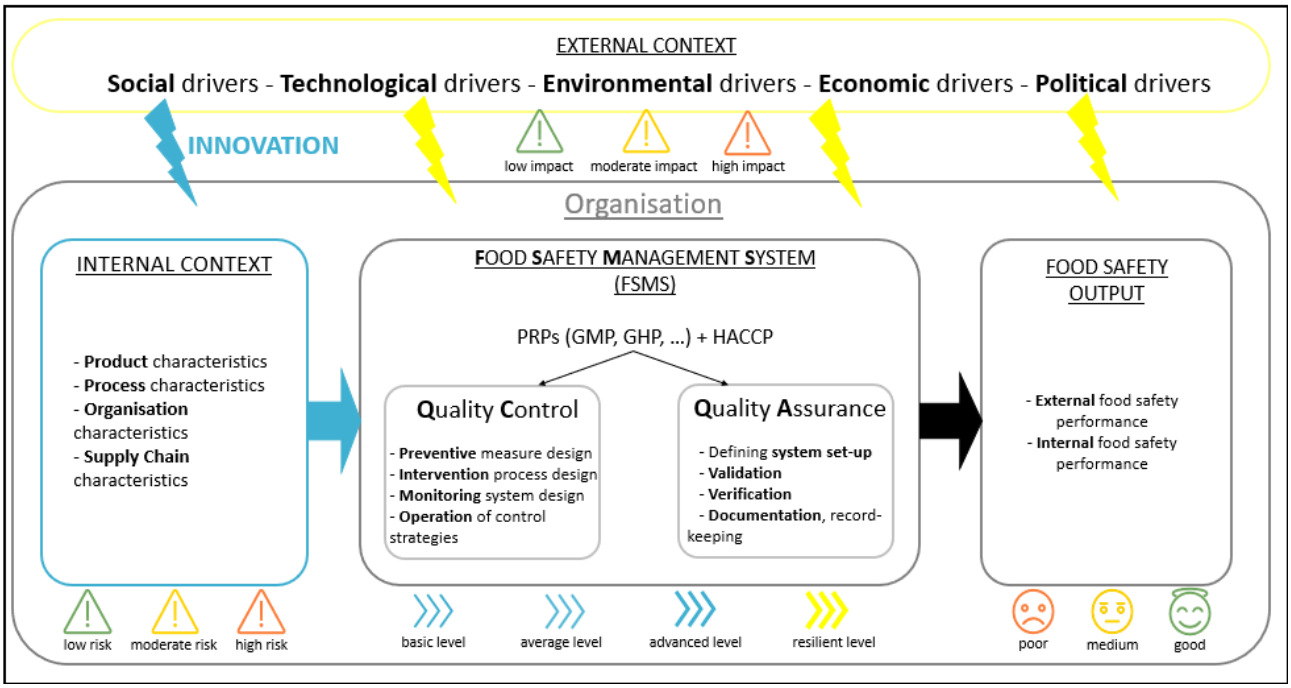

Figure 12 Impact of the drivers from the external context on the internal context via an innovation pathway (indicated with blue lightning bolt), and on the food safety management system via food safety shocks (indicated by yellow lightning bolts) eliciting the need for resilience. Vermeersch (2024)

As shown in Figure 12, that was introduced in Section 1.3, the external context, consisting of the drivers and subdrivers, impacts the FSMS (shown by the yellow lightning bolts) requiring resilience of the system to result in good food safety output. The impact can be either on how QA and QC activities are performed or on the way food safety performance is judged. The mechanisms that were presented in the previous section give real life explanations of how this might happen. When a food business operates in a low impact environment, changes in external context factors have no or limited impact on their FSMS. Resilience of the FSMS is thus not required to guarantee food safety of the output. When a business operates in a high impact environment, a high variability of food safety output is expected and resilience is needed to cope with that.

Indicators that can assess the severity of the external context impact can be based on the mechanisms that are presented for the most important drivers to consider. A first suggestion for new external context indicators stems from the overall ranking of subdrivers by the FBO's in the workshop. Food legislation is found to be the most important subdriver to consider in food safety management for these businesses. The impact that they see here has to do with changing and new legislation, and non-harmonised legislation between the different countries of their suppliers and customers. Two new indicators for external context factors can be constructed based on these subdriver effects. The first one will ask about variation of legislation in the country of production. A low impact is related to stable legislation that is not often updated. High impact is related to regularly updated legislation. Changing regulation was also mentioned by participants as a reason for impact on their FSMS for the subdrivers of Products for food production, Geographic region and Global trade. The second indicator could handle harmonisation of legislation between the different countries of suppliers and customers, as well as the production site. For countries in Europe, most legislation is harmonised. Low impact could then be considered for companies that import, export and produce only in Europe. High impact is present when supply, distribution and production happen in various countries that do not have a

harmonized legislation. Stoyanova (2019) also mentions the importance of legislative external context factors, including changing and harmonisation of legislation. Differences between regulations of different countries and compliance to new criteria dependant on the country of supply and distribution leading to complication of the FSMS were also mentioned by participants for the subdrivers of Climate change (due to low availability of ingredients and new region sourcing), Processing techniques & scale (due to upscaling to export) and Official controls & communication.

A second political subdriver that should be considered for conversion into a new indicator for external impact is Good practices & standards. Although it was not in the top 3 most indicated political subdrivers, the participants that did indicate an impact, also ranked it high. This already indicates the different levels of impact: some FBO's are under high pressure of these Good practices & standards, while others don't even notice the impact. The mechanisms of impact are mostly based on the literature review for this, where it did come out on top among the political subdrivers. Regulatory standards can be defined for product performance, process design or a combination of both. Product performance is regulated by criteria for presence of hazards, while process design standards focus on the implementation of certain procedures in process design, such as sanitation programs (Cho & Hooker, 2009). Good Agricultural Practices or GAP standards, the HACCP principle and International Standardisation Organization or ISO standards are examples of such standards and are meant to achieve international uniformity. Certain private standards exist that are aimed at improving supplier and customer relationships and eliminating the need for multiple audits through certification. These standards often apply to the entire Quality Management Systems and are based on GAP, GMP, HACCP and ISO principles. Examples are Global GAP, British Retail Consortium (BRC) and Safe Quality Food (SQF) (Jacxsens et al, 2011; Luning et al, 2009; Trienekens & Zuurbier, 2008). Based on this, two external context indicators are suggested for implementation. The first one should handle regulatory standards. Strict standards on product performance pose high requirements for the FSMS activities. Strict standards on process design require implementation and follow-up of specific processes. Stringent and often changing regulatory standards thus result in a high impact situation. When product and process standards are less stringent or stable over time, impact is low. A second external indicator could be based on private standards and the pressure for implementation based on supplier and customer requirements. High impact relates to high pressure for implementation of multiple standards, while low impact refers to limited pressure for implementation of (additional) private standards. However, this was only specifically highlighted in one paper, as an instigator for additional audits (Smith, 2019). This indicator might thus be less important to include.

The second highest ranked subdriver is climate change. Effects of climate change as observed by the workshop participants have to do with availability of quality ingredients, maintenance of the cold chain and reduced water use. Although "climate change" and "sustainability" are two concept that are often related to each other, the FBO's in this workshop did not mention this drive for sustainability as an effect of climate change. For a business, incorporation of sustainable initiatives is often forced by legislation or customer requirements, or intentionally done as part of a business strategy. For a sustainability decision to make sense, it needs to generate profit (Chladek, 2019). For the subdriver of food packaging, multiple examples talked about the switch to more sustainable packaging solutions such as reduction of material and recycled or recyclable material This evolution is also driven by European legislation, as mentioned in Matthews et al. (2021). Pressure to include sustainable alternatives could thus be a possible external context indicator, with high impact being related to high legislative pressure and/or customer requirements. The observed effect of reduced water use also falls under such a implementation driven by sustainability pressures. The main effects by FBO's concerning Climate change have to do with irregular and extreme weather events impacting availability and quality of products, and the cold chain. Both of these are also mentioned as effects of Seasonality & weather. Literature supports the idea that weather conditions impact contamination of materials. Possible external context indicators based on this subdriver could be about the weather conditions in supplier regions, and weather conditions in the production and distribution region (related to maintenance of the cold chain). Highly variable and hot weather result in higher impact on food safety in both cases.

4.2.4 Adding a resilience level to existing QA and QC indicators

To combat high impact of external context factors, a food business thus needs to be resilient in order to produce a safe output. High impact will likely result in high quality variability of input and output. Resilience means that this variability is considered, the root causes are sought, and changes in operations and activities are made to bring variability back to normal levels. To make this process fast and smooth, continuous monitoring and re-evaluation of the monitoring results are needed, and production processes should be adaptable to react quickly when inconsistencies occur (Rød et al., 2020). The Resilience Framework Matrix in Section 1.2.2.3 shows how this is a cyclical process: when variability goes out of bounds, extra attention should be given to the reason for this disturbance. This should then be communicated properly to the right people or authorities, that can then make a decision on how to handle this variability, and new procedures can be implemented (Bracco et al., 2014). To be able to do this, the company needs to be prepared for future disturbances and be able to anticipate on them in a pro-active manner. Research and innovation are key to reach this goal. An overview needs to be kept on trends in the company itself as well as trends occurring in the rest of the food system. A clear vision on the different drivers at play in the food system is needed to find the root cause for occurring problems. Research in unexpected variability can also clear up new pathways of impact of external context drivers, which will lead to more preparedness for similar situations in the future. An example of this could be, based on the mechanisms as presented based on the workshop and literature review, seasonal variation of contamination. In incoming material control, and monitoring of the product contamination, it might be evident that a high variability of food safety parameters occurs when comparing records from different times of the year. If this variability could be attributed to seasonal variation due to warm and wet weather stimulating growth of pathogens, preventive measures should be increased in these high risk seasons. The effectiveness of preventive measures and intervention strategies can be validated to see how these measures should be adapted to the seasons, and after implementation, effectiveness can be verified, and where needed, re-evaluated.

This idea of resilience has been translated into a resilience level for the assessment of QC and QA activities in food businesses. For QC activities, resilience is based on scientific and food system knowledge, variability is expected, and can be uncertain or unpredictable, but should be reduced over time, and this through the adaptability of the implemented activities. Resilience in QA activities is based on research & innovation using scientific and food system information, activities are structured in a future driven way and continuously monitored and re-evaluated. Activities should be adaptable, and a plan B should always be present. The company depends on it's own information and records, as well as food system information for this.

4.2.5 Future perspectives

If impact of external context factors are high for a specific company, the variability stemming from these impact factors should be countered by resilient food safety management. This rationale can be translated for the updated diagnostic instrument: if a company scores high for external context indicators, they should reach the resilience level in QA and QC indicators, to deliver good food safety performance. Including both of these updates into the current diagnostic instrument will help in assessing maturity of a company's FSMS better in the future. To complete this update, the mechanisms resulting from the workshop and the literature study should be further analysed and translated into new indicators for external context. A prompt is already given for possible new indicators, but these new indicators should be verified by a panel of experts before implementation. The definition for the resilience level was already applied to two FSMS indicators, but the implementation in the other indicators for QA and QC activities will require further research and verification by experts. The scoring system, as seen in Table 3 of Section 2.1 will also need to be revised for the inclusion of a new level of advancement.

CONCLUSION

Impact of drivers and subdrivers on food safety on an FBO level were assessed with an online workshop where FBO's were stimulated to think about what impacts they see and experience in light of microbiological food safety management. Their answers were then translated into more concrete mechanisms. In this way, subdrivers could be linked to specific FSMS activities that they might impact when changes in the subdriver effects occur. The results were supported by a structured literature review with the same aim. This led to a more clear and structured vision of the ways in which impact of drivers and subdrivers can influence food safety management. However, the workshop was performed with only 15 FBO's that are all situated in Belgium. This limited number of participants that all operate in the same country can lead to uncertainty on the results. To get a more complete understanding of the mechanisms at play, the workshop could be repeated with a larger sample size of FBO's from different countries. Participants also mentioned struggling with the restriction for microbiological food safety impact, and some participants still gave examples based on chemical food safety and allergen management, and even sensorial quality of the products. An extension of the workshop to include all food safety and quality issues could be interesting to get a more comprehensive result. The literature review supported the results of the workshop in some ways, but also deviated from the results in terms of subdrivers and trends that were highlighted the most. Food legislation for example was seen as the most important subdrivers from an FBO perspective, but only limited scientific research of its impact was found. There are also some methodological limitations for this literature review: the search terms were chosen were re-evaluated throughout the process but could still be optimized further.

A ranking was made of the most important subdrivers to consider in food safety management, based on the rankings provided by the FBO's in the workshop. As already mentioned, the limited amount of participants does result in some uncertainty of these results. The subdrivers that are considered to be the most important to consider for FBO's are also probably most relevant to include as part of the Food Safety Management System Diagnostic Instrument. To include the impact of drivers, new indicators can be constructed for impact of external context impact. Suggestions are made for new external context indicators, but further investigation into the mechanisms at play, and a revision of the ranking based on a larger sample size of experts are needed to construct relevant indicators.

Resilient food safety management was described based on literature review and translated into a new level of FSMS maturity in the FSMS-DI. Further implementation of this resilience level into the existing indicators is required. This resilience level will serve to asses if a business can cope with high impact of external factors. The implementation of both these external context indicators and the resilience level can help the assessment of maturity of a business's FSMS.

This research gives an indication for possible mechanisms at play when drivers and subdrivers impact food safety management, and how this could be translated into the assessment of food safety management systems with the diagnostic instrument in the future.

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APPENDICES

1. Appendix 1: Informed consent as provided and accepted by all participants of the workshop sessions

Dear Participant,

This survey is conducted as part of a thesis, that falls into the Horizon Europe FoodSafeR project, carried out partly by the Ghent University. The project aims at developing future-oriented tools for the assessment and management of emerging food safety hazards and associated risks. This thesis specifically handles the topic of resilient food safety management to anticipate on related microbiological food safety challenges. By completing this questionnaire you contribute to our research. There are no right or wrong answers, so try to answer as honestly as possible. All obtained data will be processed strictly confidentially by us and any form of anonymity will be guaranteed. Thank you very much in advance for your contribution!

Informed consent form

We ask that you read this form carefully before continuing this survey and indicate what you agree and disagree with.

I declare that I:

- **voluntarily** participate in this study and that I can **stop my participation** at any time
- consent to the **anonymous use** of my results **by the researchers**
- know that not participating or stopping my participation will **not affect me negatively in any way**
- know that I can obtain a summary of this research upon request, after the study is completed and the results are known

☐ I declare that I have received the explanation of this research and that I have been given the opportunity to ask additional questions.

☐ I declare that I agree with this informed consent form.

2. Appendix 2: Explanation of drivers, subdrivers and FSMS activities in the workshop.

Table A2.1 Explanation of FSMS activities as given in the workshop. Activity categories are indicated in bold, with the corresponding activities in the rows underneath it.

FSMS activity	Explanation
Quality Control (QC)	All activities that aim at ensuring that product and process characteristics are in an acceptable range
Preventive measures	Aim at avoiding high initial contamination of the ingredients and cross contamination during the process, e.g. hygiene policy, supplier control
Interventions	Aim at inactivating pathogens or reducing them to an acceptable level, e.g. addition of additives, heat treatments
Monitoring	Aim at following up on the status of product and process characteristics, e.g. sampling
Operation	Actual operation situation and equipment capacity, e.g. following procedures
Quality Assurance (QA)	All activities that aim at setting requirements, evaluating effectiveness of the system and organizing change
System set-up	How the system is set-up and changed over time
Validation	Checking in advance if planned QC activities are effective in reaching their goals
Verification	Checking after implementation of QC activities if they can guarantee food safety
Documentation & record-keeping	How data and procedures are maintained and stored
Performance Indicators (PI)	Food safety performance of the output
External food safety performance	How food safety performance is measured externally, e.g. audits, inspections, customer complaints
Internal food safety performance	How food safety performance is measured internalle, e.g. sampling results

Table A2.2 Explanations of drivers and subdrivers as was given in the workshop, divided into the 5 STEEP categories. Drivers are indicated in bold, with its subdrivers in the rows underneath. No structured explanation was given for geographic region, seasonality & weather and climate change.

Driver/Subdriver	Expanation
Social category	
Consumer behaviour	The behaviour of individual consumers can influence the nutritional habits /individual diets. (Changed eating habits lead to potential exposure or development of new hazards.)
Dietary choice	What food consumers choose based on nutrition and preference; e.g., vegetarian, fast food, red meat
Consumer knowledge	The individual and common knowledge of consumers in relation to food (including education & training); e.g., cooking at home, hygiene practices
Consumer awareness & attitude	Change of attitude drives choices; e.g., animal welfare, natural equals safe, herbal tea is good for you
Public awareness	The awareness on foods, diets and related hazards via governmental communication, news, social media, NGOs; e.g., high fibre, low salt, bird flu, antimicrobial resistance
Demographic development	Demographic development strongly influences dietary and nutritional needs in Europe through:
Population change	Change in the size of a population between a given time period (usually one year); e.g., birth/deaths, age/population pyramid
Prevalence of vulnerable groups	Composition of the population considering e.g., ageing, immunocompromised people
Urbanisation	Proportion of people living in towns and cities
Migration & travel	Migration movement, and on a small scale also tourism and travelling of people lead to cultural changes; e.g., exposure to different foods/hazards

Health and wellbeing	Human health and wellbeing can affect the susceptibility of the general public to food safety risks.
Human health condition	A person's wellbeing influenced by proportion of non-communicable diseases; e.g., depression, diabetes or obesity
Resistant pests & diseases	Pests and diseases can develop different resistances; e.g., antibiotic use and related antimicrobial resistance
Technological category	
Technologies in food production	Technological cross-overs may lead to new products and production systems. While some technologies can decrease the risk of hazards, others may cause unwanted side effects.
Plant-derived food production	Technologies used for the production, rearing or growing of primary products; e.g., industrialized, traditional, intensive - extensive (incl. fishing, hunting and harvesting of wild products)
Animal-derived food production	
Products for food production	Products used in food production to increase the health of livestock or for protecting and enhancing crops; e.g., food yield increasing measures (pesticide, fertilizers and its alternatives), insects for feed, measures to clean the stables
Novel food sources	Production of e.g., insects, algae for human consumption
Technologies in food processing	Innovative technologies lead to improved, more sustainable food products with longer shelf lives within whole supply chain. Some technologies may bear the risk of unwanted side products, or on the other hand may decrease the risk of hazards.
Processing techniques & scale	'Processing' means any action that substantially alters the initial product; e.g., heating, smoking, curing, maturing, drying, marinating, extraction, extrusion, novel and alternative techniques and industrial and traditional processes or a combination of those processes, risk of cross-contamination
Food packaging	Containment of food; e.g., primary/secondary contained, food packaging material, type and duration of contact, smart packaging
Upcycling for food	Using of side streams in the food chain; e.g., coffee grounds to grow mushrooms
New digital technologies	Monitoring processes and products; e.g., AI, big data, blockchain analysis
Food formulation	Macro- and micronutrients, additives, e.g. salt, carbohydrates, protein, etc. composition
Environmental category	
Environmental contamination	Environmental contamination influences competition for land and shortage of available water due to over exploitation, pollution, the impact of climate change.
Agricultural pollution	Pollution of air, land and water caused by agriculture; e.g., leaching of chemicals, veterinary product residues, plastic waste and eutrophication
Sewage treatment	Sewage treatment plant, both industrial and municipal; e.g., incomplete treatment or effluents released into the environment
Management of natural resources	The availability, accessibility and usability of natural resources are prerequisites for prospering economies including the agricultural sectors. High quality land and the availability of water and nutrients are the basis for food and renewable energy production.
Recycling	Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes; e.g., removing heavy metal, smelting of e-waste
Use of sidestreams	Using of other water sources and reusing waste including sludge, manure and fish effluent to recapture the nutrients still present for agriculture
Water & soil management	The planning, developing, distributing and optimum use of water resources and application of operations, practices, and treatments to protect soil; e.g, nutrient sourcing and use

Geographic region	/
Seasonality & weather	/
Climate change	/
Economic category	
Distribution	Across the food sector a significant horizontal and vertical restructuring is happening which effects distribution along the food supply chain
Global trade	The exchange of capital, goods, and services across international borders or territories, including trade agreements; e.g., jute bag for food contact material, imported fish
Distribution channels	Well-established paths to move products from the manufacturer to the consumer; e.g., supermarkets, local farmers market, wholesale
Political category	
Legislation, policies & governance	Standardization, legislation, policy and governance directly and indirectly influence production and consumption of food.
Official controls & communication	Food safety monitoring is the mechanism that routinely checks for safety hazards, manages compliance adherence, and ensures procedures are being correctly implemented and communicated openly; e.g., inspectors, food business operators recalls, RASFF
Good practices & standards	Practices that have been proven to work well and produce good results, and is therefore recommended as a model; e.g., ISO standards, hygiene
Food legislation	Legislation which regulates the production, trade and handling of food across the entire food chain, from the provision for animal feed to the consumer; e.g., HACCP, food contact material
Geopolitical instability	Advancing economic globalization is currently hampered through newly established/changed borders, barriers, and limits.
War & conflict	Disruptions of diplomatic relations and global markets; e.g., Russia-Ukraine raw materials
Fragmentation between nations	Political stand-off/ trade embargos; e.g., BREXIT in EU, computer chips

3. Appendix 3: Company characteristics questioned at the start of the workshop

Table 3 Questions on company characteristics as asked in the workshop, based on those asked in Spagnoli, Vlerick et al. (2023) and those asked in the FSMS diagnostic instrument.

No.	Question	Answer options
A	Is your company part of a larger company?	Yes / No
B	Is your company family owned?	Yes / No
C	What is the total number of full-time employees of your company?	<10 / 10-49 / 50-249 / >249
D	What is the place of your company in the food supply chain?	Only transformation / Transformation and distribution
E	Do you produce plant- or animal-based products?	Plant-based products / Animal-based products / Both
F	Does your company export to countries outside of Europe?	Yes / No
G	Does your company produce premium brand or private label products?	Premium brand / Private label / Both
H	Which Quality Assurance (QA) standards are implemented in your company?	PRP (GMP, GDP, GHP) / HACCP / ISO 9001 / ISO 22000 / BRC / IFS / SQF 2000 / National standard, please specify: / Other, please specify: / None
I	Which QA standards is your company certified for?	ISO 9001 / ISO 22000 / BRC / IFS / SQF 2000 / National standard, please specify: / Other, please specify: / None
J	Does your company have a QA manager?	Yes/No
K	Does your company have a QA department? How many people work in the QA department?	Yes, number of QA employees: / No

4. Appendix 4: Examples of how subdrivers could impact FSMS activities in a fictitious company, as provided in the workshop to help the participants along

Fictitious company: A Flemish company that sells ice cream under a premium brand and under private label, as well as to restaurant

Social category example: In light of sustainability, consumers demand more and more a short-chain approach, and for companies to use locally sourced materials (subdriver: consumer awareness & attitude). Because of this, the company needs to select new suppliers and adapt their incoming material control based on this (FSMS activity: QC - preventive measures)

Technological category example: New processing techniques are researched to improve the microbiological quality of ice cream while maintaining a clean label, such as the use of low-dose gamma irradiation (subdriver: processing techniques & scale). Incorporating this new intervention equipment requires the company to validate the effectiveness of this technique (FSMS activity: QA - validation), but also a new calibration program for this equipment (FSMS activity: QC - interventions)

Environmental category example: In the storage and distribution of ice cream, the cold chain needs to be maintained. Global warming has resulted in a rise of the global temperature and more extreme weather events such as heat waves, especially in summer, when ice cream consumption is highest (subdriver: climate change). The storage equipment should have the cooling capacity to handle these variable / high outside temperatures and maintain the desired inside temperature (FSMS activity: QC - operation).

Economic category example: Using different distribution channels (retail, restaurants) can result in many different client / stakeholder requirements (subdriver: distribution channels). This puts a higher pressure on translating these stakeholder requirements into the company's own FSMS (FSMS activity: QA - system set-up)

Political category example: Further harmonisation of EU legislation, such as the harmonisation of the regulation for official controls in EU Regulation 625/2017 (subdriver: food legislation), results in a different, more harmonised approach to official FSMS evaluation (FSMS activity: PI - external food safety performance).

5. Appendix 5: Raw data of the answers from the expert elicitation workshop

Table A5.1 Answers from the workshop showing the social subdrivers indicated by each participant as having an impact on food safety management, the specific FSMS activities that the subdrivers impact, and examples about the mechanisms of these impacts. Examples talking about different issues than microbiological food safety management are indicated in italics and disregarded for further processing. When an example references another subdriver than the one indicated, the indicated subdriver is shown in italics, and the subdriver that it does reference is given.

Participant	Subdriver	FSMS activity	Example	Session
1	Dietary choice	System set-up	*Allergen management, plant-based solutions*	1
		Preventive measures	By asking the right questions before system set-up	
		Internal food safety performance	Pre-requisites definition	
	Consumer awareness & attitude	Operation	Moving towards a more plant-based diet increase the availability on the market of plant-based solutions	
		Validation	Validation of cleaning to avoid cross-contamination	
	Consumer knowledge	Operation	Driver for new solutions	
	Public awareness	Operation	Development of solutions to meet customer expectations	
	Population size	Internal food safety performance	Dietary needs and targeted products while ensuring the safety of the products	
	Prevalence of vulnerable groups	Internal food safety performance	Groups with special needs have an impact on the pre-requisites	
	Urbanisation	Operation	Increase of the activities may have an impact on how food safety is targeted within the factory	
	Migration & travel ->/	Operation	Different regulatory frameworks with special impact on food safety	
	Human health condition ->/	Operation	Sick people is strictly forbidden to work at the facilities due to the food safety impact	
	Resistant pests & diseases	Operation	Better raw materials with lower contaminants, decreasing the food safety risk	
2	Dietary choice	Validation	Less salt, more clean label → influence shelf life	1
	Consumer knowledge ->Consumer awareness & attitude	Internal food safety performance	Knowledge causes additional requests towards nutritional value	
	Human health condition	Internal food safety performance	Less salt, less fat	

	Resistant pests & diseases	External food safety performance	Avocado validation pests in country of origin → risk analysis	
3	Dietary choice	Internal food safety performance	*The presence of allergens or vegan products implicate directly impact on preventive measures, validation, verifications, etc*	1
	Consumer knowledge	Internal food safety performance	Shelf life and storage conditions must be validated (+worst case)	
	Human health condition	Validation	Validation must be done to assure the product is safe for YOPI	
	Resistant pests & diseases	Preventive measures	Extra controls necessary, pest monitoring plans of suppliers are needed, extra costs	
4	Dietary choice	Internal food safety performance	Meer bio-producten -> extra contole + handeling (extra afspoelstap na ontsmetting)	1
	Consumer knowledge -> Consumer awareness & attitude	Internal food safety performance	Minder E-nummers gewenst -> andere alternatieven zoeken (HPP – stap ipv bewaarmiddel)	
	Human health condition	Internal food safety performance	Afwezigheid listeria of salmonella	
	Resistant pests & diseases	External food safety performance	Extra controle bij container aankomst, geen sporen van ongedierte	
5	Dietary choice	System set-up	Specific demand of retailer	1
	Consumer awareness & attitude -> Consumer knowledge	Preventive measures	Wrong usage of goods	
	Consumer knowledge	Preventive measures	Misusage of goods	
	Public awareness -> Consumer knowledge	Preventive measures	Cold chain	
	Migration & travel	Monitoring	New ingredient	
	Human health conditions	Preventive measures	Supplier selection	
	Resistant pests & diseases	Monitoring	Raw material	

6	Dietary choice	External food safety performance	/	1
		Operation	/	
	Consumer awareness & attitude	Preventive measures	Rekening houden met veranderende vraag van consument – ander aanbod	
	Consumer knowledge	Preventive measures	Consumenten op juiste wijze voorlichten	
	Public awareness	Preventive measures	Hier ook correct informeren van de consumenten, product aanbod verrijken. Kan op verschillende niveaus een impact hebben. De verschillende drivers zijn relevant voor bedrijven in onze sector maar vanuit de sectorfederatie is het niet mogelijk om hier exacte voorbeelden of situaties van te geven.	
	Population size	Preventive measures	Zelfde opmerking, niet mogelijk om hier concrete voorbeelden te geven. Kan een impact hebben op export (meer export vraag) maar hier spelen er veel meer factoren mee	
	Prevalence of vulnerable groups	Preventive measures	Zelfde opmerking, niet mogelijk om hier concrete voorbeelden te geven. Onze producten moet correct worden vermeld in de voedingstabellen, waardoor de meerwaarde om deze producten in een evenwichtig dieet op te nemen ook worden meegenomen.	
	Urbanisation	Preventive measures	Zelfde opmerking, niet mogelijk om hier concrete voorbeelden te geven	
	Migration & travel	Operation	Zelfde opmerking, niet mogelijk om hier concrete voorbeelden te geven. Kan een rol spelen in de tewerkstelling	
	Human health conditions	Internal food safety performance	Zelfde opmerking, niet mogelijk om hier concrete voorbeelden te geven	
	Resistant pests & diseases	Preventive measures	Zelfde opmerking, niet mogelijk om hier concrete voorbeelden te geven	
7	Dietary choice	System set-up	*Dit antwoord mag je negeren maar ik kon geen tabblad terug gaan*	1
8	Dietary choice	Monitoring	New products/suppliers = modification system set-up & documentation	1
	Consumer knowledge	Monitoring	Increase customer knowledge -> additional analyses/monitoring	
	Population size	Documentation & record-keeping	New suppliers & sourcing regions -> impact on documentation, monitoring, validation/verification	
		Monitoring	New suppliers & regions sourcing	
		Documentation & record-keeping	New sourcing regions = eg. modification VACCP	
	Prevalence of vulnerable groups	Monitoring	Additional vulnerable groups -> modification plans	

	Resistant pests & diseases	Monitoring	New diseases -> modification monitoring plans	
		System set-up	New diseases -> modification HACCP	
9	Consumer awareness & attitude	Internal food safety performance	Consument wil langere houdbaarheid – druk op sales – gevaar microbiologie	2
	Migration & travel	Operation	Andere eetgewoonten – introductie nieuwe producten	
	Resistant pests & diseases	Operation	Ziekte personeel – snel nieuwe mensen moeten opleiden en inzetten in productie – aandacht werkmethodiek/hygiënisch werken	
10	Dietary choice	System set-up	Producten met claims dienen vaak als eerste op de lijn versneden te worden terwijl dit microbiologisch gezien niet de ideale set-up is	2
		Operation	Door het introduceren van de verschillende claims dient er meer reinigingswerk uitgevoerd te worden, operationeel zorgt dit voor meer kuisactiviteiten en risico op kruiscontaminaties	
	Consumer awareness & attitude -> Consumer knowledge	Preventive measures	Optimale bewaaromstandigheden worden verbroken -> uitgroei van microbiologie mogelijk maar de consumenten klagen liever	
		External food safety performance	Impact vanuit de thuissituatie wordt onvoldoende meegenomen als een risico door externe partijen zoals auditbureau's en FAVV -> risico naar de eindconsument blijft onze verantwoordelijkheid terwijl we geen zicht hebben op wat de klant thuis doet	
	Consumer knowledge	Validation	Onvoldoende kennis -> extra veiligheidsmarge inbouwen -> microbiologie is echter geen 100% zekere wetenschap	
	Migration & travel	System set-up	Introductie van nieuwe eetgewoontes -> onvoldoende kennis van deze producten beschikbaar -> microbiologische gevaren niet altijd volledig 100% gekend en beheersd	
		Interventions	Onbekende producten -> initiële condities zijn niet altijd 100% gekend -> nood aan striktere maatregels voor de microbiologische afdodingen zonder volledig 100% kennis van het product	
	Resistant pests & diseases	Preventive measures	Aanwezigheid van resistente microbiologie in de omgeving -> meer nood aan hygiëne bij de grondstoffen om dit niet binnen te nemen in de bedrijven	
		System set-up	Bijsturingen naar gelang de meldingen uit de buitenomgeving noodzakelijk -> meer aanwezigheid van Listeria in productieomgevingen (?) /STEC	
11	Dietary choice	External food safety performance	Nutriscores verbeteren leidt tot wijziging ingrediënten	2
	Consumer awareness & attitude	Monitoring	Negatieve publiciteit zorgt voor verandering van leveranciers	
	Public awareness	External food safety performance	(Sociale) media zetten aan tot andere consumptie-patroon	

		Operation	Meer dierenwelzijn doet processen (farm to fork) wijzigen	
	Migration & travel	Monitoring	Andere culturen = andere eetgewoonten = andere producten	
	Human health conditions	Documentation & record-keeping	Toename obesitas = meer 'light' = meer kunstmatige producten	
	Resistant pests & diseases	Documentation & record-keeping	Covid-crisis = afstand houden = meer aandacht voor hygiëne in productie	
12	Migration & travel	Operation	*Innovating products to different cultures → change of lines + buying products and ingredients from countries outside EU → van give some challenges regarding pesticide residues etc → monitoring plan per product per region (low risk vs high risk)*	2
		External food safety performance	Innovating products for different cultures → different types of certification necessary in production facilities, >1 type of HALAL certification, kosher, … → a lot of audits and time and money	
	Resistant pests & diseases	Validation	More resistant pests and diseases → will need to execute validation of heat treatments on products are enough for reduction to acceptable level → type of intervention will not change, just validation → if NOK, process parameter changes	
		Monitoring	More monitoring if pests and diseases are not reduced to acceptable level by standard heat treatments → in first place; when validated, less additional monitoring – go back to standard monitoring	
13	Dietary choice	Validation	Bv lager zoutgehalte / uitgroei pathogenen (1 horde minder in hordensysteem) kan wijzigen	2
	Consumer awareness & attitude	Verification	Meer ready to eat producten (geen afdoding meer van pathogenen door consumer) / of meer (korte of onvolledige) opwarming in een microgolf door tijdsgebrek (ipv door verhitting of langdurige verhitting in oven of friteuse bv) / in welke mate is consument zich bewust van gevaren als bv koudeketen onderbroken is (of bv niet op tijd geconsumeerd is of tijdelijk bij een hogere temperatuur) /	
		Documentation & record-keeping	Validatie gegevens bijhouden, trendanalyses bijhouden, mate van misbruik of fout gebruik inschatting	
	Consumer knowledge	Validation	Als afwijking vastgesteld wordt (bv verpakking is open bv lekkage) en in welke mate heeft consument kennis om juist te handelen	
	Migration & travel	Validation	Nieuwe grondstoffen in R&D	
	Human health condition	Verification	Doelgroep: behoren er meer consumers tot yopi's dan vooraf ingeschat. Als bv meer mensen met overgewicht	
	Resistant pests & diseases	System set-up	/	

14	Dietary choice	Internal food safety performance	Dietary choices may have to do with claims on pack. Implementation includes validation monitoring, verification	2
		Validation	See explanation above	
	Consumer awareness & attitude	External food safety performance	Consumer awareness and attitude will be visible by consumer / customer complaints and questions?	
	Consumer knowledge	External food safety performance	More attention will have to be paid to info on product pack	
	Public awareness	External food safety performance	Same as for awareness & attitude	
	Population size	External food safety performance	*It will have no impact*	
	Prevalence of vulnerable groups	Internal food safety performance	*This factor has no impact on the FSMS since this already build to protect this type of consumers*	
	Urbanisation	External food safety performance	*This factor has no impact*	
	Migration & travel	Internal food safety performance	*No impact*	
	Human health conditions	External food safety performance	*No impact*	
	Resistant pests & diseases	Verification	Resistance of pathogenic microbes has an impact on the FSMS since implemented preventive measures may not be sufficient enough after some periods. Therefore, verification will become an important factor to manage the effectiveness of the FSMS	
		Documentation & record-keeping	Documentation of changes to are being implemented to counter resistance is important to build background knowledge and manage the case efficiently. Each time verification shows that the preventive measures are no longer effective, an optimisation step needs to be developed and validated	
		Operation	A optimised preventive measure includes changes in operations	
15	Dietary choice	Interventions	Less sugar – lower water activity – addition interventions might to be implemented	2
		Monitoring	Producing product with higher water activity might trigger additional testing requirements	
		Operation	Additional intervention are linked with extra operation activities	
	Consumer awareness & attitude	Preventive measures	Supplier management of preventive measures → we might be obliged to source from specific regions for example	

		System set-up	Example: Awareness of incidents in the sector might give a trigger to redesign/improve the system	
	Consumer knowledge -> Consumer awareness & attitude	Preventive measures	Dietary knowledge might impact product design e.g. no preservatives	
	Public awareness	Monitoring	Might trigger extra testing by regulators	
		External food safety performance	Might impact number of audits	
		System set-up	Might impact revision of internal or industry processes/standards	
	Population size	Preventive measures	Increasing demand for example chocolate consumption might impact supplier management which is on of preventive measures	
	Prevalence of vulnerable groups	Operation	Additional process might be implemented	
	Urbanisation	Preventive measures	Less agriculture land – limited number of suppliers	
	Migration & travel	Preventive measures	Operators travelling to exotic places	
	Human health conditions	Interventions	Stricter intervention on micro hazards control	
	Resistant pests & diseases	Preventive measures	Pest control	

Table A5.2 Answers from the workshop showing the technological subdrivers indicated by each participant as having an impact on food safety management, the specific FSMS activities that the subdrivers impact, and examples about the mechanisms of these impacts. Examples talking about different issues than microbiological food safety management are indicated in italics and disregarded for further processing. When an example references another subdriver than the one indicated, the indicated subdriver is shown in italics, and the subdriver that it does reference is given.

Participant	Subdriver	FSMS activity	Example	Session
1	Plant-derived food production	Operation	Product reformulation	1
	Novel food sources	Operation	Product reformulation	
	Products for food production	Internal food safety performance	Ensure all incoming raw materials are duly checked for food safety contaminants	
	New digital technologies	Operation	New digital technologies can help companies to start preventive food safety and avoid food safety issues & crisis	

	Food formulation	Internal food safety performance	New formulations must be duly checked for possible new food safety risks	
	Food packaging	Internal food safety performance	Food packaging can introduce food safety risks that must be checked before introducing it	
2	Plant-derived food production	Internal food safety performance	Avocado is plant based so forms base of our company	1
	Novel food sources	Internal food safety performance	New risk → risk analysis, HACCP, CCP/PRP	
		Preventive measures	Validation & verification	
	Products for food production	External food safety performance	Validation towards specification sheets	
		Preventive measures	Validation, external food safety performance	
	Processing techniques & scale	Internal food safety performance	With new machines validation HACCP, risk analysis	
	Food formulation	Internal food safety performance	Risk analysis modified nutritional value	
		Validation	Risk analysis lower salt content → shelf life analysis	
	Food packaging	External food safety performance	*DoC and migration*	
3	Plant-derived food production	Operation	*The presence of endogeneous plant material must be prevented*	1
		Internal food safety performance	*Presence of endogenous material must be monitored and registered*	
	Novel food sources	System set-up	In case of novel food sources the whole system set-up must be revised	
	Products for food production	System set-up	The whole system must be revised, validated and adjusted to the products for food production	
	Processing techniques & scale	Internal food safety performance	Processing techniques & scale have an impact on new lines, each technique must be validated	
	Food formulation	System set-up	System must be designed in a way you can produce safe and with respect for the recipes	

	Food packaging	Internal food safety performance	MAP gassing can have an effect on food safety	
4	Plant-derived food production	Monitoring	Slechte oogst -> minder kwalitatieve product	1
	Products for food production	Monitoring	Algemene ingrediënten, controle goederen inkomst	
	Processing techniques & scale	System set-up	Upscaling nieuwe innovatie	
	Upcycling for food	Interventions	Afval pitten hergebruiken voor olie	
	New digital technologies	Operation	Introductie tables voor effeciëntere werking	
	Food packaging	Operation	Andere soorten verpakking, zorgt voor ander inpakmethode	
5	Plant-derived food production	Preventive measures	Juices	1
	Products for food production	System set-up	Water	
	Processing techniques & scale	System set-up	Washing and drying technologies	
	Food packaging	Preventive measures	New packaging, legislation, client spec	
6	Animal-based food production	Preventive measures	Kan hier geen concrete voorbeelden voor geven	1
	Products for food production	Preventive measures	Zie vorige opmerking, geen concrete voorbeelden. Wel mogelijke impact, watergebruik, maar ook de bijkomende microbiologische belasting van de primaire grondstoffen (levende dieren)	
	Processing techniques & scale	Operation	Zie vorige opmerking, geen concrete voorbeelden	
	Food formulation	System set-up	Zie vorige opmerking, geen concrete voorbeelden	
	Food packaging	Preventive measures	Zie vorige opmerking, geen concrete voorbeelden	
7	Products for food production	Internal food safety performance	Wanneer we microbiologische analyses doen op eindproducten met een aardbei grondstof of op een aardbei grondstof rechtstreeks vinden we vaak positieve resultaten voor Bacillus Cereus. Ondertussen hebben we ontdekt dat Bacillus thuringiensis bij aardbeien teelt kan gebruikt worden als insecticide. Bij labo analyses wordt dit eruit gehaald als Bacillus Cereus. Als we dit weten zou het geen probleem	1

			kunnen zijn alleen hebben we nog geen concreet bewijs dat aanwezigheid van bacillus thuringiensis wel veilig is.	
8	Animal-derived food production	System set-up	Animal food production = specific regulations eg micro	1
		Monitoring	Animal food production = specific regulations eg micro	
	Products for food production	Monitoring	Regulations water quality, cleaning products, additives	
	Processing techniques & scale	Documentation & record-keeping	New techniques = modification HACCP studies & several documents	
		Interventions	New techniques = possible new interventions/monitoring by workers/QC	
	New digital technologies	System set-up	Digitization = mainly impact on set-up & documentation	
	Food packaging	Documentation & record-keeping	New packaging = modification of documentations in QA system	
9	Products for food production	System set-up	Nieuw product -	2
	Processing techniques & scale	Validation	Nieuwe desinfectietechniek	
	Food packaging	Verification	Gerecycleerde verpakkingen – waarborgen microbiologische kwaliteit eindproduct	
10	Plant-derived food production	Preventive measures	Hoge beginwaarden qua microbiologie / matrixen die onvoldoende gekend zijn -> aanpassingen aan processen nodig	2
		Verification	Door de variabele matrixen van plant-based is er meer nood aan validatie -> wisselende resultaten voor de borging van de microbiologie	
	Novel food sources	System set-up	Nieuwe grondstoffen / ongekende microbiologische gevaren -> studie te herwerken en meestal in combinatie met behouden van huidige producties	
		Interventions	Initiële microbiologische belading minder goed gekend -> afdoding van microbiologie kan vaak niet op gekende manier doorgaan	
	Upcycling for food	System set-up	“Afval” stroom hergebruiken -> herwerken van de studie -> bijkomende maatregels te nemen / afspraken met de leveranciers	
		Operation	“Afval” stroom -> hygiene bij de dagelijkse verwerking nog belangrijker maar indruk bij de productie dat het er niet meer toe doet -> meer risico op microbiologische gevaren	
	Food packaging	Validation	Switch naar monomateriaal is niet zonder gevaren -> barrières niet even sterk -> sneller bederf in de verpakkingen + technologie nog volop in ontwikkeling	

11	Plant-derived food production	Validation	*Residu-analyses: bij overschrijding, recall*	2
	Animal-derived food production	Verification	*Geneesmiddelen residu's: bij overschrijding, recall*	
	Processing techniques & scale	Verification	-	
	Food formulation	Documentation & record-keeping	-	
	Food packaging	Validation	*Verpakkingstechnologie ifv commerciële aspecten (kleurbehoud) eerder dan voedselveiligheid*	
12	Plant-derived food production	Operation	Based on type of production process and harvesting process etc → more/less foreign bodies & spoilage → do we seen already in the field? → due to automation, (extensive vs intensive crops) less manual work so less people taking out the 'bad' products, you need to trust on equipment to see product that is spoiled	2
	Products for food production	Internal food safety performance	Change regulation pesticides & fertiliser (banned products & lowering MRL) → more and more products exceeds MRL or had been spoiled due less use of pesticides & need to try new combinations of pesticides & fertilizers → more sampling of products → also a lot go to waste due to bad products if too 'less' pesticides → most problems with biological produced crops	
	New digital technologies	Operation	Use of AI in optical sorter → not working properly → a lot of tests, see thing that aren't there and the other way around → testing	
13	Processing techniques & scale	Validation	Bv microgolftechnologie (indien implementatie om te ontdooien of bij verhitting)	2
	Upcycling for food	Monitoring	Als vermeerdering van productielijnen, meerdere lijnen controleren ipv 1 productielijn; of als werken in meerdere ploegen ipv 1 ploeg (enkel dag)	
	New digital technologies	Operation	Meer sensoren; … die parameters in productie proces opvolgen (temperatuur product na verhitting, temperatuur na invriezen)	
	Food formulation	Validation	Bv minder zout in recepturen;	
	Food packaging	Validation	Verpakkingshoeveelheid steeds verminderen (minder bescherming, minder dikke folie,.. of product is minder beschermd tegen externe factoren cfr bij diepvries transport	
14	Plant-derived food production	Preventive measures	In order to avoid cross contamination of plant based materials with animal based materials, separation in time or space is essential having impact on GSMS activities seen monitoring will be important	2

		System set-up	Introduction of plant based products in an animal based product production environment involves analyses of other hazards (contaminants, microbiology,…)	
		Validation	Each plant based product group to be introduced will need validation and set up of monitoring programs	
	Novel food sources	Documentation & record-keeping	In our business, novel foods will only be used as ingredient, so management of documentation will be key	
	Products for food production	Monitoring	New products for food production will include need for management of supplier documentation and setup of monitoring of each new class of products	
		Documentation & record-keeping	Management of supplier documentation and authority control programs	
	Processing techniques & scale	Validation	New processing techniques include validation to ensure food safety of the product	
		Documentation & record-keeping	New processing techniques include documented control points to ensure process is successful	
		Verification	Periodic verification of way of working will be needed	
	Upcycling for food	Operation	*No impact*	
	New digital technologies	Validation	New digital technologies do need to be validated	
		Monitoring	New digital technologies will increase efficiency of FSMS	
	Food formulation	Monitoring	New ingredient groups will include extension of the monitoring plan	
		System set-up	New quality label ingredients may have the consequence that a new FSMS subsystem needs to be set up	
	Food packaging	Monitoring	A new class of food packaging or packaging technology may include that shelf life of the involved products needs to be validated	
		Documentation & record-keeping	Management of supplier documentation for special type of packaging (recyclability)	
15	Novel food sources	Validation	Validation of processes for other ingredients	2
		System set-up	Micro hazard analysis for new ingredients	
	Processing techniques & scale	External food safety performance	Delivering across the glob might trigger additional audits; bigger scale potentially more complaints	
		Monitoring	If exporting to certain countries different micro-criteria might be required	
	Upcycling for food	System set-up	To identify microbiological hazards that might occur during upcycling	
	New digital technologies	Documentation & record-keeping	Will help to record, store and analyse micro data – trending	

	Food formulation	Validation	Less sugar, no preservatives – to validate if changes are not impacting micro stability of the product	
	Food packaging	Validation	To validate that for example recycled packaging has the same functionality – e.g. fmoisture transfer that can increase water activity of the product that can lead to spoilage -> soft bakery. Sealing integrity	

Table A5.3 Answers from the workshop showing the environmental subdrivers indicated by each participant as having an impact on food safety management, the specific FSMS activities that the subdrivers impact, and examples about the mechanisms of these impacts. Examples talking about different issues than microbiological food safety management are indicated in italics and disregarded for further processing. When an example references another subdriver than the one indicated, the indicated subdriver is shown in italics, and the subdriver that it does reference is given.

Participant	Subdriver	FSMS activity	Example	Session
1	Agricultural pollution	Internal food safety performance	Agricultural pollution may have an impact on the raw materials used. Additional checks must be added to avoid the risk of non-compliance	1
	Sewage treatment	Internal food safety performance	Sewage treatment must be part of the Environmental Monitoring Plan as there is a risk of pathogens	
	Recycling	Internal food safety performance	*Several chemical contaminants are known to come form recycling (ie, mineral oil hydrocarbons from recycled packaging, allergen cross-contamination)*	
	Water & soil management	Operation	Water & soil may come with chemical and microbiological risks and must be monitored	
	Geographic region	Internal food safety performance	Depending on the region there are different regulatory frameworks that must be followed	
	Seasonality & weather	Internal food safety performance	May affect the microbiological environment of a factory. Moreover, it may have an impact of chemical contaminants in certain raw materials (mycotoxins in cereals due to weather conditions)	
	Climate change	Internal food safety performance	It may impact the selection of certain raw materials, economic impact linked to fraud and presence/absence of certain contaminants	
2	Recycling	System set-up	Use of RPET in packaging	1
	Seasonality & weather	External food safety performance	*Avocado grown in southern countries, variability of fat content and viscosity*	
3	Agricultural pollution	Monitoring	*Pesticide monitoring*	1
	Geographic region	Monitoring	*Cadmium is more presence in some regions*	
	Seasonality & weather	Preventive measures	Multiple suppliers from multiple countries are necessary to have multiple options when quality is bad because of seasonality & weather conditions	

4	Recycling	Internal food safety performance	Afval van pitten voor olie gebruiken	1
	Geographic region	Preventive measures	Ontwikkeling van land	
	Seasonality & weather	Monitoring	Verschillende leveranciers zoeken uit verschillende continenten die verschillende seizoenentijden hebben, zodat er constant kwaliteitsvol en voldoende product geleverd kan worden	
	Climate change	Monitoring	Minder goede oogsten, meer verschillende leveranciers zoeken	
5	Agricultural pollution	Preventive measures	Raw material on the field	1
	Sewage treatment	Preventive measures	Used water	
	Water & soil management	Preventive measures	Misusage of water by supplier	
	Geographic region	Preventive measures	New sourcing region	
	Seasonality & weather	Monitoring	Problems on the fields caused by weather conditions (temperature, rain, …)	
	Climate change	Monitoring	Duration of product season are changing eg: pumpkin season was very short	
6	Agricultural pollution	Preventive measures	Onze grondstoffen zijn “levende dieren”, dus hier is wel degelijk een impact om hier aan te geven welke impact dit zou kunnen zij op microbieel vlak is zeer moeilijk. Kan hier ook geen concrete voorbeelden geven. Het voorkomen om deze grondstoffen binnen te krijgen is een van de belangrijkste stappen	1
	Sewage treatment	Monitoring	Sommige bedrijven gaan het water van hun waterzuivering gaan hergebruiekn. Dus monitoring van de kwaliteit van het water is belangrijk vooraleer dit is in verdere stappen kan worden ingezet. Gebruik recuperatiewater (vb. reinigen stallen) of volledig zuiveren van het recuperatiewater naar drinkwaterkwaliteit. Of de risico's naar het lozen van dit recuperatiewater	
	Water & soil management	Monitoring	Kwaliteit van het ontvangen water , vb. indien men werkt met putwater	
	Geographic region	Monitoring	*Naar microbiologische impact heb ik hier niet onmiddellijk een idee, maar naar chemische verontreiniging kan dit wel een impact hebben op het FSMS (vb. PFAS en regio's die gekend zijn als vervuilde zone's)*	
7	Water & soil management	Internal food safety performance	In de nabije toekomst zullen we minder putwater mogen oppompen volgens onze vergunning. Putwater gebruiken we momenteel voor reiniging van machines en dergelijken (contactwater). We zullen binnenkort reversed osmose water terugkrijgen uit onze waterzuiveringsinstallatie en bekijken momenteel hoe we dit kunnen borgen in ons FSMS.	1

8	Agricultural pollution	System set-up	Water quality origin (suppliers) = impact on raw materials -> modification documentation/system/validation	1
		Monitoring	Water quality origin (suppliers) = impact on raw materials -> modification monitoring plan	
	Recycling	Monitoring	Recycling raw material @ supplier – impact on monitoring plan	
	Water & soil management	Monitoring	Water management @ origin/supplier = impact on monitoring plan raw materials	
	Geographic region	Documentation & record-keeping	Raw materials from different geographic region = impact on documentation (eg specifications)	
		Monitoring	Raw materials from different geographic regions = impact on monitoring plan microbiology	
	Seasonality & weather	Monitoring	Seasonality = possible impact on bacteriological quality of raw materials -> modification of monitoring plan	
		Documentation & record-keeping	Seasonality -> possible impact on validation/verification of product groups	
	Climate change	Monitoring	Climate change -> possible impact @ suppliers = modification on sampling plan	
		System set-up	Climate change @ suppliers -> possible impact on system set-up	
9	Agricultural pollution	Preventive measures	Vervuilde grondstoffen – recalls tot gevolg	2
		Operation	Extra controles in productie	
	Recycling	Internal food safety performance	Te doorgedreven hergebruik waardoor voedselveiligheid in gevaar komt	
	Climate change	Operation	Warmere temperaturen zorgen voor uitdagingen bij gekoeld transport in zomer – deuren vrachtwagen gaan open en volledige laadruimte te hoge temperatuur	
10	Sewage treatment	System set-up	Waterzuivering -> andere risico's en verplichtingen wegens eigen beheer -> meer restrisico naar microbiologie toe indien het fout loopt	2
	Seasonality & weather	Preventive measures	Meer neerslag = lagere kwaliteit van grondstoffen -> meer nood aan reducties qua microbiologie	
		External food safety performance	Aankoop van grondstoffen uit andere regio's door seizoenen -> minder vertrouwne in de kwaliteit en de controles van buiten EU -> verhoogde microbiologische metingen nodig (?)	
	Climate change	Monitoring	Nieuwe micro-organismen kunnen gedetecteerd worden in regio's van aankoop terwijl er daar vroeger nooit problemen mee waren	
11	Agricultural pollution	Documentation & record-keeping	*Steeds meer forever chemicals in het milieu = in het voedingsproduct, vaak dure analyses voor organisatie en/of overheid*	2
			Teveel N = minder biodiversiteit, meer pesticiden nodig	
	Recycling	Monitoring	*Migratie van chemische componenten (Mosh/Moah) vanuit verpakking naar voeding*	

12	Agricultural pollution	Preventive measures	*Pollution → more attention to preventive measures; more samples; drift is an important one; drift is hugh problem → but more related to chemicals than microbiological*	2
	Climate change	Operation	Due to climate change → products in south of Europe are burnt due to hot weather, in Belgium are soaked due to a lot of rain → crop cycle disrupted → less products produced by our factories → more products sourced outside Europe with their own problems (exceedance pesticides, …)	
		External food safety performance	More complaints as more products are 'non conform', the A-grade quality from previous years, we cannot produce that anymore → complaints releated to 'poor quality'	
13	Recycling	System set-up	Bv rework – hoe vaak kan de cyclus zich herhalen? Dient cyclus onderbroken te worden? Hoe monitoring?	2
	Seasonality & weather	Operation	DV opslag; koel houden van productie- en receptiezones; beslasting koelgroepen bij (langdurig) warm weer in de zomer; snellere correcties nodig bij technisch falen van koeling of te hoge producttemperatuur en mogelijks uitgroei m.o.	
14	Agricultural pollution	Monitoring	Pollution resulting in contamination of incoming ingredients and raw materials	2
		Monitoring	Pollution resulting in contamination of process water	
	Sewage treatment	Monitoring	Norms to sewage do need to be monitored	
	Recycling	Operation	Recycling management does involves definition of way of working for separation of waste materials	
		Documentation & record-keeping	Separation of waste flows includes record keeping and documentation for recyclable products	
	Use of sidestreams	System set-up	Cutting loss of products to be used as rework involves setup of FSMS subsystem	
	Water & soil management	Monitoring	Quality parameters need to be monitored	
	Seasonality & weather	Operation	Cooling systems need more follow up (QC) during high summer temperatures	
	Climate change	Operation	Reduction of water use may have impact on hygiene management	
		Documentation & record-keeping	Shortage in ingredients availability – recipe flexibility – traceability/shelf life of products	
		Operation	High temperatures – impact on frequency of monitoring/verification	
15	Geographic region	Monitoring	For some materials in some regions/countries extra testing might be done	2
	Seasonality & weather	Operation	Shortage of certain raw material due weather might require revision of new suppliers – impact on company operation	
	Climate change	Monitoring	e.g. for some spices dry weather might results in higher TPC results	

Table 4 Answers from the workshop showing the economic and political subdrivers indicated by each participant as having an impact on food safety management, the specific FSMS activities that the subdrivers impact, and examples about the mechanisms of these impacts. Examples talking about different issues than microbiological food safety management are indicated in italics and disregarded for further processing. When an example references another subdriver than the one indicated, the indicated subdriver is shown in italics, and the subdriver that it does reference is given.

Participant	Subdriver	FSMS activity	Example	Session
1	Global trade	Operation	Different food safety issues may come from different regions. Additionally traceability is more challenging as sometimes there are trading companies involved	1
	Distribution channels	Operation	*The economic impact when selling to the artisan market is different when we talk about retailers. The latter has a larger distribution/impact*	
	Official controls & communication	System set-up	Ensuring all our products are safe and manufactures in such a way that always meet authorities expectations	
	Good practices & standards	Preventive measures	Quality and Food Safety Culture	
	Food legislation	System set-up	The system set-up must always be in line with local legislation	
	War & conflict	Operation	Availability of raw materials	
	Fragmentation between nations	Operation	Availability of raw materials	
2	Global trade	Internal food safety performance	Conform legislation of each country	1
	Distribution channels	System set-up	Validation of transporteurs	
	Official controls & communication	System set-up	Validation of control	
	Good practices & standards	Monitoring	CCP	
	Food legislation	Internal food safety performance	Conform as food product	
		Monitoring	Food product so conformity is needed	
3	Official controls & communication	External food safety performance	Official audits by authorities	1
	Good practices & standards	System set-up	GP's must be implemented in our organisation to assure food safety & quality	
	Food legislation	System set-up	We need to produce and import/export conform food legislation. Designs of equipment must be conform legislation	

	War & conflict	Preventive measures	Multiple suppliers are needed to make sure import is possible. Because of the war in the Red Sea our goods are sometimes longer on the road	
4	Global trade	Preventive measures	Overzees product, internationaal bedrijf	1
	Distribution channels	Preventive measures	Verschillende handelsroutes bekijken (boot, over de weg)	
	Good practices & standards	Preventive measures	Sociale normen steeds belangrijker	
	War & conflict	Preventive measures	Andere leveranciers zoeken, geen handel met land in conflict (subsidies)	
5	Global trade	Preventive measures	Sourcing from new areas	1
	Distribution channels	Preventive measures	New channels	
	Official controls & communication	Monitoring	Different interpretation of legislation by different departments in same country of different MS	
	Good practices & standards	System set-up	Changes of legislation, new versions of standards	
	Food legislation	System set-up	New legislation, new interpretation	
	War & conflict	Preventive measures	New sourcing areas	
	Fragmentation between nations	Monitoring	Different legislation in other countries	
6	Distribution channels	System set-up	Veel verschillende eindklanten, elke met hun eigen eisen	1
		Operation	De verschillende eisen van de verschillende klanten hebben eveneens een invloed op de operationele werking van het bedrijf	
	Official controls & communication	System set-up	Voor onze sector heeft dit een zeer grote impact, de controle graad bij onze bedrijven ligt vele male hoger dan bij andere bedrijven in ander sectoren. Dit zorgt voor veel druk bij de mensen die op de QA werken	
	Good practices & standards	Documentation & record-keeping	Naast de operationele druk is er ook een grote administratieve druk	
	Food legislation	System set-up	Snel wijzigende wetgevingen en bijkomende verstrengen maken het voor vele kleinere bedrijven moeilijk om dit zelf nog volledig op te kunnen volgen	
	War & conflict	Operation	Vb. sterke stijging van de hulpgrondstoffen, of verpakkingen, maar ook de stijgende energiekosten. Dit heeft voor vele bedrijven een grote impact gehad op hun operationele procesvorming	
	Fragmentation between nations	System set-up	Een voorbeeld in onze sector kan hier ook zeker Brexit zijn. Bedrijven hebben hun huidige systematiek hierop moeten afstellen. Extra documentaire werkdruk	

8	Global trade	Documentation & record-keeping	Disruption chain= raw materials from new regions -> impact on documentation & monitoring	1
	Distribution channels	Documentation & record-keeping	Disruption supply chain -> new suppliers/regions = impact on documentation	
		Monitoring	Disruption supply chain -> new suppliers/regions = impact on monitoring plan	
	Official controls & communication	Monitoring	Official controls = may affect several parts of Quality assurance (documentation, validation, …)	
		Operation	Official controls = may affect several parts of Quality Control (monitoring, measures, …)	
	Good practices & standards	Documentation & record-keeping	Good practices -> observation internal audits = mainly impact on documentation	
		Operation	Good practices -> observation internal audits = mainly impact on operations	
	Food legislation	Documentation & record-keeping	Modification legislation, possible impact on system (validation, verification, docs)	
		Monitoring	New legislation -> mainly impact on monitoring plan	
	War & conflict	Documentation & record-keeping	Conflict -> increase import duties -> sourcing new suppliers/ regions -> impact on documentation	
		Monitoring	Conflict -> increase import duties -> sourcing new suppliers/ regions -> impact on monitoring plan	
9	Food legislation	External food safety performance	Lange doorlooptijd om EU wetgevingen om te zetten in KB, cfr KB water	2
	Fragmentation between nations	Documentation & record-keeping	Verschillende regels tussen landen	
10	Global trade	System set-up	Grondstoffen van buiten EU = onvoldoende kennis bij de leveranciers van de eisen -> meer risico op overschrijdinge	2
		Documentation & record-keeping	Aanleveringen van buiten EU -> nood aan extra documenten / analyses -> twijfel aan echtheid van documenten op vlak van microbiologische analyses / accreditaties labo's	
	Official controls & communication	External food safety performance	Interpretatie sterk afhankelijk van de inspecteur die aanwezig is -> andere manier van opzet nodig om te voldoen aan de eisen van het LCE + vernieuwing qua mensen dus drang om zich te bewijzen -> onderzoeken naar microbiologische activiteiten die eigen zijn aan het product/proces met waarschuwingen	
		System set-up	Wijzigingen in omzendbrieven -> verduidelijkingen die een andere aanpak vragen -> herwerken van het analyseplan	
	Food legislation	Internal food safety performance	Meer nood aan omgevingscontroles en de interpretatie / trends van deze gegevens -> meer kennis nodig van microbiologie intern	

	Fragmentation between nations	System set-up	Andere eisen door Brexit of andere interpretatie van de wetgeving door lokaal FAVV (bv Nederland en de Listeria interpretatie) -> andere manier van benadering -> microbiologische resultaten die bij ons geen gevaar zijn vormen daar wel een gevaar	
11	Global trade	Monitoring	Grote productie bedrijven bevoorraden meerdere landen om prijs te drukken, lage lonen = minder gekwalificeerd personeel	2
	Official controls & communication	Monitoring	Grote verschillen in controles = andere standaarden per land	
	Food legislation	Operation	Europese wetgeving niet over gelijk toegepast, oneerlijke concurrentie (minder controles)	
	War & conflict	Verification	Alternatieve bronnen van grondstoffen zoeken, zeker niet altijd van gelijkwaardige kwaliteit	
		Operation	Tekort aan bepaalde grondstoffen, om toch te kunnen leveren aanvullen met minderwaardige grondstoffen	
	Fragmentation between nations	Monitoring	Minder kennisuitwisseling, tussen landen	
12	Official controls & communication	Documentation & record-keeping	A lot of documentation necessary to comply with regulations → store all documents and extras, not easy to have localised system	2
	Food legislation	Internal food safety performance	More and more sampling → 'new' components found → also sample and analyses→ time & money necessary → +change of regulations → pro-active approach needed to implement to new regulations in time	
	War & conflict	Internal food safety performance	Higher prices → sourcing ingredients outside of Europe, mainly Asia → not same maturity level of FSMS as here → hygiene etc not the same → have more unexplained contamination	
	Fragmentation between nations	Documentation & record-keeping	Everywhere other regulation → need to comply with all to export, not easy → requires a lot of documents, certificated, …	
13	Global trade	Operation	Grote verdelers / toeleveranciers hebben vaak meerdere vestigingen door overnames; … en kunnen grondstoffen aanvoeren vanuit verschillende werelddelen, hierdoor extra stakeholders (en extra aandacht of opvolging nodig indien bv klanteneis met betrekking tot afkomst)	2
	Distribution channels	Internal food safety performance	Portaalsites van elk distribution channel/ bijhouden van informatie / up to date houden / wirwar van referentienummers en artikelnummers tussen verschillende distribution channels/ …	
		Documentation & record-keeping	Intern system opbouwen/bijhouden welke info bij welk distribution channel dient up to date gehouden te worden	
	Food legislation	System set-up	Wijziging food legislation → bv wel/niet rookaroma's verder toegelaten (verlenging of niet toelating in toekomst …)	

		Operation	Als wijziging aan food legislation → bv heet water 82°C of ander systeem om messen te ontsmetten bij vers vlees of vleesbereidingen; dit heeft impact op de werkvloer en operationele activiteiten	
	War & conflict	Operation	Niet tijdig of stop aanvoer van bepaalde grondstoffen / zoeken naar alternatieven (bij andere leveranciers, andere grondstoffen, of andere afkomst…) cfr geen zonnebloemolie meer beschikbaar in 2023 - overschakeling naar koolzaadolie of ander	
	Fragmentation between nations	Operation	Bv bij falen van machine; tekort aan micro chips; machines buiten gebruik	
14	Global trade	Verification	Export to new countries involves need for compliance to new norms	2
		Documentation & record-keeping	Export to non-EU countries needs documentation for export certificates	
		Verification	Export to countries may involve shelf life extension	
	Distribution channels	System set-up	Customer specific book of charges to be implemented	
	Official controls & communication	External food safety performance	Official controls = resource of info for risk analysis	
	Good practices & standards	Operation	Clear factory guidelines on the workfloor based upon good practices and standards do maximize effective management of FSMS	
	Food legislation	Monitoring	Legal norms are a food source for minimum quality requirements for incoming materials. On the other hand, non-harmonised legal norms (different norms in the same food product subsectors) are a challenge for a FSMS)	
		External food safety performance	Harmonised legislation makes it easier to source from different countries	
	War & conflict	System set-up	Unavailability of materials is a challenge for business continuity, and also for a FSMS that needs to be installed to allow changes in materials	
	Fragmentation between nations	System set-up	Different guidelines in different nations, with local interpretation, do make it a challenge to comply with local guidelines, especially when your company has no local QA department to check compliance	
		Monitoring	Dependent upon national guidelines, different monitoring plans for the same product may be needed	
15	Global trade	External food safety performance	Exposure to high number if costumer requirements	2
	Official controls & communication	External food safety performance	Controls might results in identified improvements opportunities	
	Good practices & standards	System set-up	Shared goods practices and industry standards contribute to system improvements	

	Food legislation	Monitoring	Extra testing might be required	
		Validation	Validation my be required by regulators in some regions	
		External food safety performance	Food regulators might be visiting plants	
	War & conflict	Preventive measures	Raw material limitations	
	Fragmentation between nations	Monitoring	Different testing requirements between countries	

Table A5.5 Top 5 rankings given by the workshop participants answering the question which subdrivers are most important to consider in their company's FSMS

Participant	Session	Ranking	Participant	Session	Ranking
1	1	1. Climate change 2. Global trade 3. Food formulation 4. Novel food sources 5. Distribution channels	9	2	1. Processing techniques & scale 2. Consumer awareness & attitude 3. Food packaging 4. Agricultural pollution 5. Climate change
2	1	1. Good practices & standards 2. Human health conditions 3. Processing techniques & scale 4. Consumer knowledge 5. Food packaging	10	2	1. Plant-derived food production 2. Climate change 3. Novel food sources 4. Consumer awareness & attitude 5. Food packaging
3	1	1. Good practices & standards 2. Products for food production 3. Dietary choice 4. Food packaging 5. Human health condition	11	2	1. Food legislation 2. Animal-derived food production 3. Consumer awareness & attitude 4. Food packaging 5. Dietary choice
4	1	1. Good practices & standards 2. Resistant pests & diseases 3. Seasonality & weather 4. Products for food production 5. Consumer knowledge	12	2	1. Climate change 2. Food legislation 3. Products for food production 4. Resistant pests & diseases 5. Agricultural pollution
5	1	1. Good practices & standards 2.Processing techniques & scale 3. Water & soil management 4. Seasonality & weather 5. Food legislation	13	2	1. Processing techniques & scale 2. Consumer awareness & attitude 3. New digital technologies 4. Distribution channels 5. Food legislation
6	1	1. Food legislation 2. Official controls & communication 3. Products for food production 4. Sewage treatment 5. Dietary choice	14	2	1. Resistant pests & diseases 2. Fragmentation between nations 3. Use of sidestreams 4. Distribution channels 5. Global trade
7	1	1. Water & soil management 2. Products for food production 3. Dietary choice	15	2	1. Climate change 2. War & conflict 3. Food legislation 4. Novel food sources 5. Food formulation
8	1	1. Food legislation 2. Global trade 3. New digital technologies 4. Climate change 5. Processing techniques & scale			

6. Appendix 6: Initial and focused coding of the workshop results

Table A6.1 Initial and focused coding of the examples provided by the workshop participants on the mechanisms at play between subdrivers and FSMS activities, done for the top 3 most indicated social subdrivers

Subdriver	FSMS activity	Example	Initial coding	Focused coding
Resistant pests & diseases	Preventive measures	Extra controls necessary, pest monitoring plans of suppliers are needed, extra costs	Pests -> Extra pest controls	More pests -> Improve pest control
		Zelfde opmerking, niet mogelijk om hier concrete voorbeelden te geven	/	/
		Pest control	Pests -> Pest control	More pests -> Improve pest control
		Raw material	Resistant pests & diseases -> Raw material	More resistant MO -> Increase material control More pests -> Increase material control
		Better raw materials with lower contaminants, decreasing the food safety risk	Lower contaminants -> better raw materials	More resistant MO -> increase material control
		An optimized preventive measure includes changes in operation	Resistant pests & diseases -> optimized preventive measure	More resistant MO -> increase material control More resistant pests -> improve pest control
		Extra controle bij containeraankomst, geen sporen van ongedierte	Pests -> Extra material control	More pests -> Increase material control
	Monitoring	New diseases → modification monitoring plans	New diseases -> Modifictation monitoring plans	New diseases -> Modificate monitoring plans
		More monitoring if pests and diseases are not reduced to acceptable level by standard heat treatments --> in first place; when validated, less additional monitoring - go back to standard monitoring	Pests/diseases not reduced enough by heat treatment -> More monitoring	MO/Pests resistant to treatments -> Modificate monitoring plans
	Operation	Ziekte personeel - snel nieuwe mensen moeten opleiden en inzetten in productie - aandacht werkmethodiek / hygiënisch werken	Sickness staff -> Attention to hygienic work	Sickness staff -> More attention to hygienic working

		Aanwezigheid van resistente microbiologie in de omgeving --> meer nood aan hygiëne bij de grondstoffen om dit niet binnen te nemen in de bedrijven	Resistant microbiology in environment -> More need of hygiene	More resistant MO -> More attention to hygienic working
		Covid-crisis = afstand houden = meer aandacht voor hygiëne in productie	Pandemic -> More attention to hygienic work	Sickness staff -> More attention to hygienic working
	System set-up	New diseases --> modification HACCP	New diseases -> Modification HACCP	New diseases -> Revise system set-up
		Bijsturingen naar gelang de meldingen uit de buitenomgeving noodzakelijk --> meer aanwezigheid van Listeria in productieomgevingen(?) / STEC	More resistant pathogens -> Modification system set-up	More resistant MO -> Revise system set-up
		/	/	/
	Validation	More resistant pests and diseases --> will need to execute validation of heat treatments on products are enough for reduction to acceptable level --> type of intervention will not change, just validation --> if NOK, process parameter changes	Pests/ diseases not reduced enough by heat treatments -> Validation of process parameters	MO/Pests resistant to treatments-> Validate technology
		Avocado validation on pests in country of origin --> risk analysis	Pests -> Validation	More pests -> New validation
	Verification	Resistance of pathogenic microbes has an impact on the FSMS since implemented preventive measures may not be sufficient enough after some periods. Therefore, verification will become an important factor to manage the effectiveness of the FSMS.	Resistance of pathogenic microbes -> Verification to manage effectiveness	More resistant MO -> Improve verification of effectiveness
	Documentation & record-keeping	Documentation of changes to are being implemented to counter resistance is important to build background knowledge and manage the case efficiently. Each time verification shows that the preventive measures are no longer effective, an optimization step needs to be developed and validated.	Preventive measures no longer effective -> Documentation of changes	MO/Pests resistant to treatments -> Documentation of changes
Dietary choice	Preventive measures	By asking the right questions before system set-up	/	/
		Meer bio-producten --> extra controle + handeling (extra afspoelstap na ontsmetting)	Bio-products -> Extra controls	Bio-products -> Increase material control
	Intervention	Less sugar - lower water activity - addition interventions might to be implemented	Less sugar -> Additional interventions	Less sugar/salt -> Additional intervention steps
	Monitoring	Producing product with higher water activity might trigger additional testing requirements	Less sugar -> Additional testing	Less sugar/salt -> More sampling

		Dietary choices may have to do with claims on pack. Implementation includes validation, monitoring, verification.	Claims -> Implement monitoring	Claims -> Modificate monitoring plans
	Operation	/	/	/
		Door het introduceren van de verschillende claims dient er meer reinigingswerk uitgevoerd te worden, operationeel zorgt dit voor meer kuisactiviteiten en risico op kruiscontaminaties	Claims -> More cleaning operations	Claims -> More attention to hygienic work
		Additional intervention are linked with extra operation activities	Less sugar -> Extra operation	Less sugar/salt -> Adapt operational activities
		Producten met claims dienen vaak als eerste op de lijn versneden te worden terwijl dit microbiologisch gezien niet de ideale set-up is	Claims -> Change in operation sequence	Claims -> Adapt operational activities
	System set-up	Specific demand of retailer	Specific demand retailer -> System set-up	New retailer demands -> Revise system set-up
		New products/suppliers = modification system set-up & documents	New products -> Modification FSMS	New products -> Revise system set-up
	Validation	Less salt, more clean label --> influence shelf life	Less salt -> Shelf life validation	Less sugar/salt -> Validate shelf life
		Bv lager zoutgehalte / uitgroei pathogenen (1 horde minder in hordensysteem) kan wijzigen	Less salt -> Validate pathogen growth	Less sugar/salt -> Validate shelf life
		Dietary choices may have to do with claims on pack. Implementation includes validation, monitoring, verification.	Claims -> Implement validation	New validation
	Verification	Dietary choices may have to do with claims on pack. Implementation includes validation, monitoring, verification.	Claims -> Implement verification	Claims -> Improve verification of effectiveness
	Documentation & record-keeping	New products/suppliers = modification system set-up & documents	New products -> Modification documents	New products -> Modification documentation
	External food safety performance	Nutriscores verbeteren leidt tot wijziging ingrediënten	/	/
		/	/	/
	Internal food safety performance	Pre-requisites definition	/	/
Consumer awareness & attitude	Preventive measures	Rekening houden met veranderende vraag van consument - ander aanbod	/	/

		Negatieve publiciteit zorgt voor verandering van leveranciers	Negative publicity -> Change in suppliers	Negative publicity -> Change suppliers
		Supplier management of preventive measures → we might be obliged to source from specific regions for example	Specific region sourcing -> Supplier management	Specific region sourcing -> Change suppliers
	Intervention	Minder E-nummers gewenst -> andere alternatieven zoeken (HPP - stap ipv bewaarmiddel)	Less additives -> Alternative intervention steps	Less additives -> Additional intervention steps
	Operation	Moving towards a more plant-based diet increase the availability on the market of plant-based solutions	More plant-based -> Operation	More plant-based -> Adapt operational activities
	System set-up	Example: Awareness of incidents in the sector might give a trigger to redesign/improve the system	Awareness of incidents -> Redesign system	Negative publicity -> Revise system set-up
	Validation	Validation of cleaning to avoid cross-contamination	More plant-based -> Validation of cleaning	More plant-based -> New validation
		Meer ready to eat producten (geen afdoding meer van pathogenen door consumer) / of meer (korte of onvolledige) opwarming in een microgolf door tijdsgebrek (ipv door verhitting of langdurige verhitting in oven of friteuse bv) / in welke mate is consument zich bewust van gevaren als bv koudeketen onderbroken is (of bv niet op tijd geconsumeerd is of tijdelijk bij een hogere temperatuur) /	More ready-to-eat -> Validation consumer behaviour	More ready-to-eat -> New validation
	Documentation & Record-keeping	Validatie gegevens bijhouden, trendanalyses bijhouden, mate van misbruik of fout gebruik inschatting	More ready-to-eat -> Documentation of trends	More ready-to-eat -> Documentation of changes
	External food safety performance	Consumer awareness and attitude will be visible by consumer / customer complaints and questions?	Consumer awareness -> Customer complaints	Consumer awareness -> More complaints
	Internal food safety performance	Knowledge causes additional requests towards nutritional value	/	/
		Consument wil langere houdbaarheid – druk op sales – gevaar microbiologie	/	/

Table A6.2 Initial and focused coding of the examples provided by the workshop participants on the mechanisms at play between subdrivers and FSMS activities, done for the top 3 most indicated technological subdrivers

Subdriver	FSMS activity	Example	Initial coding	Focused coding
Food packaging	Preventive measures	Zie vorige opmerking, geen concrete voorbeelden.	/	/
	Intervention	Andere soorten verpakking, zorgt voor ander inpakmethode	Different packaging -> New packaging technology	New packaging -> New machines

		MAP gassing can have an effect on food safety	MAP gassing -> Implement as intervention	MAP gassing -> Additional intervention step
	System set-up	New packaging, legislation, client spec	New packaging -> Client requirement	New packaging -> Incorporate stakeholder requirements
	Validation	Switch naar monomateriaal is niet zonder gevaren -> barrières niet even sterk -> sneller bederf in de verpakkingen + technologie nog volop in ontwikkeling	Monomaterials -> Different barrier properties	Sustainable packaging -> Validate shelf life
		A new class of food packaging or packaging technology may include that shelf life of the involved products needs to be validated	New class of packaging -> Shelf life validation	New packaging -> Validate shelf life
		Verpakkingshoeveelheid steeds verminderen (minder bescherming, minder dikke folie,... of product is minder beschermd tegen externe factoren cfr bij diepvriestransport	Less packaging -> Less protection	Sustainable packaging -> Validate shelf life
		To validate that for example recycled packaging has the same functionality - e.g. fmoisture transfer that can increase water activity of the product that can lead to spoilage -> soft bakery. Sealing integrity	Recycled packaging -> Validate functionality	Sustainable packaging -> Validate shelf life
		Food packaging can introduce food safety risks that must be checked before introducing it	/	/
	Verification	Gerecycleerde verpakkingen - waarborgen microbiologische kwaliteit eindproduct	Recycled packaging -> Guarantee safety end product	Sustainable packaging -> Improve verification of effectiveness
	Documentation & Record-keeping	New packaging = modification of documentations in QA system	New packaging -> Modification documentation	New packaging -> Modification documentation
		Management of supplier documentation for special type of packaging (recyclability)	Recyclability of packaging -> Supplier documentation	Sustainable packaging -> Supplier document management
Products for food production	Preventive measures	Zie vorige opmerking, geen concrete voorbeelden. Wel mogelijke impact, watergebruik, maar ook de bijkomende microbiologische belasting van de primaire grondstoffen (levende dieren)	Water use -> incoming material quality	Water quality -> Increase material control
		algemene ingrediënten, controle goederen inkomst	Ingredients -> Control incoming materials	Quality raw materials -> Increase material control

		Ensure all incoming raw materials are duly checked for food safety contaminants	Raw materials -> Good control necessary	Quality raw materials -> Increase material control
	Monitoring	New products for food production will include need for management of supplier documentation and setup of monitoring of each new class of products.	New products -> Setup monitoring	New products -> Modification monitoring planse
		Change regulation pesticides & fertiliser (banned products & lowering MRL) --> more and more products exceeds MRL or has been spoiled due less use of pesticides & need to try new combinations of pesticides & fertilizers --> more sampling of products; --> also a lot go to waste due to bad products if too 'less' pesticides --> most problems with biological produced crops	Change regulation pesticides/fertilizer -> More sampling	Regulation change -> More sampling
		Regulations water quality, cleaning products, additives	Regulation water quality -> Monitoring	Water quality -> Modification monitoring plans
	System set-up	Nieuw product	New product -> System set-up	New products -> Revise system set-up
		Water	Water -> System set-up	Water quality -> Revise system set-up
		The whole system must be revised, validated and adjusted to the products for food production	Adjust to products -> Revise system	New products -> Revise system set-up
	Validation	Validation towards specification sheet	Specification sheets -> Validation	Specification sheets -> New validation
	Documentation & Record-keeping	Management of supplier documentation and authority control programs	Products for food production -> Management of supplier documentation	New products -> Supplier document management
	External food safety performance	Validation, external food safety performance	/	/
	Internal food safety performance	Wanneer we microbiologische analyses doen op eindproducten met een aardbei grondstof of op een aardbei grondstof rechtstreeks vinden we vaak positieve resultaten voor *Bacillus cereus*. Ondertussen hebben we ontdekt dat *Bacillus thuringiensis* bij aardbeien teelt kan gebruikt worden als insecticide. Bij labo analyses wordt dit eruit gehaald als *Bacillus cereus*. Als we dit	Bacillus thuringiensis in primary production -> Disturbed lab results	Use of biological products -> Disturbed lab results

		weten zou het geen probleem kunnen zijn alleen hebben we nog geen concreet bewijs dat aanwezigheid van *Bacillus thuringiensis* wel veilig is.		
Processing techniques & scale	Intervention	New techniques = possible new interventions/monitoring by workers/QC	New techniques -> New intervention	New techniques -> New machines
	Monitoring	If exporting to certain countries different micro criteria might be required	Export -> Different criteria	Export -> New criteria
		New techniques = possible new interventions/monitoring by workers/QC	New techniques -> New monitoring	New techniques -> Modification monitoring plans
	Operation	Zie vorige opmerking, geen concrete voorbeelden	/	/
	System set-up	Upscaling nieuwe innovatie	Upscaling -> System set-up	Upscaling -> Revise system set-up
		Washing and drying technologies	Technologies -> System set-up	New techniques -> Revise system set-up
	Validation	Nieuwe desinfectietechniek	New disinfection technique -> Validation	New techniques -> New validation
		Bv microgolftechnologie (indien implementatie om te ontdooien of bij verhitting)	Implement microwave tehcnology -> Validation	New techniques -> Validate technology
		New processing techniques include validation to ensure food safety of the product.	New processing techniques-> Validation	New techniques -> Validate technology
		Processing techniques & scale have an impact on new lines. Each technique must be validated	New lines -> Validation technique	New techniques -> Validate technology
		With new machines validation HACCP, risk analysis	New machines -> Validation	New techniques -> New validation
	Verification	Periodic verification of way of working will be needed.	Processing techniques & scale -> Periodic verification	New techniques -> Improve verification of effectiveness
		-	/	/
	Documentation & Record-keeping	New techniques = modification HACCP studies & several documents	New techniques -> Modification documents	New techniques -> Modification documentation
		New processing techniques include documented control points to ensure process is successful	New processing techniques -> Documented control	New techniques -> Documentation of changes

	External food safety performance	Delivering across the globe might trigger additional audits; bigger scale potentially more complaints	Global delivery -> Additional audits Upscaling -> More complaints	Export -> Additional audits Upscaling -> More complaints

Table A6.3 Initial and focused coding of the examples provided by the workshop participants on the mechanisms at play between subdrivers and FSMS activities, done for the top 3 (with a shared 3rd place) most indicated environmental subdrivers

Subdriver	FSMS activity	Example	Initial coding	Focused coding
Climate change	Preventive measures	Minder goede oogsten, meer verschillende leveranciers zoeken	Bad harvest -> Search new suppliers	Low availability ingredients -> Change suppliers
		Reduction of water use may have impact on hygiene management	Reduction of water use -> Hygiene management	Reduce water use -> Hygiene management
		It may impact the selection of certain raw materials, economic impact linked to fraud and presence/absence of certain contaminants	Presence of contaminants -> Selection of raw material	Variable quality ingredients -> Increase material control
		Due to climate change --> products in south of europe are burnt due to hot weather, in belgium are soaked due to a lot of rain --> crop cycle disrupted --> less products produced by our factories --> more products sourced outside Europe with their own problems (exceedance pesticides, …)	Less products produced -> Change suppliers	Low availability ingredients -> Change suppliers
	Monitoring	Nieuwe micro-organismen kunnen gedetecteerd worden in regio's van aankoop terwijl er daar vroeger nooit problemen mee waren	Region of sourcing -> New micro-organisms	Region of sourcing -> New criteria
		Duration of product season are changing eg: pumpkin season was very short	/	/
		Climate change --> possible impact @ suppliers = modification on sampling plan	Impact at supplier -> Modification sampling plan	Variable quality ingredients -> Modification monitoring plans
		High temperatures - impact on frequency monitoring / verification	Higher temperatures -> Frequency monitoring	Changing weather -> Modification monitoring plans
	Operation	Warmere temperaturen zorgen voor uitdagingen bij gekoeld transport in zomer - deuren vrachtwagen gaan open en volledige laadruimte te hoge temperatuur	Warmer temperatures -> Challenges with cooled transport	Changing weather -> Failing cold chain
	System set-up	Climate change @ suppliers --> possible impact on system set-up	Impact at supplier -> System set-up	Variable quality ingredients -> Revise system set-up

	Documentation & Record-keeping	Shortage in ingredients availability - recipe flexibility - traceability / shelf life of products	Shortage in ingredients -> Traceability	Low availability ingredients -> Traceability
	External food safety performance	More complaints as more products are 'non conform', the A-grade quality from previous years, we cannot produce that anymore --> complaints releated to 'poor quality'	Poor quality -> More complaints	Variable quality ingredients -> More complaints
	Internal food safety performance	E.g for some spices dry weather might results in higher TPC results	Dry weather -> Higher TPC results	Changing weather -> Disturbed lab results
Seasonality & weather	Preventive measures	Multiple suppliers from multiple countries are necessary to have multiple options when quality is bad because of seasonality & weather conditions	Bad quality -> Multiple suppliers needed	Variable quality ingredients -> Multiple supplier control
		Shortage of certain raw material due weather might require revision of new suppliers - impact on company operation	Shortage of raw materials -> Revision of new suppliers	Low availability ingredients -> Change suppliers
		Verschillende leveranciers zoeken uit verschillende continenten die verschillende seizoenstijden hebben, zodat er constant kwaliteitsvol en voldoende product geleverd kan worden	Low availability of quality ingredients -> Multiple suppliers needed	Variable quality ingredients -> Multiple supplier control Low availability ingredients -> Multiple supplier control
		Problems on the field caused by weather conditions (temperature, rain,...)	Problems on the field -> Preventive measures Weather conditions -> Preventive measures	Variable quality ingredients -> Increase material control Changing weather -> Increase material control
	Intervention	Meer neerslag = lagere kwaliteit van grondstoffen -> meer nood aan reducties qua microbiologie	Lower quality ingredients -> Need for reduction steps	Variable quality ingredients -> Additional intervention steps
	Monitoring	Seasonality = possible impact on bacteriological quality of raw materials --> modification of monitoring plan	Bacteriological quality raw material -> Modification monitoring plan	Variable quality ingredients -> Modification monitoring plans
		Aankoop van grondstoffen uit andere regio's door seizoenen --> minder vertrouwen in de kwaliteit en de controles van buiten EU --> verhoogde microbiologische metingen nodig (?)	Low quality ingredients -> More sampling	Variable quality ingredients -> More sampling
	Operation	DV opslag; koel houden van productie- en receptiezones; belasting koelgroepen bij (langdurig) warm weer in de zomer; snellere correcties nodig bij technisch falen van koeling of te hoge producttemperatuur en mogelijks uitgroei m.o.	Warm weather -> Technical failing cooling system	Changing weather -> Failing of cold chain

		Cooling systems need more follow up (QC) during high summer temperatures.	High summer temperatures -> Cooling system follow up	Changing weather -> Failing of cold chain
	Validation	Seasonality --> possible impact on validation/verification of product groups	/	/
	Verification	Seasonality --> possible impact on validation/verification of product groups	/	/
	Internal food safety performance	May affect the microbiological environment of a factory. Moreover, it may have an impact of chemical contaminants in certain raw materials (mycotoxins in cereals due to weather conditions)	Microbiological environment of factory -> Internal PI	Microbiological environment -> Disturbed lab results
Agricultural pollution	Preventive measures	Raw material on the field	Raw material -> Preventive measures	Contamination raw materials -> Increase material control
		Onze grondstoffen zijn "levende dieren", dus hier is wel degelijk een impact, om hier aan te geven welke impact dit zou kunnen zij op microbieel vlak is zeer moeilijk. Kan hier ook geen concrete voorbeelden geven. Het voorkomen om deze grondstoffen binnen te krijgen is een van de belangrijkste stappen	Incoming contamination -> Prevention	Contamination raw materials -> Increase material control
		Vervuilde grondstoffen - recalls tot gevolg	Contaminated incoming materials -> Preventive measures	Contamination raw materials -> Increase material control
		Pollution resulting in contamination of incoming ingredients and raw materials	Contamination incoming materials -> Preventive measures	Contamination raw materials -> Increase material control
		Agricultural pollution may have an impact on the raw materials used. Additional checks must be added to avoid the risk of non-compliance.	Raw materials -> Additional checks	Contamination raw materials -> Increase material control
	Monitoring	Pollution resulting in contamination of process water	Contamination process water -> Monitoring	Water quality -> Modification monitoring plans
		Extra controles in productie	Agricultural pollution -> Extra controls	Contamination raw materials -> More sampling
		Water quality origin (suppliers) = impact on raw materials -> modification monitoring plan	Water quality -> Modification monitoring plan	Water quality -> Modification monitoring plans

	System set-up	Water quality origin (suppliers) = impact on raw materials -> modification documentation/system/validation	Water quality -> Modification system	Water quality -> Revise system set-up
Geographic region	Preventive measures	Ontwikkeling van land	/	/
		New sourcing region	/	/
	Monitoring	Raw materials from different geographic regions = impact on monitoring plan microbiology	Different geographic regions -> Impact on monitoring plan	Different sourcing regions -> Modification monitoring plans
		For some materials in some regions/countries extra testing might be done	Some sourcing regions/countries -> Extra testing	Different sourcing regions -> More sampling
	Documentation & Record-keeping	Raw materials from different geographic region = impact on documentation (eg specifications)	Different geographic regions -> Impact on documentation	Different sourcing regions -> Modification documentation
	Internal food safety performance	Depending on the region there are different regulatory frameworks that must be followed	Depending on region -> Different regulations	Different sourcing regions -> Different regulations

Table A6.4 Initial and focused coding of the examples provided by the workshop participants on the mechanisms at play between subdrivers and FSMS activities, done for the most indicated economic subdriver and the top 3 most indicated political subdrivers

Subdriver	FSMS activity	Example	Initial coding	Focused coding
Global trade	Preventive measures	Overzees product, internationaal bedrijf	/	/
		Sourcing from new areas	/	/
	Monitoring	Export to new countries involves need for compliance to new norms	Export -> New norms	Export -> New criteria
	Operation	Grote productie bedrijven bevoorraden meerdere landen om prijs te drukken, lage lonen = minder gekwalificeerd personeel	Multiple country supply -> Less qualifies personnel	Multiple country supply -> More attention to hygienic working
	System set-up	Grote verdelers / toeleveranciers hebben vaak meerdere vestigingen door overnames; … en kunnen grondstoffen aanvoeren vanuit verschillende werelddelen, hierdoor extra stakeholders (en extra aandacht of opvolging nodig indien bv klanteneis met betrekking tot afkomst)	More stakeholders -> Extra attention to customer requirements	More stakeholders -> Incorporate stakeholder requirements
	Validation	Export to countries may involve shelf life extension	Export -> Shelf life extension	Export -> Validation shelf life
	Documentation & Record-keeping	Disruption chain= raw materials from new regions -> impact on documentation & monitoring	New region sourcing -> Impact on documentation	New region sourcing -> Modification of documentation

		Different food safety issues may come from different regions. Additionally traceability is more challenging as sometimes there are trading companies involved	Different sourcing regions -> Challening traceability	Multiple country supply -> Traceability
		Aanleveringen van buiten EU -> nood aan extra documenten / analyses -> twijfel aan echtheid van documenten op vlak van microbiologische analyses / accreditaties labo's	Sourcing outside EU -> Supplier document analysis	New region sourcing -> Supplier documentation management
		Export to non-EU countries needs documentation for export certificates	Export -> Need for right documentation	Export -> Modification of documentation
	External food safety performance	Exposure to high number of customer requirements	More customers -> More customer requirements	More stakeholders -> More complaints
	Internal food safety performance	Grondstoffen van buiten EU = onvoldoende kennis bij de leveranciers van de eisen -> meer risico op overschrijdingen	Sourcing outside EU -> High risk of non-compliance	New region sourcing -> High risk of non-compliance
		Conform legislation of each country	Different countries -> Conform legislation	Multiple country supply -> Different regulations
Food legislation	Preventive measures	Harmonised legislation makes it easier to source from different countries	Harmonised legislation -> Different country sourcing easier	Differing regulator requirements -> Change suppliers
	Monitoring	Legal norms are a good source for minimum quality requirements for incoming materials. On the other hand, non-harmonised legal norms (different norms in the same food product subsectors) are a challenge for a FSMS.	Non-harmonised legislation -> Different norms	Differing regulator requirements -> New criteria
		Food product so conformity is needed	/	/
		New legislation --> mainly impact on monitoring plan	New legislation -> Monitoring plan	New legislation -> Modification monitoring plans
		Extra testing might be required	New requirements -> Extra testing	New legislation -> More sampling
	Operation	Europese wetgeving niet overal gelijk toegepast, oneerlijke concurrentie (minder controles)	/	/
		Als wijziging aan food legislation --> bv heet water 82°C of ander systeem om messen te ontsmetten bij vers vlees of vleesbereidingen; dit heeft impact op de werkvloer en operationele activiteiten	New legislation -> Change operational activities	New legislation -> Adapt operational activities

		Wijziging food legislation --> bv wel/niet rookaroma's verder toegelaten (verlenging of niet toelating in toekomst…)	Change in legislation -> Change operational activities	New legislation -> Adapt operational activities
	System set-up	The system set-up must always be in line with local legislation	Local legislation -> System set-up	New legislation -> Incorporate stakeholder requirements
		We need to produce and import/export conform food legislation. Designs of equipment must be conform legislation.	Import/export -> Conform legislation	Differing regulator requirements -> Incorporate stakeholder requirements
		New legislation, new interpretation	New legislation -> New interpretation	New legislation -> Incorporate stakeholder requirements
		Snel wijzigende wetgevingen en bijkomende verstrengen maken het voor vele kleinere bedrijven moeilijk om dit zelf nog volledig op te kunnen volgen	Quick changing legislation -> Keep up in system	New legislation -> Revise system set-up
	Validation	Validation might be required by regulators in some regions	Regulator requirements -> Validation	Differing regulator requirements -> New validation
	Documentation & Record-keeping	Modification legislation, possible impact on system (validation, verification, docs)	Modification legislation -> Impact on documentation	New legislation -> Modification documentation
	External food safety performance	Lange doorlooptijd om EU wetgevingen om te zetten in KB, cfr KB water	New legislation implementation -> Documentation & record-keeping	New legislation -> Modifciation documentation
		Food regulators might be visiting plants	Regulators -> Plant visits	Differing regulator requirements -> Additional audits
	Internal food safety performance	Conform as food product	/	/
		Meer nood aan omgevingscontroles en de interpretatie / trends van deze gegevens -> meer kennis nodig van microbiologie intern	/	/
		More and more sampling --> 'new' components found --> also sample and analyse --> time & money necessary --> + change of regulations --> pro-active approach needed to implement to new regulations in time	Change of regulation -> Implement new criteria	New legislation -> Different regulations
Official controls & communication	Monitoring	Different interpretation of legislation by different departments in same country of different MS	Different interpretation of legislation -> Monitoring	Interpretation of legislation -> New criteria

		Official controls = may affect several parts of Quality Control (monitoring, measures,…)	Official controls -> Monitoring/measures	Official controls -> Modification monitoring plans
	System set-up	Wijzigingen in omzendbrieven -> verduidelijkingen die een andere aanpak vragen -> herwerken van het analyseplan	Different interpretation of legislation -> Modificate monitoring plans	Interpretation of legislation -> Modification monitoring plans
		Ensuring all our products are safe and manufactured in such a way that always meet authorities expectations	Authority expectations -> System set-up	Authority expectations -> Revise system set-up
		Voor onze sector heeft dit een zeer grote impact, de controle graad bij onze bedrijven ligt vele male hoger dan bij andere bedrijven in ander sectoren. Dit zorgt voor veel druk bij de mensen die op de QA werken	High degree of control -> System set-up	High degree of control -> Revise system set-up
	Validation	Validation of control	Controls -> Validation	Official controls -> New validation
		Official controls = may affect several parts of Quality assurence (documentation, validation, …)	Official controls -> Validation	Official controls -> New validation
	Documentation & Record-keeping	A lot of documentation necessary to comply with regulations --> store all documents and extras, not easy to have localised system	Lot of documentation necessary -> Localised system	Authority expectations -> Modifications documentation
	External food safety performance	Interpretatie sterk afhankelijk van de inspecteur die aanwezig is -> andere manier van opzet nodig om te voldoen aan de eisen van het LCE + vernieuwing qua mensen dus drang om zicht te bewijzen -> onderzoeken naar microbiologische activiteiten die eigen zijn aan het product / proces met waarschuwingen	Interpretation differs -> Differences in audit requirements	Interpretation of legislation -> Differing auditing results
		Grote verschillen in controles = andere standaarden per land	Differences in standards -> Differences in controls	Interpretation of legislation -> Differing auditing results
		Official controls = resource of info for risk analysis	Official controls -> Resource of info	Official controls -> Resource of info
		Controls might results in identified improvements opportunities	Controls -> Identified improvement opportunities	Official controls -> Resource of info
		Official audits by authorities	/	/
War & conflict	Preventive measures	Multiple suppliers are needed to make sure import is possible. Because of the war in the Red Sea our goods are sometimes longer on the road.	Import restricted -> Multiple suppliers needed	New sourcing areas -> Multiple supplier control

		Andere leveranciers zoeken, geen handel met land in conflict (subsidies)	Import restricted -> New suppliers	New sourcing areas -> Change suppliers
		New sourcing areas	New sourcing areas -> Preventive measures	New sourcing areas -> Multiple supplier control
		Niet tijdig of stop aanvoer van bepaalde grondstoffen / zoeken naar alternatieven (bij andere leveranciers, andere grondstoffen, of andere afkomst…) cfr geen zonnebloemolie meer beschikbaar in 2023 - overschakeling naar koolzaadolie of ander	Low availability of ingredients -> New suppliers	Low availability of ingredients -> Change suppliers
		Raw material limitation	Raw material limitation -> Preventive measures	Low availability of ingredients -> Change suppliers
	Monitoring	Conflict --> increase import duties --> sourcing new suppliers/regions --> impact on monitoring plan	Increased import duties -> Monitoring plan	Higher costs -> Modification monitoring plans
	Operation	Availability of raw materials.	/	/
		Vb. sterke stijging van de hulpgrondstoffen, of verpakkingen, maar ook de stijgende energiekosten. Dit heeft voor vele bedrijven een grote impact gehad op hun operationele procesvoering.	Higher costs -> Adapt operational activities	Higher costs -> Adapt operational activities
		Tekort aan bepaalde grondstoffen, om toch te kunnen leveren aanvullen met minderwaardige grondstoffen	/	/
	System set-up	Unavailability of materials is a challenge for business continuity, and also for a FSMS that needs to be installed to allow changes in materials	Unavailability of materials -> FSMS needs regular updates	Low availability of ingredients -> Revise system set-up
	Verification	Alternatieve bronnen van grondstoffen zoeken, zeker niet altijd van gelijkwaardige kwaliteit	Alternative sourcing -> Verification	New sourcing areas -> Improve verification of effectiveness
	Documentation & Record-keeping	Conflict --> increase import duties --> sourcing new suppliers/regions --> impact on documentation	Increased import duties -> Documentation	Higher costs -> Modification of documentation
	Internal food safety performance	Higher prices --> sourcing ingredients outside of Europe, mainly Asia --> not same maturity level of FSMS as here --> hygiene etc not the same --> have more unexplained contamination	Sourcing outside EU -> More unexplained contamination	New sourcing areas -> Disturbed lab results

7. Appendix 7: Coupling of drivers and indicators through internal discussion

Table A7.1 Coupling of drivers, subdrivers and indicators as compiled through internal discussion. Coupling is grouped per category of drivers. Where all subdrivers belonging to one driver are considered to have an impact, the name of the driver is used and indicated in italics

Indicators	**Social**	**Technological**	**Environmental**	**Economic**	**Political**
Context					
Contamination initial materials	*Consumer behaviour*	*Technology in food production*	Use of sidestreams *Environmental conditions* *Geographic region* *Climate change* *Seasonality and weather*	Global trade	Food legislation
Contamination final product	Consumer awareness and attitude	*Technology in food processing*	*Climate change*		*Legislation, policies and governance*
Packaging concept	Public awareness	Food packaging	Recycling	Global trade	Food legislation
Interventions	Consumer awareness and attitude	*Technology in food processing*			
Changes in the production process	Dietary choice	Processing techniques and scale			
Rate of changes	Dietary choice Public awareness	Upcycling for food Food formulation Novel food sources			
Technological staff					
Variability of workforce composition					
Operator competences					
Management commitment					
Employee involvement					
Formalization					Good practices & standards
Information systems		New digital technologies			
Role in the safety of the chain	Consumer knowledge				
Supplier relationship					
Customer relationship	Consumer knowledge				

	Prevalence of vulnerable groups Human health conditions				
Requirements of stakeholders	Public awareness Consumer awareness and attitude				*Legislation, policies and governance*
Quality Control					
Hygienic design of equipment and facilities		*Technology in food production*			Good practices and standards
Storage conditions			*Geographic region* *Climate change* *Seasonality and weather*	*Distribution*	
Sanitation programs					Good practices and standards
Personal hygiene requirements					Good practices & standards
Incoming material control			Geographic region	Global trade	Good practices and standards Food legislation
Product specific preventive measures			Sewage treatment Water and soil management		Good practices and standards Food legislation
Full/partial physical intervention		Processing techniques and scale			
Packaging equipment		Food packaging			
Maintenance and calibration programs					
Intervention strategies	Resistant pests and diseases Consumer awareness and attitude				
Analysis of CCPs and CPs					
Standards and tolerances design					

Analytical methods to asses pathogens					
Measuring equipment to asses product/proces status					
Calibration programs for measuring and analytical equipment					
Sampling plan for microbial assessment					
Corrective measures					
Actual availability of procedures					
Actual compliance to procedures					
Actual hygienic performance of equipment and facilities					
Actual storage/cooling capacity					
Actual process capability of full/partial physical intervention					
Actual process capability of packaging					
Actual performance of measuring equipment					
Actual performance of analytical equipment					
Quality Assurance					
Translation of stakeholders requirements into own FSMS					*Legislation, policies and governance*
Systematic use of feedback to modify FSMS					
Validation of preventive measures					

Validation of intervention process					
Validation of monitoring systems					
Verification of people related processes					
Documentation		New digital technologies			
Record keeping system		New digital technologies			
External food safety performance					
Food safety management system evaluation					Official controls & communication
Seriousness of remarks					Official controls & communication
Microbiological food safety complaints	Consumer knowledge Consumer awareness and attitude				
Hygiene related complaints	Consumer knowledge Consumer awareness and attitude				
Internal food safety performance					
Product sampling					
Judgement criteria					
Non-conformities					

8. Appendix 8: Coding of papers found for the impact of subdrivers on context indicators

Table A8.1 Initial and focused coding of the passage found in literature on the mechanisms at play between subdrivers and FSMS activities, done for the top 3 social subdrivers

Subdriver	Context indicator	Passage found in literature	Initial coding	Focused coding	Reference
Consumer awareness & attitude	Packaging concept	"Meanwhile, a growing number of consumers are aware of the potential negative health effects of chemical preservatives, which has prompted the food industry to find natural products used and developed as alternatives." "It is evident that natural preservatives combined with either lower levels of synthetic/chemical ones, or with other hurdles, such as non-thermal sterilization processing, modified atmosphere packaging, and edible films and coatings, will enhance the performance of various natural preservatives discussed in the review."	Natural preservatives -> MAP packaging as extra hurdle	Natural preservatives -> Importance of packaging in shelf life	Mei et al. (2019)
		"The integration of traditional food products into the digital marketplace represents a significant evolution within the food processing and preservation domain, marking a dynamic confluence of heritage culinary practices and contemporary consumer expectations." "Our study underscores the pivotal role of microbiological safety, sensory qualities, packaging efficiency, and alignment with consumer preferences in the online marketplace." "This focus on packaging efficiency not only enhances consumer appeal but also aligns with sustainability considerations crucial for online sales success."	Traditional food products -> Importance of packaging efficiency Digital marketplace -> Importance of packaging efficiency Sustainability considerations -> importance of packaging efficiency	Tradition food products -> Importance of packaging in shelf life Digital marketplace -> Importance of packaging in shelf life Sustainability -> Importance of packaging in shelf life	Aussanasuwannakul & Butsuwan (2024)
		"Minimally processed (MP) onion is convenient to use and can be packaged under different forms such as ready-to-cook (RTC) or ready-to-eat (RTE). Market supply of MP onions depends upon availability of these products which in turn is related to consumer demand and purchasing behavior." "A combination process has been standardized which includes, gamma irradiation Dmin 60 Gy treatment to fresh onions, minimal processing (de-skinning and scooping) followed by packaging and storage at 4–6 °C. his combinatorial approach resulted in extended shelf-life of RTE (Ready-to-Eat) as well as RTC (Ready-to-Cook) onions."	Minimal processing -> Packaging to extend shelf life	Minimal processing -> Importance of packaging in shelf life	Khade et al. (2023)

		"Nowadays, the increase in consumer demand for minimally processed foods prone to spoilage compromises food safety and quality" "antimicrobial packaging to extend the shelf life of food products, emphasizing fresh and minimally processed fruits and vegetables, meat, and dairy products"	Minimally processed food -> Antimicrobial packaging	Minimal processing -> Active packaging	Fadiji et al. (2023)
		"Over the past few years, considerable attention has been given in developing biodegradable food packaging in the academia and industrial sections to elucidate the environmental challenges associated with petroleum-based packaging materials including biological incompatibility and increased carbon footprint tending towards amplified global warming" "consumer preference for transparent packaging materials" "Edible packaging is available as edible films or edible coatings, where, the materials of edible packaging should have the biodegradability similar to the food products."	Carbon foot print -> Biodegradable packaging e.g. edible coatings	Sustainability -> Biodegradable/biobased alternatives	Ghosh & Katiyar (2022)
		"Interest in edible films and coatings has increased in recent decades due to consumer demand for environmentally friendly packaging solution"	Environmental friendly solutions -> Edible films	Sustainability -> Biodegredable/biobased alternatives	Silva et al. (2023)
		"Food preservation and food safety concerns among food producers and consumers are becoming increasingly important globally. The use of alternative techniques for food processing instead of heat treatment have recently been reported in the food industry" "consumer demand for raw or unprocessed food is increasing with the rising interest in healthy lifestyles." "In addition to recently published articles, the synergistic hurdle effect of CP with other novel technologies such as nanotechnology on food or food packaging materials could be further studied and used more extensively to ensure food safety."	Aversion for use of heat treatments -> Alternative sterilization techniques	Minimal processing -> Alternative packaging sterilization	Ucar et al. (2021)
		"Many countries are now moving towards the banning of single-use plastics." "These bio-based polymers have the possibility of replacing traditional polymers demonstrating analogous physical, chemical, thermal and mechanical properties as depicted by polypropylene (PP) and low-density polyethylene (LDPE)"	Ban of single use plastics -> Bio-based packaging material	Sustainability -> Biodegradable/biobased alternatives	Jaffur et al. (2021)

		"Food packaging is one of the crucial elements of the product from a consumer's perspective and very important in modern commercial trade" "On the other hand, the widespread utilization of petroleum-based plastic packaging has become a major global concern because their production and disposal are causing many environmental problems." "For this reason, there has been a growing interest in the design and fabrication of biodegradable packaging materials from natural and biological resource" "While maintaining the food quality and safety is one of the functions in food packaging, the modern-day packaging must also inform the consumer about the food quality and their suitability to be consumed" "Furthermore, the use of smart packaging based on chemo-responsive natural colorants even along with nanomaterials can be a promising strategy to provide numerous advantages to the food industry by minimizing food waste, foodborne diseases, spoilage and deterioration of food products."	Environmental impact -> Biodegradable packaging Better consumer information -> Smart packaging	Sustainability -> Biodegradable/biobased alternatives Better consumer information -> Smart packaging	Alizadeh-Sani et al. (2020)
Dietary choice	Contamination final product	"Poultry meat represents an important part of the U.S. economy and diet. However, it remains one of the food categories responsible for the most outbreak-associated foodborne illness cases. Therefore, the food safety and public health communities continue to examine appropriate antimicrobial interventions to reduce product contamination and the risk of foodborne disease. "	Poultry meat -> high product contamination	Poultry meat -> High risk for product contamination	Cano et al. (2019)
	Packaging concept	"Traditional fermented foods play a major role in many Ghanaian diets." "The difficulties in implementation food safety management systems as reported by these industries included raw materials specifications, no quality points in processing operations and testing for packaging materials prior to use."	Industrialization of traditional fermented food -> Testing for packaging materials	Industrial traditional food -> Importance of packaging for shelf life	Dzikunoo et al. (2021)
		"Similar to other regions, RTEs are widely consumed in low-and middle-income countries (LMICs) due to ease of production, availability, affordability, and palatability" "Based on the type of processing technique and packaging material, RTEs could range from traditionally processed foods such as chaat in India, matoke in Uganda, and warankasi in Nigeria to industrially processed foods such as bread, biscuits, canned sardine ice cream, and pizza."	Industrial ready-to-eat -> Type of packaging material	Ready-to-eat -> Importance of packaging for shelf life	Makinde et al. (2020)

		"we focus on the processing and characteristics of Xygalo Siteias, mentioning perspectives for the further microbiological characterization of the product, the determination of its shelf-life in combination with new packaging-materials, as well as the attention it deserves as a food important for breeders, the local economy, and consumers, since it is associated with the Cretan-Mediterranean diet type" "Furthermore, appropriate packaging solutions could minimize quality changes in soft cheeses, resulting in an increased shelf life as well as quality maintenance"	Traditional cheese -> Appropriate packaging solutions	Industrial traditional food -> Importance of packaging for shelf life	Lapidakis & Fragkiadakis (2022)
		"With the continuous progress of economic society and the diversification of people's diet culture, food safety has become the focus of attention of the government and consumers." "It can also be seen from the above data that the microbial contamination status of different food types and packaging forms is different."	Diversification of diet -> Packaging form	Diversification of diet -> Importance of packaging for shelf life	Bai (2019)
Resistant pests & diseased	Contamination final products	"Despite its importance, goat cheese is often made under inadequate hygienic-sanitary conditions and usually uses raw goat's milk, increasing the risk of product contamination. " "From a health point of view, it is even more alarming when it comes to *S. aureus* carrying resistance genes."	Resistant pathogens -> High risk for product contamination	Resistant pathogens -> High risk for product contamination	Aragao et al. (2021)
	Packaging concept	"According to the World Health Organization, antimicrobial resistance is one of the emerging threats to global health. Therefore, the development of new strategies to mitigate resistant bacterial strains is highly desirable." "In this work, a self-sterilizing and potentially biodegradable material is developed, providing a green alternative for single-use packaging in the medical, food, and cosmetic industry."	Antimicrobial resistant pathogens -> Self-sterilizing packaging	Resistant pathogens -> Alternative sterilization for packaging	Langerreiter et al. (2024)
		"This study offers a comprehensive analysis of the microbiome along beef processing using whole metagenomics with a particular focus on antimicrobial resistance and virulence-associated genes distribution." "A different microbiome composition was found in raw beef samples stored under different temperature and packaging conditions." "Finally, we highlighted a distinct distribution of ARGs. Samples stored in AIR packaging harbored a lower diversity of antibiotic families, which decreases over time."	Antimicrobial resistance -> Depends on packaging type	Resistant pathogens -> Importance of packaging for shelf life	Sequino et al. (2024)

Table A8.2 Initial and focused coding of the passages found in literature on the mechanisms at play between subdrivers and FSMS activities, done for the top 3 technological subdrivers

Subdriver	Context indicator	Passage found in literature	Initial coding	Focused coding	Reference
Food packaging	Packaging concept	"Various innovative food packaging techniques have been developed with the application of advanced interdisciplinary approach and they continue to contribute to the development of the packaging industry" "In recent years, smart food packaging technologies, namely, intelligent packaging and active packaging are increasingly applied in the food sector. However, in many cases, these modernized packaging methods are still under research and have not been adopted at the commercial scale"	Innovative packaging techniques -> Smart packaging	Innovation in packaging -> Smart packaging	Pou et al. (2022)
		"To overcome these issues, advanced packaging systems are actively engaged in the food industries to enhance the quality, security, and shelf-life of the food products during storage" "The packaging system should also optimize the integrated interactions of chemical, physical, and biological processes between the food and the packaging system to retain the quality and freshness of the food product. The research on active packaging systems has currently received widespread attention towards developing efficient packaging films to protect the food products from inherent and external factors"	Advances packaging systems -> Active packaging	Innovation in packaging -> Active packaging	Rangaraj et al. (2021)
		"As a result, the packaging industry views a paradigm shift towards developing and applying eco-friendly, safe, and non-toxic biopolymers-based active films" "Consequently, biopolymers have gained significant attention in the packaging industries due to their biodegradability and abundant availability from various natural sources, making them effective alternatives for fossil-based plastics"	Eco-friendly packaging -> biopolymers	Sustainability -> Biodegradable/biobased packaging	
		"Moreover, various innovative packaging systems that comprise active and smart/intelligent packaging materials are widely explored in the food industry. Active packaging (AP) is a modification of traditional packaging that offers protection against the growth of pathogenic microorganisms during food storage. The antimicrobial effect of AP is attributed to its incorporation of antimicrobial (natural or synthetic) agents into the packaging material"	Innovative packaging systems -> active antimicrobial packaging	Innovation in packaging - > Active packaging	Suvarna et al. (2022)

		"Modern society has extensively investigated the replacement of traditional food packaging systems with new ones. These packaging systems are an effective way to extend or maintain shelf life and preserve quality for a range of fresh products such as vegetables, fruits, meat and fish." "Special attention is paid to the MAP and active packaging."	Packaging for fresh products -> New packaging to extend shelf life	Packaging for fresh food -> Importance of packaging for shelf life	Zouharova et al. (2023)
		"On the other hand, the widespread utilization of petroleum-based plastic packaging has become a major global concern because their production and disposal are causing many environmental problems." "For this reason, there has been a growing interest in the design and fabrication of biodegradable packaging materials from natural and biological resource" "While maintaining the food quality and safety is one of the functions in food packaging, the modern-day packaging must also inform the consumer about the food quality and their suitability to be consumed" "Furthermore, the use of smart packaging based on chemo-responsive natural colorants even along with nanomaterials can be a promising strategy to provide numerous advantages to the food industry by minimizing food waste, foodborne diseases, spoilage and deterioration of food products."	Environmental problems -> Biodegradable packaging Consumer information -> Smart packaging	Sustainability -> Biodegradable/biobased packaging Consumer information -> Smart packaging	Alizadeh-Sani et al. (2020)
		"Human health has been influenced by the quality of foods and their types. The demands of high food quality products with improved quality and shelf life are on the rise globally. For that, packaging materials play a vital role in saving the food quality, especially the third generation of packaging that indicates the spoiling metabolism of food throughout using smart, responsive materials." "Interactive packaging has a scientific basis for additional information about food products because these codes give all required data."	Additional information -> Smart packaging	Consumer information -> Smart packaging	Ibrahim et al. (2021)
		"To tackle the environmental pollution problem, scientists have begun to explore the possibility of using natural, biodegradable and renewable packaging materials for food packaging applications."	Environmental pollution -> Biodegradable packaging	Sustainability -> Biodegradable/biobased packaging	Kontominas (2020)
		"Finally, packaging technology, especially MAP, can be implemented to prolong the shelf-life of seafoods"	Seafood -> Packaging technology to prolong shelf life	Packaging of fresh food -> Importance of packaging for shelf life	Olatunde & Benjakul (2018)

		"Therefore, biodegradable packaging materials incorporating natural compounds became popular, offering an eco-friendly to environmental concerns and food safety challenges"	Eco-friendly -> Biodegradable packaging materials	Sustainability -> Biodegradable/biobased packaging	Acharya et al. (2024)
		"Notwithstanding, adequate packaging has played a remarkable role in reducing meat deterioration and extending shelf life."	Meat -> Adequate packaging to extend shelf life	Packaging of fresh food -> Importance of packaging for shelf life	Bassey et al. (2022)
		"The intelligent detection of fresh meat quality has the advantages of providing more convenient, faster, low-cost and non-destructive detection than the traditional detection methods." "Fortunately, intelligent film prepared by combining natural pigments such as anthocyanin and curcumin with biopolymer matrix (cellulose, chitin, starch, agar, etc.) can effectively reduce and avoid leaching problems. It can even replace traditional plastic packaging materials"	Fresh meat -> Smart packaging	Packaging of fresh food -> Smart packaging	Zhang et al. (2023)
Processing techniques & scale	Packaging concept	"A novel way to diminish this problem is the use of edible packaging, edible coatings, or edible films, which can provide an additional protective layer(s) for fresh products, thus increasing their shelf life by delaying microbial spoilage and providing moisture and gas barrier properties"	Novel ways to diminish problems -> Edible packaging	New technology -> Biodegradable/biobased packaging	Mitelut et al. (2021)
		"Modern technology has come to affect the use and acceptance of traditional packages by the new generation. These modern packaging of food have grave effect on the immediate environment since the packaging materials employed are not biodegradable. Traditional packaging materials are biodegradable even though it has its limitations in shelf-life extension and product protection."	Modern technology -> Better product protection	New technology -> Better product protection	Dzikunoo et al. (2021)
		"Surfaces might be cleaned with cold plasma before packing or as part of the packaging procedure." "Materials for packaging are decontaminated with cold plasma outside, where the shade effect is minimal because the plasma circulates all around the exterior"	Cold plasma technology -> Decontamination of packaging	New technology -> Alternative sterilization for packaging	Harikrishna et al. (2023)
		"Recent studies reported the potential application of this parameter in novel food processing techniques such as reducing atmosphere drying (RAD) of food products and reducing atmosphere packaging (RAP) of fresh food products for preserving the quality attributes and extending the shelf-life of food products."	Novel food processing techniques -> Better product protection	New technology -> Better product protection	Alwazeer (2020)

		"During the processing of polymers, the mechanical, thermal, optical, and other properties have been improved by using optimized processing parameters ." "This paper intends to present a comprehensive review of active agents incorporated in both synthetic and natural substrates used for enhancing the antioxidant and the antimicrobial properties of the polymer matrix as well as the bulk processing technologies involved in the food packaging applications during the last 10 years.	Optimized polymer processing -> Better properties New technology -> Active packaging	New technology -> Better product protection New technology -> Active packaging	Stanley et al. (2023)
		"This review focuses on the emerging nonthermal technologies that can be used to improve the safety of nuts during processing." "Packaging materials including modified atmosphere packaging (MAP) and films and coatings can be used as a carrier of different types of antimicrobials agents such as organic acids and essential oils, and plant extracts. These packaging materials may reduce the risk associated with pathogenic and spoilage microorganisms."	Emerging nonthermal technologies -> Active packaging	New technology -> Active packaging	Gyawali et al. (2014)
	Intervention	"UV processing is a non-thermal technology that has been widely used and has shown great potential in the past decades for sterilization in food processing. Especially in recent years, the emergence of new technologies in combination with LEDs and pulses has accelerated the trend of UV applications in meat and meat products. As an effective decontamination tool UVA, UVB, and UVC can effectively break the genetic material of pathogenic bacteria under certain circumstances, causing the dissociation of DNA molecules to form pyrimidine dimers and thus inactivating the pathogens."	Emergence of new technologies -> Effective decontamination	New technology -> Effectiveness of intervention	Wang et al. (2023)
Novel food sources	Packaging concept	"HPP is a novel non-thermal food processing technology. This processing is special in that after the food is sealed with a flexible packaging, the microorganisms and enzymes in the food are inactivated with high pressure of 100–600 MPa under room temperature" "The HPP-based hurdle strategy may facilitate the food production process to achieve clean labeling as consumers are increasingly seeking safe and healthy novel foods with less additives."	Healthy novel foods -> In-package inactivation of pathogens	Healthy novel foods -> In-package pathogen inactivation	Wu et al. (2022)

		"Combined effects of packaging and storage conditions have been tested by … who observed that storage at room temperature (20 °C) could guarantee microbiological, chemical and sensorial stabilities only if opaque vacuum packaging was applied" "Refrigeration and freezing, as well as air containing packaging, vacuum packaging and modified atmosphere packaging (MAP) are common preservation methods used for edible insects products."	Edible insect products -> Packaging to guarantee microbiological stability	Edible insects -> Importance of packaging for shelf life	Ojha et al. (2021)
		"Recently, production and consumption of dried foods and food ingredients have increased in many countries due to convenient transportation" "Therefore, the present study aimed to investigate the growth of micro-organisms in dried foods including dried seaweed, dried kelp, and dried pumpkin at different storage temperatures and RH during storage. " "Thus, the packaging method affects the growth of bacterial populations in dried foods with open bag than that in a closed bag or air-tight container at high RH."	Dried seaweed -> Packaging method affects bacterial growth	Seaweed -> Importance of packaging for shelf life	Hyun et al. (2018)
		"Seaweeds are one of the world's largest unexploited, low trophic, renewable global biomass resources." "Main food safety concerns include the presence of pathogenic bacteria, PTEs such as iodine, cadmium and inorganic arsenic, as well as unintended allergen presence attributed to cross-contamination with biofouling organisms. These obstacles can be tackled using general food hygiene practices, careful selection of seaweeds for consumption and targeted processing and packaging technology."	Seaweed -> Targeted packaging technology	Seaweed -> Importance of packaging for shelf life	Blikra et al. (2021)
		"Most of the published research deals with the nutritional or health benefits that edible seaweeds can promote in food formulations, rather than valuing them as an ingredient with gastronomic potential" "The use of MAP proved to be a promising method for preserving minimally processed seaweed, surpassing the effectiveness of vacuum packaging in most of the studies."	Seaweed -> MAP packaging for preservation	Seaweed -> Importance of packaging for shelf life	Moreira-Leite et al. (2023)

Table A8.3 Initial and focused coding of the passages found in literature on the mechanisms at play between subdrivers and FSMS activities, done for top 3 environmental subdrivers (with a tie for third place)

Subdriver	Context indicator	Passage from literature	Initial coding	Focused coding	Reference
Seasonality & weather	Packaging concept	"It can be seen from the test results of three years and different seasons that the microbial contamination of food in summer is serious. This is mainly because the bulk food are in high temperature in summer, and the protection is not in place to cause the microorganism to exceed the standard. The package of pre-packaged food is in good condition and within the warranty period. Its microbiological indicators are not affected by seasonal change."	More contamination in high temperatures -> Packaging to keep food in good condition	Seasonal variation in contamination -> Importance of packaging for shelf life	Bai et al. (2019)
		"Food packaging with efficient antibacterial ability is highly desirable and challenging in facing the crisis of microbial contamination." "Also, this film can release BB NPs to inactivate bacteria under all weather conditions."	Weather conditions -> Antibacterial activity of packaging	Weather conditions -> Active packaging	Li et al. (2021)
		"However, this seasonal fruit is highly perishable, and a large proportion of it goes unharvested and wasted worldwide. Spray drying of the fruit pulp can impart improved shelf life, ensuring long-term availability for consumers to exploit its health benefits. The storage quality varies according to the type of packaging material and the storage environment."	Seasonal fruit -> Storage quality of packaging	Seasonal fruit -> Importance of packaging in shelf life	Kumar et al. (2023)
		"The development of jamun jam is very important to preserve the nutritious value of fruit and make it available during off season" "Moreover, jamun fruit in Pakistan is wasted due to postharvest losses, and through this study, it is concluded that these losses can be cut down through value addition and proper packaging material."	Seasonal fruit -> Proper packaging material	Seasonal fruit -> Importance of packaging in shelf life	Aslam et al. (2019)
	Intervention	"Season also remained a risk factor; the odds of Salmonella contamination were higher in the summer than in winter. Poultry contamination typically follows a seasonal pattern" "Although meat and poultry safety has improved since implementation of the pathogen reduction HACCP rule in 1996 (22), Salmonella remains a major concern. The proposed Healthy People 2030 goals continue to target a reduction in outbreaks of Salmonella infection (among other foodborne pathogens) linked to poultry"	Seasonal pattern of contamination -> Focus on reduction	Seasonal variation in contamination -> Effectiveness of intervention	Beczkiewicz & Kowalcyk (2021)

		"The analysis of variance (ANOVA) revealed that temperature and tempering solution and their interaction significantly impacted the pathogen load" "Temperatures at which the tempering process may be carried out during different seasons of the year did not significantly influence the effectiveness of the saline organic acid solutions against the pathogenic microorganisms tested. However, the average temperatures experienced by wheat kernels in storage bins during the winter and fall months may favor the survival of pathogenic microorganisms."	Survival of pathogens seasonal -> Effectiveness of intervention	Seasonal variation in contamination -> Effectiveness of intervention	Sabillon et al. (2020)
Recycling	Packaging concept	"Food packaging based on nanoparticles embedded biopolymers can alleviate environmental concerns by lowering the amount of packaging materials required and enhancing packaging recyclability."	Improve recyclability -> Nanoparticles embedded biopolymers	Improvements in recyclability -> Biodegradable/biobased packaging	Wani et al. (2023)
		"control batches were packaged in gas barrier recycled polyethylene terephthalate (XrPet) trays and wrapped with a XrPet film. Samples were then stored at 20 °C and inspected at regular intervals for chemical-physical, microbiological and sensory parameters. Results show that the new packaging solution could considerably extend the shelf life of cheesecakes, thereby reducing food waste and decreasing the overall environmental impact."	Reduced shelf life of recycled packaging -> Choice of packaging focused on shelf life	Reduced shelf life of recycled packaging -> Importance of shelf life in packaging	Gutierrez et al. (2017)
		"Sustainable plastic multilayer films (different OTR values with high recyclability scores) for fish matrices combined with consolidated stabilizing food technologies have provided the real applicability of innovative measures at the industrial level." "This study has served to highlight, at the food industry level, the recent evolution in innovative production systems and their respective environmental sustainability (salt content reductions for each transporting carton resulting in major productive volume reductions, less salt wasting, and lower carbon emissions) compared to the traditional salted cod fish trades, and the practical applicability of new multilayer films with high recyclability, as a means of reducing environmental pollution."	Multilayer films with high recyclability -> Performance and practical applicability	Improvements in recyclability -> Better protection	Ferri et al. (2023)

		"Nanocomposites are reported to be an effective strategy that possesses high acid resistance capacity, effective recyclability, high thermostability, and enhanced storage stability" "It is a simple and reliable method that uses nanomaterials for food packaging to improve freshness, provide antibacterial protection, and regulate water vapor permeability."	Effective recyclability -> Antibacterial protection	Improvements in recyclability -> Active packaging	Ansari (2023)
Use of sidestreams	Interventions	"The wash process requires high volumes of water, which are usually reduced by water reuse. To maintain the microbiological quality of the process water, intervention strategies are needed. Chemical disinfection is the most common method to maintain the microbial quality of process water."	Reuse of process water -> Chemical disinfection	Reuse of water -> Disinfection necessary	Gadelha et al. (2019)
		"In addition to the current known hazards, emerging microbiological hazards e.g. due to new production systems in primary production (reuse of agricultural/industrial water, aquaponics, urban agriculture, etc.), will be addressed. " "To avoid cross-contamination of the product due to the use of contaminated water, water disinfection treatments are needed to eliminate, or reduce to an acceptable level, microorganisms of public health concern but these treatments should not have an adverse effect on the quality and safety of the produce.."	Reuse of water -> Water disinfection treatment	Reuse of water -> Disinfection necessary	Koutsoumanis et al. (2023)
Climate change	Packaging concept	"Meanwhile, the ongoing climate changes fostered by agricultural practices could enhance the degradation of non-renewable resources, further impairing crop yields and agricultural production" "These conditions drive the development of suitable materials for the preparation of functional and biodegradable packaging with low environmental impact."	Degradation of non-renewable resources -> Biodegradable packaging	Degradation of non-renewable resources -> Biodegradable packaging	Rahim et al. (2021)
		"New threats of such diseases emerging have been augmented by biodiversity loss and climate change. Deforestation, for example, forces humans to come in contact with new types of animals that carry disease vectors that are otherwise harmful for human health. Long term climate change also poses challenges for the re-emergence of previously eliminated communicable diseases from changing ecological environments" "Proper handling of food, improving storage quality for	Emerging diseases -> Enhanced packaging standards	Emerging diseases -> Better protection	Aiyar & Pingali (2020)

		livestock and food products and enhanced packaging standards will reduce cross-species transmission."			

Table A8.4 Initial and focused coding of the passages found in literature on the mechanisms at play between subdrivers and FSMS activities, done for the economic subdriver and the top political subdrivers

Subdriver	Context indicator	Passage from literature	Initial coding	Focused coding	Reference
Distribution channel	Packaging concept	"Currently, smart food packaging methods, such as microbial sensors, time–temperature indicators (TTIs), critical temperature indicators (CTIs), freshness indicators, gas indicators, moisture regulators, ethylene remover, antioxidant, C02, and 02, scavengers, and antimicrobial activities systems are rapidly progressing" "Time-temperature indicator (TTI) in food packaging records the time and temperature history of a product package (cumulative effect of temperature on the packaged product) during packaging, distribution, storage, and retailing."	Time in supply chain -> Smart packaging	Distribution control -> Smart packaging	Pou et al. (2022)
		"Based on different materials and reaction principles, sensors like electrochemical sensors, fluorescence sensors, biosensors and gas sensors are widely used in the field of intelligent food packaging." "Microbe TTI can be used as an effective indicator by combining with a "use by date" label. It can also be used to improve distribution control and management of the supply chain and food safety by attaching to a single product unit"	Distribution control -> Smart packaging	Distribution control -> Smart packaging	Liu et al. (2019)
		"Intelligent packaging is an emerging and exciting branch of packaging science and technology that offers great opportunities for enhancing food safety, quality, and convenience, and consequently decrease the number of retailer and consumer complaints. The introduction of quality and freshness indicators (e.g. temperature indicators, TTI, and gas-level controls), the increased convenience of product manufacturing and distribution methods, the invention of smart permeability films, and theft and counterfeiting evidence systems will help maximize the safety and quality of food products"	Convenience of distribution -> Smart packaging	Distribution control -> Smart packaging	Fang et al. (2017)
		"The nanosensor signals expressed in nanometers are developed to detect changes in structural and functional properties of materials at nano level (1nm = 10−9) and are embedded in food packaging material to	Monitor freshness in distribution ->	Distribution control -> Smart packaging	Chisenga et al. (2020)

		monitor freshness of perishable products during production, processing, and distribution."	Nanosensors in food packaging		
		"Smart packaging possesses an inherent property or integral part of a package, product, or package/product design, which provides intelligence suitable to identify and monitor the condition of packaged food during distribution in response to the external and internal environments."	Monitor condition of food in distribution -> Smart packaging	Distribution control -> Smart packaging	Ahmed et al. (2018)
		"The handling of fresh fruits and vegetables in reusable plastic crates (RPCs) has the potential to increase the sustainability of packaging in the fresh produce supply chain. However, the utilization of multiple-use containers can have consequences related to the microbial safety of this type of food." "Reusable plastic crates (RPCs) are utilized in different steps of the fruit and vegetable supply chain, including harvest, handling, packaging, and transport operations, as well as in the retail sector"	Retail sector -> Packaging with influence on safety	Spoilage in distribution -> Importance of packaging to shelf life	Lopez-Galvez et al. (2021)
		"Meat is easy to spoilage during distribution in supply chain due to microbial contamination and oxidation reaction." "To extend the shelf life and regulate the quality of fresh meat, for example, a combination of aerated packaging or the addition of natural preservatives can be used." "The intelligent detection of fresh meat quality has the advantages of providing more convenient, faster, low-cost and non-destructive detection than the traditional detection methods."	Spoilage in distribution -> Packaging to extend shelf life Spoilage in distribution -> Intelligent packaging	Spoilage in distribution -> Importance of packaging to shelf life Spoilage in distribution -> Smart packaging	Zhang et al. (2023)
		"Moreover, breaks in the cold chain during distribution and retail must be avoided." "Results of this research showed that packaging fresh-cut wild rocket and sea fennel with a PLA-based film is a feasible alternative to common plastic used in the fresh-cut industry, avoiding the waste of polymers in landfills. The biodegradable film has good oxygen barrier properties for packaging wild rocket."	Breaks in the cold chain -> Protection by packaging	Refrigeration in supply chain -> Importance of packaging to shelf life	Gomez et al. (2023)
		"This makes ANNs useful tools for food quality and safety, such as modeling microbial growth; analyzing spectroscopic data; and predicting food products' food safety and physiochemical, sensory, and functional properties during processing, storage, and distribution." "The findings of the current study indicated that using ANN regression models to predict the fruit quality of stored date fruits is a promising application of ANN,	Influence of distribution -> Quality attributes significantly affected by packaging	Spoilage in distribution -> Importance of packaging to shelf life	Ahmed et al. (2023)

		which can help improve the efficiency of producing and supplying perishable goods like date fruits." "The quality attributes of the fruits were significantly affected by MAP gases of CO2, O2, and N, packaging materials, storage temperature, and storage time."			
		"Various novel preservation technologies have been successfully proposed to effectively prolong the shelf-life of shrimp with high quality, showing high market values throughout the supply chain of shrimps." "ensure aquatic products safety for a long time of storage and distribution" "MAP is a great potential method for packaging fresh shrimp products."	Ensure quality in distribution -> MAP packaging	Spoilage in distribution -> Importance of packaging to shelf life	Peng et al. (2022)
	Interventions	"The results from this study demonstrate that the continuous use of refrigeration along the food-supply chain has the potential to select for *L. monocytogenes* variants with enhanced cold and heat tolerance, highlighting the impact that microbial intervention strategies can have on the evolution of bacterial strains and likewise, food safety." "mutations remain a large concern for the food industry as arising strains may possess enhanced survival capabilities that render current intervention and safety measures ineffective."	Refrigeration in supply chain -> Render interventions ineffective	Refrigeration in supply chain -> Effectiveness of intervention	Hingston et al. (2019)
		"Along the supply chain, processing operations are more critical steps in controlling final risks compared to cold storage and primary production." "it was assumed that, depending on the supply chain, a product is most likely to be on the shelves of a retailer and sold between two and five days and the duration of keeping a product in the freezer was assumed between 0 and 90 days."	Cold storage in supply chain -> Still need for proper intervention	Refrigeration in supply chain -> Effectiveness of intervention	Dogan et al. (2019)
Good practices & standards	Contamination final product	"After microbiological analysis it was found that all samples of coalho cheese were out of standards and unfit for human consumption in accordance with Ordinance n° 146/1996 of the Ministry of Agriculture, Livestock and Supply of Brazil." "Despite its importance, goat cheese is often made under inadequate hygienic-sanitary conditions and usually uses raw goat's milk, increasing the risk of product contamination."	Standards -> Guideline for product contamination	Standards -> Guideline for product contamination	Aragao et al. (2021)

	Packaging concept	"These approaches have certainly intensified the strength of food processing technology and improved food quality and maintenance standards during shelf life." "The significant nuances in food packaging include nanocomposites, antimicrobial nano-pack tailored with metal ions, metal oxides, nano clay and other biopolymers, which are key components inactive, intelligent, and biodegradable packaging"	Standards -> Packaging technology	Standards -> Importance of packaging for shelf life	Pushparaj et al. (2022)
		"There are existing guidelines about migration of chemical substances, absence of holes or blemishes in the paper, but guidelines for microbial analysis need to be formulated so that regulatory authorities and manufacturing units strictly follow the standards for microbial limits in paper and paperboard used to pack or contain food items."	Standards -> Microbial limits	Standards -> Better protection	Zaidi et al. (2022)
		"The development of new active packaging systems is constantly increasing due to technological advances, leading to higher food safety and quality standards as well as waste minimization and sustainability. Edible films and coatings are active packaging technologies that can meet standards, are primarily natural in origin, and are biodegradable."	Standards -> Active packaging Standards -> Biodegradable	Standards -> Active packaging Standards -> Biodegradable/biobased packaging	Ahmed et al. (2022)
		"Enhancing mechanical strength, moisture and oxygen barrier capabilities, and exhibiting antibacterial properties, thereby effectively extend the shelf life of packaged food items, ensuring heightened food safety standards"	Standards -> Antibacterial properties	Standards -> Active packaging	Rajendran et al. (2024)
		"The addition of APE and EOs into the packaging matrix demonstrated the potential to prolong the storage of food products by preserving food quality (pH, colors, and lipid oxidation) and safety during storage, and the inhibition zones of some extracts against the pathogens demonstrated are weaker in comparison to the standard antibiotic drug used (WHO standards)"	Standards -> Addition of substances with antibacterial properties	Standards -> Active packaging	Kong et al. (2023)
		"Our data also suggest a need for enforcement of processing standards during the on-site packaging of ice."	Standards -> Packaging process	Standards -> Packaging operation	Lee et al. (2017)
		"Food production and marketing sectors are in absolute need to maintain product quality to meet global standards." "The application of nanomaterials in food packaging is three important reasons, i.e., smart, improved, and active food packaging"	Standards -> Smart packaging Standards-> Active packaging	Standards -> Smart packaging Standards-> Active packaging	Manikandan & Min (2023)

			Standards -> Improved packaging	Standards -> Better protection	
		"However, the pH changes and bacterial growth in the cold-stored fresh pork meat samples were minimal and very similar in the three tested multilayer films, successfully accomplishing the requirements of the food quality and safety standards at the end of storage."	Standards -> Accomplishing food safety	Standards -> Better protection	Hernandez-Garcia et al. (2022)
		"Furthermore, among the production processes, high hygienic standards combined with efficient technologies, i.e., HPP, and new packaging materials, can be valid alternatives to the classic films to give substantial solutions to the growing environmental necessity of sustainability."	Standards -> Valid alternative for classic film	Standards -> Better protection	Ferri et al. (2023)
		"The lack of adequately enforced food-safety standards in managed agricultural production systems creates the necessary conditions for diseases to mutate into highly contagious strains" "Proper handling of food, improving storage quality for livestock and food products and enhanced packaging standards will reduce cross-species transmission."	Standards -> Enhances packaging standards	Standards -> Better protection	Aiyar & Pingali (2020)
		"Bread produced by local bakeries showed lower standards in packaging and microbial quality" "A high frequency of contamination in packed and unpacked bread may be attributed to ineffective and inefficient packaging of products. "	Standards -> Ineffective and inefficient packaging	Standards -> Packaging operations	Ali et al. (2023)
		"On one hand, food companies need of fast and affordable methods to keep constant higher sensory and safety standards, on the other hand, food scientists and operators find difficult conjugating these exigencies by means of univocal parameters." "Beyond the correct rearing practices and the observance of the best hygiene and manufacturing protocols in the processing, oxidation can be prevented with the use of right packaging according to the storage conditions and the destination of the product "	Safety standards -> Right packaging for products	Standards -> Importance of packaging for shelf life	Esposito et al. (2021)
		"However, our understanding of how these events originate and what agronomic, packaging, and environmental factors influence the survival, persistence, and proliferation of human pathogens remains of scientific debate." "It reflects on 20 years of research, industry guidelines, and	Standards -> Knowledge on packaging impact	Standards -> Importance of packaging for shelf life	Gutierrez-Rodriguez & Adhikari (2018)

		federal standards and how they have evolved to our current understanding of fresh produce safety"			
		"Additionally, intelligent packaging systems (IPSs) provide real-time information to consumers about the status of the product. ""Additionally, ensuring the compatibility of IPSs with existing industrial processes and standards can be a hurdle."	Standards -> Smart packaging	Standards -> Smart packaging	Sani et al. (2024)
		"There is the urgent need for strict enforcement of food safety regulations in Ghana to ensure that packaging materials used by food vendors as well as the mode of treating these materials meet standards that safeguard public health"	Standards -> Ensure protection by packaging	Standards -> Importance of packaging for shelf life	Abrokwah et al. (2020)
		"Besides radiation and cold storage, packaging in low density polyethylene bags in sealed condition was found to help in retaining the quality of these products during storage." "According to 'revised microbiological standards for fruits and vegetables and their products' under the latest regulation of Food Safety and Standards Authority of India (FSSAI); the microbiological limit (w.r.t. aerobic plate count) is 1 × 10^6 CFU g−1"	Standards -> Packaging to retain quality during storage	Standards -> Importance of packaging for shelf life	Bandyopadhyay et al. (2020)
		"Herbs for medicinal purposes must meet the same quality and safety standards as are set for medicines." "The greening of the production of herbs and spices goes in two directions, one concerning innovative packaging solutions for this group of food products, and the other concerning the obtained raw material"	Standards -> Innovative packaging	Standards -> Smart packaging	Smiechowska et al. (2021)

9. Appendix 9: Coding of papers found for the impact of subdrivers on FSMS activities

Table A9.1 Initial and focused coding of the passages found in literature on the mechanisms at play between subdrivers and FSMS activities, done for the top 2 social subdrivers

Subdriver	FSMS activity	Passage from literature	Initial coding	Focused coding	Reference
Dietary choice	Preventive measures	"Pork and pork products play an important role in the diet of Vietnamese people, contributing over 52.7% of the total meat intake" "Unsatisfactory food safety outcomes were associated with management (long transportation time) and poor hygiene practices (i.e. not separating pork and other meat and storing pork at inappropriate temperature) in both traditional and modern channels in rural and urban areas."	Pork as a diet staple -> Importance of hygiene practices	Diet staple -> Hygiene management	Ngo et al. (2021)
		"Aromatic herbs are characteristic of the Mediterranean diet pattern and, as with many agricultural products, may be exposed to a wide range of microbial contamination during pre and post-harvest processing." "The results highlight the importance of preventing contamination at the primary production, processing, distribution and retailing"	Herbs as part of the diet -> Importance of preventive measures	Diet staple -> Hygiene management	Oliveira et al. (2018)
		"Fish is a fundamental part of a healthy diet, being a source of proteins, lipids, vitamins, and minerals, contributing to nutritional needs through food by consumers" "These microorganisms, several of them enterobacteria that are pathogenic to humans, can be autochthonous to fish or exogenous due to contamination of the product when it is captured in water contaminated with fecal matter or in post-capture phases (handling, transformation, conservation, distribution, commercialization, and preparation prior to consumption) under inadequate hygiene conditions and practices, including failures in thermal processes."	Fish as part of the diet -> Importance of adequate hygiene	Diet staple -> Hygiene management	Cortes-Sanchez et al. (2023)
		"Ready-to-eat foods (RTEs) are foods consumed without any further processing. They are widely consumed as choice meals especially by school-aged children and the fast-paced working class in most low- and middle-income countries (LMICs), where they contribute substantially to the dietary intake." "Good personal hygiene is necessary during actual food preparation as well as during food pack-aging in order to limit RTE contamination"	Ready to eat foods -> Good personal hygiene necessary	Ready-to-eat food -> Hygiene management	Makinde et al. (2020)
		"Fermented vegetables are common part of the Cambodian diet." " The presence of Staphylococcus Spp. (10%) and Listeria spp. (10%) may also	Fermented vegetables as part of diet-> Hygiene	Diet staple -> Hygiene management	Chrun et al. (2017)

		point to unhygienic food handling procedures, inadequate sanitary processing places, and keeping temperature abuse over a period of time to allow for bacterial growth."			
	Monitoring	"The results documented the analysis of traditional cottage industry doenjang and suggest the need for constant monitoring to ensure the safety of food for the consumer." "The typical Korean diet contains a significant quantity of doenjang owing to its unique taste and health benefits"	Typical diet component -> Need for constant monitoring	Diet staple -> Continuous monitoring	Bahuguna et al. (2023)
		"Meat is one of the most consumed agro-products because it contains proteins, minerals, and essential vitamins, all of which play critical roles in the human diet and health." "These concerns are prompting the meat industry to begin to redefine and reevaluate standards for measuring and monitoring the quality and safety characteristics of meat and meat products"	Meat as a critical part of the diet -> Redefine standards for monitoring	Diet staple -> Modification monitoring plans	Khaled et al. (2021)
	Operation	"In Eastern countries, seed sprouts have been employed for dietary applications for so many years, but in the Western countries, the food usage of sprouted seeds can be traced back to the 1980s when there was remarkable demand by consumers for exotic, nutritional, and healthy foods, though in recent years, attention on sprout foods has been on issues related to minimal processing and absence of additives" "Sprouting as a processing operation is green, cost-effective, requires little technicality, requires less time, and with substantial output;"	Sprouts as part of the diet -> Ease of operation	Diet staple -> Ease of operation	Kehinde et al. (2022)
	Validation	"Australian apples significantly contribute to the Australian economy and dietary requirements." "Lack of validation could result in use of activities and processes that do not achieve the intended food safety outcomes if, for example, the system is challenged by increased contamination levels."	Apples as part of diet -> Need for validation of activities	Diet staple -> Need for validation	Frankish et al. (2022)
	Documentation & record-keeping	"Milk and dairy products are socially significant products in the population diet." "Taking into account constant improvement of the existing and the development of new innovative technologies, the increase in the range of the produced products, the strengthening of the requirements to shelf life. And other factors, the evaluation criteria of the quality and safety are constantly expanding and new methods are developed, which are	New products -> Introduced in documentation	New products -> Modification documentation	Ivkova et al. (2021)

		introduced into the official registration documentation for new types of products.			
	External food safety performance	"Australian apples significantly contribute to the Australian economy and dietary requirements. Their safety is ensured by food safety management systems (FSMS) audited by commercial entities."	Apples as part of diet -> Audits by commercial entities	Diet staple -> Additional audits	Frankish et al. (2022)
Resistant pests & diseases	Preventive measures	"Limited hygiene standards and improper handling may lead to incomplete sterilization and aggravate the risk of pathogen contamination." "In addition, many antibiotic resistance genes were found in gene cassettes, segments of DNA with one or two opening reading frames that lack promoters"	Antibiotic resistance -> Need for hygiene standards	Antimicrobial resistance -> Hygiene management	Yang et al. (2024)
		"Salmonella is not a normal bacterial component of fish microbial flora, and the occurrence of this pathogen is commonly related to its breeding, as well as to the industrialization environment, due to inefficient hygiene practices, equipment and inadequate food handling." "Salmonella antibiotic-resistant strains have been isolated in fish in Brazil and worldwide, which evidences the transference of resistance genes among the aquatic microbial population, which can lead to more severe and difficult to treat foodborne infections."	Antibiotic resistant -> Hygiene to prevent contamination	Antimicrobial resistance -> Hygiene management	Fernandes et al. (2018)
		"The predominance of specific *L. monocytogenes* serogroups and the different antimicrobial resistance patterns emphasize the need for constant surveillance and intervention to mitigate public health risks. " "The presence of L. monocytogenes in dairy products after pasteurization underscores the necessity of maintaining proper food hygiene throughout the production process."	Antimicrobial resistance -> Necessity for proper hygiene	Antimicrobial resistance -> Hygiene management	Aleksic et al. (2024)
		"During sample collection were found inadequate hygiene conditions in the environment used for cheese production. From a health point of view, it is even more alarming when it comes to S. aureus carrying resistance genes."	Resistance of pathogens -> Adequate hygiene conditions	Antimicrobial resistance -> Hygiene management	Aragao et al. (2021)
		"In accordance with our results, raw milk can be considered a source of AMR bacteria and genes; this points out the importance of properly informing food business operators about the risk associated with poor hygiene practices in the dairy production environment and consumers of	Antimicrobial resistance -> Hygiene practices	Antimicrobial resistance -> Hygiene management	Rubiola et al. (2022)

		the potential microbial food safety risks derived from raw milk products consumption."			
		"the most important measures to mitigate AMR applicable for all the food-production sectors investigated, both at pre- and post-harvest, involve the correct implementation of effective general measures (good hygiene practices, biosecurity) to prevent/reduce occurrence and transmission of pathogens and other microorganisms"	Antimicrobial resistance -> Correct implementation of hygiene practices	Antimicrobial resistance -> Hygiene management	Koutsoumanis et al. (2021)
		"Very high levels of resistance were observed for clindamycin (57%) and high resistance levels (>20–50%) to ciprofloxacin, oxacillin, levofloxacin and daptomycin, confirming the L. monocytogenes resistance trend to a wide range of antimicrobial agents. ""Persistence of L. monocytogenes in food processing environments is still considered the major source of RTE food contamination and this persistence appears to be the result both of improper hygiene conditions and of the high adaptive capacity of this bacterium"	Antimicrobial resistance -> Proper hygiene conditons	Antimicrobial resistance -> Hygiene management	Rugna et al. (2021)
	Monitoring	"Metagenomic evaluation of Arabian fermented foods, including the identification of probiotics, pathogenic bacteria, and ARGs, illustrates the importance of microbiological analysis in evaluating their health effects."	Antimicrobial resistance -> Importance of microbiological analysis	Antimicrobial resistance -> Improve microbiological analysis	Yasir et al. (2023)
		"In general, the taxonomic assignments obtained evidence the benefits of focusing AMR monitoring activities also on less frequently assessed non pathogenic bacterial species, therefore highlighting the added value of metagenomic studies to complement FPE microbiological surveys."	Antimicrobial resistance -> New monitoring technologies	Antimicrobial resistance -> New monitoring technologies	Alvarez-Molina et al. (2023)
		"Whole genome sequencing (WGS) has been broadly used to provide detailed characterization of foodborne pathogens." "Numerous government agencies, industry and academia have developed new applications in food safety using WGS approaches such as outbreak detection and characterization, source tracking, determining the root cause of a contamination event, profiling of virulence and pathogenicity attributes, antimicrobial resistance monitoring, quality assurance for microbiology testing, as well as many others."	Antimicrobial resistance -> New monitoring technologies	Antimicrobial resistance -> New monitoring technologies	Allard et al. (2018)

		"This review highlights the need to include agriculturally-derived AMR in monitoring food safety risks from plant-based foods, and the challenges facing its surveillance."	Antimicrobial resistance -> Need for monitoring	Antimicrobial resistance -> Continuous monitoring	Brunn et al. (2022)
		"Continuous monitoring of Listeria spp., particularly Listeria monocytogenes, in foods is a mandatory task for food safety and microbiology sectors. This study aimed to determine the prevalence and antimicrobial resistance patterns of L. monocytogenes in milk and dairy products retailed in Egypt."	Antimicrobial resistance -> Continuous monitoring	Antimicrobial resistance -> Continuous monitoring	Elafify et al. (2022)
		"The presence of ESBL and MBL in fruits and vegetables is an indicator for spreading antimicrobial resistance in the environment. ""Therefore, the study underlines the need for periodic monitoring of produce at various levels of production and sale are required to achieve satisfactory levels of microbial load.	Antimicrobial resistance -> Periodic monitoring	Antimicrobial resistance -> Continuous monitoring	Saksena et al. (2019)
		"The rate of contamination with Salmonella in the poultry and egg samples, besides the presence of antimicrobial resistant and MDR Salmonella isolates harboring the virulence genes in these samples, could significantly affect food safety and subsequently, human health. Therefore, continuous monitoring of animal-source foods, enhancement of poultry farm control measures, and limiting the use of antibiotics for prophylactic purposes in food producing animals, are essential for reducing the zoonotic risk of this foodborne pathogen for consumers and also choosing effective antibiotics for the treatment of salmonellosis."	Antimicrobial resistance -> Continuous monitoring	Antimicrobial resistance -> Continuous monitoring	Bahramianfard et al. (2021)
	Verification	"Very high levels of resistance were observed for clindamycin (57%) and high resistance levels (>20–50%) to ciprofloxacin, oxacillin, levofloxacin and daptomycin, confirming the L. monocytogenes resistance trend to a wide range of antimicrobial agents." "In conclusion, microbiological sampling of food and environments after sanitization are commonly used as verification procedure for the absence of L. monocytogenes in food plants and to give assurance of food safety, but the findings of this study underlined that the presence without recognizing of the real pattern of contamination and the characteristics of the strains could not be	High levels of resistance -> Include strain characterization in verification	Antimicrobial resistance -> Verification of strains	Rugna et al. (2021)

		considered as the conclusive assessment of a potential risk for public health."			
	Documentation & record-keeping	"Antimicrobial resistance (AMR) among foodborne pathogens becomes one of the top challenges for the environment, public health, and food safety sectors. However, less is known about antimicrobial-resistant foodborne pathogens in the Middle East region. Possibly because of the lack of surveillance, documentation, and reporting."	Antimicrobial resistance -> Documentation to follow up	Antimicrobial resistance -> Documentation for follow-up	Alsayeqh et al. (2021)

Table A9.2 Initial and focused coding of the passages found in literature on the mechanisms at play between subdrivers and FSMS activities, done for the top 3 technological subdrivers

Subdriver	FSMS activity	Passage from literature	Initial coding	Focused coding	Reference
Novel food sources	Preventive measures	"As insects and insect-based foods are receiving more attention and are already being marketed in some European countries, more insects farms are being established. Rearing companies often optimise their practices by trial and error and no general hygiene codes are available." "Further research on the impact of other rearing practices, hygiene measures and the substrate on the microbiota of edible insects is necessary in order to provide additional guidelines for the emerging insect-rearing industry to ensure food safety of their end products."	Microbiota of edible insects -> Hygiene measures are necessary	Edible insects -> Hygiene management	Wynants et al. (2017)
		"From the food hygiene point of view, the importance of NCA as passive transmitters of microorganisms is far more important as their role of vectors for several infectious diseases; "	Insects as transmitters of MO -> Hygiene	Edible insects -> Hygiene management	Grabowski et al. (2017)
		"The data show complex ecosystems with large variations in microbial load and diversity among the analysed edible insects." "The above-mentioned microbial groups play important and unique roles in food matrices (as well as in edible insects) and are relevant from the perspectives of hygiene and safety." "microbial hazards should be limited through the implementation of good hygienic practices during rearing, handling, processing, and storage, as well as the implementation of an appropriate HACCP system for edible insect supply chains"	Large variations in edible insect microbial load -> Good hygienic practices	Edible insects -> Hygiene management	Garofalo et al. (2019)
		"Climate change will impede availability of edible insects; hence, necessitating upscaling of mass production technologies and sound conservation practices. Safety and hygiene, on the other hand, hamper the	Edible insects -> Hygiene as a barrier	Edible insects -> Hygiene management	Egonyu et al. (2021)

		acceptability of insects as food and/or feed, particularly in developed countries."			
	Monitoring	"The result indicates that it is urgent to carry out monitoring measures for Vibrio parahaemolyticus in coastal areas. Hence, it is necessary to strengthen the microbiological detection of algae food and hygiene supervision in the manufacturing environment."	Algae food -> Strengthen microbiological detection	Algae -> Improve microbiological analysis	Wu et al. (2022)
		"Rather unexplored so far is the unculturable fraction of the insect microbial community and its importance in food safety. Last but not least, the most important microbiological challenge may well be situated in the further development of the sector: upscaling in terms of capacity and number of companies will increase the complexity of the sector. That will have implications for monitoring and control of biological contaminants"	Increase in edible insect consumption -> Implications for monitoring	Edible insects -> Modification monitoring plans	Vandeweyer et al. (2021)
Processing techniques & scale	Interventions	"UV processing is a non-thermal technology that has been widely used and has shown great potential in the past decades for sterilization in food processing. Especially in recent years, the emergence of new technologies in combination with LEDs and pulses has accelerated the trend of UV applications in meat and meat products. As an effective decontamination tool UVA, UVB, and UVC can effectively break the genetic material of pathogenic bacteria under certain circumstances, causing the dissociation of DNA molecules to form pyrimidine dimers and thus inactivating the pathogens."	Emergence of new technologies -> Non-thermal decontamination	New technology -> Effective intervention techniques	Wang et al. (2023)
	Operation	"New non-thermal food processing techniques, which achieve microbiological inactivation in food materials without the application of heat directly …are emerging and novel alternatives to the conventional thermal processing techniques" "Increase in mass transfer is of industrial interest owing to a reduction in operation time."	New food processing techniques -> Reduction in operation time	New technology -> Ease of operation	Al-najjar et al. (2023)
		"Recent studies reported the potential application of this parameter in novel food processing techniques such as reducing atmosphere drying (RAD) of food products and reducing atmosphere packaging (RAP) of fresh food products for preserving the quality attributes and extending the shelf-life of food products. This paper aims to help the technical and operational personnel working in food industry sectors as well as the	Novel food processing techniques -> Understanding of personnel	New technology -> Knowledge of personnel	Alwazeer (2020)

		scientific community to have an updated and a comprehensible review about the Eh parameter permitting its consideration for potential applications in food industries."			
New digital technologies	Monitoring	"It also needs to be connected to new technologies, such as the Internet of Things (IoT) (artificial intelligence, machine learning). Moving to the industry 4.0 era after the outbreak of the pandemic, the IoT is receiving more attention in various industries, including monitoring in real-time and being measured online."	Internet of Things -> Monitoring	Digital technology -> New monitoring technology	Wu et al. (2022)
		"Geographical Information Systems (GISs) can be an unraveling solution. GISs relates informational data to a geographic location and can be dynamically used to grow food businesses " "In terms of growing food businesses, GISs can be used for logistics and traceability to identify vulnerable areas in terms of monitoring and evaluating time and temperature within food safety procedures."	Geographical Information Systems -> Monitoring	Digital technology -> New monitoring technology	Varyvoda et al. (2021)
		"This study combined artificial intelligence (AI) and optical imaging to detect bacteria at the microcolony stage within 3 h of inoculation. " "Our method has the potential to be widely applied in food industries, environmental monitoring, and clinical settings and could aid in the rapid detection of bacteria."	Artificial intelligence -> Rapid bacteria testing	Digital technology -> Improve microbiological analysis	Ma et al. (2023)

Table A9.3 Initial and focused coding of the passages found in literature on the mechanisms at play between subdrivers and FSMS activities, done for the top 3 environmental subdrivers

Subdriver	FSMS activity	Passage from literature	Initial coding	Focused coding	Reference
Seasonality & weather	Preventive measures	"Some foodborne diseases are linked to specific weather and climatic conditions and are prevalent at specific times and seasons of the year" "For example, the Salmonella transmission risk increases with high rainfall" "environments where pathogens can easily find their way into food and water if not hygienically maintained"	Seasonal risk on pathogens -> Hygiene	Seasonal variation in contamination -> Hygiene management	Dzudzor et al. (2024)
		"Notably, human pathogens such as genera Vibrio was detected in Q3 and there was a significant increase in the relative abundance of Staphylococcus showing that a greater attention is recommended in hotter season, while other seasons showed only few bacteria to be recognized. In addition, two distinctive rate of Bacillus spp. and the	Seasonal risk on pathogens -> Improvement of hygiene processes	Seasonal variation in contamination -> Hygiene management	Lim et al. (2021)

		Firmicute/Proteobacteria ratio were observed by the warmer or colder seasons" "Taken together, our results would be a powerful reference to hygiene managers for improvement of food processes."			
		"The increased level of outbreaks during the summer months is often attributed to the increased ambient temperatures which favour the multiplication of pathogens" "This may lead to increased demands being placed on food operators which can result in less attention being paid to proper food hygiene, cooking temperatures and food storage"	Seasonal risk on pathogens -> Need for proper hygiene	Seasonal variation in contamination -> Hygiene management	Hull-Jackson & Adesiyun, (2019).
		"According to Table 1, it can be deduced that the non-conformity is higher in summer and autumn compared to the other seasons;" "The high rate of non-compliance during summer revealed in our study could be due to the increasing temperature or lack of hygiene;"	Seasonal risk on non-compliance -> Hygiene	Seasonal variation in contamination -> Hygiene management	Amaiach et al. (2023)
	Interventions	"Season also remained a risk factor; the odds of Salmonella contamination were higher in the summer than in winter. Poultry contamination typically follows a seasonal pattern" "Although meat and poultry safety has improved since implementation of the pathogen reduction HACCP rule in 1996 (22), Salmonella remains a major concern. The proposed Healthy People 2030 goals continue to target a reduction in outbreaks of Salmonella infection (among other foodborne pathogens) linked to poultry"	Seasonal pattern of contamination -> Focus on reduction	Seasonal variation in contamination -> Effective intervention techniques	Beczkiewicz & Kowalcyk (2021)
		"The analysis of variance (ANOVA) revealed that temperature and tempering solution and their interaction significantly impacted the pathogen load" "Temperatures at which the tempering process may be carried out during different seasons of the year did not significantly influence the effectiveness of the saline organic acid solutions against the pathogenic microorganisms tested. However, the average temperatures experienced by wheat kernels in storage bins during the winter and fall months may favor the survival of pathogenic microorganisms."	Survival of pathogens seasonal -> Effectiveness of intervention	Seasonal variation in contamination -> Effectiveness of intervention	Sabillon et al. (2020)
	Monitoring	"The dynamic and seasonal environments of fermented food facilities are largely uncharacterized and can produce rich microbial communities."	Microbiological environment -> Monitoring indoor air	Microbiological environment -> Specific monitoring	Madrid et al. (2017)

		"Monitoring indoor air particles is critical for maintaining healthy building environments."			
		"With regard to influence of environmental conditions on Norovirus presence, we have proved seasonal pattern of virus occurrence i.e., the largest number of positive samples was noticed during winter, while other physico-chemical factors were not of great significance. It was found that count of E. coli did not correlate with Norovirus prevalence. From the aspect of food safety, an upgrade of monitoring plans could lead to obtaining safer products."	Seasonal presence of virus occurrence -> Upgrade monitoring plans	Seasonal variation in contamination -> Modification monitoring plans	Ilic et al. (2017)
		"Specifically, the odds of produce contamination from Salmonella was 2.4 times greater during rainy season than samples obtained during the dry season" "Surveillance and monitoring of produce contamination throughout the food chain are suggested to enhance produce food safe"	Seasonal contamination -> Monitoring of product contamination	Seasonal variation in contamination -> Continuous monitoring	Srisamran et al. (2022)
		"Seasonal occurrence of individual bacteria was found while monitoring the microbial situation at food service facilities. This seasonality was observed in all the bacteria we detected (B. cereus, S. aureus, and E. coli)." "The data highlight the need of regular monitoring of the occurrence of agents of alimentary diseases at food service facilities as an important part of the HACCP plan to prevent the occurrence of FBDO."	Seasonal occurrence of bacteria -> Regular monitoring	Seasonal variation in contamination -> Continuous monitoring	Bogdanovicova et al. (2019)
		"FIB concentrations were high in the warm season and low in the cold season" "Identification of stable spatial patterns can be a useful component of the microbial water quality monitoring design and implementation."	Concentrations of bacteria dependent on season -> Water quality monitoring	Seasonal variation in contamination -> Specific monitoring	Jeon et al. (2020)
	Operation	"The dynamic and seasonal environments of fermented food facilities are largely uncharacterized and can produce rich microbial communities." "The ability to measure air parameters continuously over an extended period of time allows a facility manager to view past environmental conditions and make informed decisions about future operations within the building."	Microbiological environment -> Adapt operations	Microbiological environment -> Adapt operations	Madrid et al. (2017)
		"By accurately allocating resources during perilous seasons and potentially devising season-specific fruit handling, storage and transport guidelines, stakeholders can optimise operations and mitigate risks, with	Seasonal quality variation -> Adapt operations	Seasonal variation in contamination -> Adapt operations	Du Plessis et al. (2023)

		these findings proffering a crucial comprehension of the seasonal dynamics in fruit damage claims, thereby fortifying the agricultural sector's resilience and enhancing overall food safety."			
Use of sidestreams	Interventions	"The wash process requires high volumes of water, which are usually reduced by water reuse. To maintain the microbiological quality of the process water, intervention strategies are needed. Chemical disinfection is the most common method to maintain the microbial quality of process water."	Reuse of process water -> Chemical disinfection	Reuse of water -> Effective intervention technique	Gadelha et al. (2019)
		"In addition to the current known hazards, emerging microbiological hazards e.g. due to new production systems in primary production (reuse of agricultural/industrial water, aquaponics, urban agriculture, etc.), will be addressed. " "To avoid cross-contamination of the product due to the use of contaminated water, water disinfection treatments are needed to eliminate, or reduce to an acceptable level, microorganisms of public health concern but these treatments should not have an adverse effect on the quality and safety of the produce.."	Reuse of water -> Water disinfection treatment	Reuse of water -> Effective intervention technique	Koutsoumanis et al. (2023)
	Monitoring	"The proper operation of water disinfection treatment (e.g. application rate, in-use concentration and residual concentration on ffFVHs) as well as of the monitoring of the efficacy has to be conducted in a proper and safe way."	Reuse water -> Monitoring of efficacy of treatments	Reuse water -> Continuous monitoring	Koutsoumanis et al. (2023)
	Operation	"Water quality is critical to prevent microbial and chemical risks in any of the postharvest and processing operations related to fresh and fresh-cut fruits and vegetables. The wash process requires high volumes of water, which are usually reduced by water reuse."	Reuse water -> Reduce water use in operation	Reuse water -> Adapt operations	Gadelha et al. (2019)
		"The proper operation of water disinfection treatment (e.g. application rate, in-use concentration and residual concentration on ffFVHs) as well as of the monitoring of the efficacy has to be conducted in a proper and safe way. As established by FAO and WHO (2019), water quality must be maintained throughout the processing operation and special attention is required for common wash and flume systems and reused water."	Reused water -> Special attention in operation	Reuse water -> Knowledge of personnel	Koutsoumanis et al. (2023)

	Validation	"In the context of process water for ffFVHs, the goal of the validation is obtaining evidence about the reliably achievable microbiological quality of the process water to avoid cross-contamination during the handling and processing operations. Validation procedures allow definition of the appropriate operational conditions associated with the water management strategy (e.g. performance standard of water disinfection and/or replenishment related to certain physico-chemical parameters of the process water) allowing to control the target microorganisms (e.g. generic E. coli as indicator organism)"	Process water -> Validation of microbiological quality	Reuse water -> Need for validation	Koutsoumanis et al. (2023)
	Verification	"Verification is conducted as part of a FSMS, to demonstrate that the applied water management strategies are being applied as required, and the process water reached the required microbiological quality (defined as fit-for-purpose for the intended use) to avoid cross-contamination of the ffFVHs via the water."	Process water -> verification of correct application of strategies	Reuse water -> Verification of strategies	Koutsoumanis et al. (2023)
Water & soil management	Interventions	"To avoid cross-contamination of the product due to the use of contaminated water, water disinfection treatments are needed to eliminate, or reduce to an acceptable level, microorganisms of public health concern but these treatments should not have an adverse effect on the quality and safety of the produce.."	Reuse water -> Disinfection treatments	Reuse water -> Effective intervention technique	Koutsoumanis et al. (2023)
	Monitoring	"A good water management plan implies that any intervention (as a water management strategy) has to be validated, monitored and verified in their operation." "The operational monitoring of the applied water management strategies aims at the follow-up of defined process parameters and conditions. Operational monitoring parameters should be selected from the evaluated factors in the validation study."	Good water management -> Monitoring of defined process parameters	Good water management -> Specific monitoring	Koutsoumanis et al. (2023)
	Operation	"The proper operation of water disinfection treatment (e.g. application rate, in-use concentration and residual concentration on ffFVHs) as well as of the monitoring of the efficacy has to be conducted in a proper and safe way. As established by FAO and WHO (2019), water quality must be maintained throughout the processing operation and special attention is required for common wash and flume systems and reused water."	Reused water -> Special attention in operation	Reuse water -> Knowledge of personnel	Koutsoumanis et al. (2023)

	Validation	"A good water management plan implies that any intervention (as a water management strategy) has to be validated, monitored and verified in their operation. The goal of the validation is obtaining evidence about the achievable microbiological quality of the process water to avoid cross-contamination during the handling and processing operations."	Good water management -> Validation of interventions	Good water management -> Need for validation	Koutsoumanis et al. (2023)
	Verification	"A good water management plan implies that any intervention (as a water management strategy) has to be validated, monitored and verified in their operation. The goal of the validation is obtaining evidence about the achievable microbiological quality of the process water to avoid cross-contamination during the handling and processing operations."	Good water management -> Verification of intervention	Good water management -> Verification of strategies	Koutsoumanis et al. (2023)

Table A9.4 Initial and focused coding of the passages found in literature on the mechanisms at play between subdrivers and FSMS activities, done for the top economic subdriver and the top 3 political subdrivers

Subdriver	FSMS activity	Passage from literature	Initial coding	Focused coding	Reference
Distribution channel	Preventive measures	"Reusable plastic crates (RPCs) are utilized in different steps of the fruit and vegetable supply chain, including harvest, handling, packaging, and transport operations, as well as in the retail sector" "To exploit the potential environmental benefits of RPCs while ensuring food safety, it is necessary to guarantee the hygiene of this type of container."	Crates used in transport to retail -> Hygiene	Transport to distribution -> Hygiene management	Lopez-Galvez et al. (2021)
		"The main reason is that bacterial growth is influenced by the interaction between time and temperature. When the transport time is reduced, the effectiveness of the temperature intervention is discounted accordingly. Considering the apparent high monetary costs and demands on resources, a recommendation is to consider interventions to either reduce transport time through systematic supply chain management or control temperature through wide application of cold chain systems. " "Based on the results, more restrictive hygiene requirements for workers directly contacting fruit is highly recommended, with an emphasis on the processing stage."	Time & temperature of transport influence bacterial growth -> More restrictive hygiene requirements	Transport to distribution -> Hygiene management	Ortuzar et al. (2020)
		"The corresponding higher SPC substantiates the need for improved manufacturing processes and cold chain management along the food distribution network." "While our microbial survey has certain limitations	Disruption of cold chain -> Improved hygiene processes	Cold chain -> Hygiene management	Chau et al. (2017)

		in its sampling design as discussed above, our findings do point to a need for improved manufacturing and retail hygiene processes."			
	Interventions	"The results from this study demonstrate that the continuous use of refrigeration along the food-supply chain has the potential to select for *L. monocytogenes* variants with enhanced cold and heat tolerance, highlighting the impact that microbial intervention strategies can have on the evolution of bacterial strains and likewise, food safety." "mutations remain a large concern for the food industry as arising strains may possess enhanced survival capabilities that render current intervention and safety measures ineffective."	Refrigeration in supply chain -> Render interventions ineffective	Cold chain -> Effectiveness of intervention	Hingston et al. (2019)
		"Along the supply chain, processing operations are more critical steps in controlling final risks compared to cold storage and primary production." "it was assumed that, depending on the supply chain, a product is most likely to be on the shelves of a retailer and sold between two and five days and the duration of keeping a product in the freezer was assumed between 0 and 90 days."	Cold storage in supply chain -> Still need for proper intervention	Cold chain -> Effective intervention technique	Dogan et al. (2019)
	Operation	"Along the supply chain, processing operations are more critical steps in controlling final risks compared to cold storage and primary production." "it was assumed that, depending on the supply chain, a product is most likely to be on the shelves of a retailer and sold between two and five days and the duration of keeping a product in the freezer was assumed between 0 and 90 days."	Cold storage in supply chain -> Pressure on processing operation	Cold chain -> Adapt operations	Dogan et al. (2019)
		"When exporting fruit, it is crucial to control time and temperature factors in the supply chain. Failure to do so can result in the fruit not meeting market requirements, leading to a decline in quality, shelf life and food safety." "By accurately allocating resources during perilous seasons and potentially devising season-specific fruit handling, storage and transport guidelines, stakeholders can optimise operations and mitigate risks, with these findings proffering a crucial comprehension of the seasonal dynamics in fruit damage claims, thereby fortifying the agricultural sector's resilience and enhancing overall food safety.	Cold chain -> Optimize operations	Cold chain -> Ease of operation	Du Plessis et al. (2023)

	Documentation & Record-keeping	"Indicators and sensors, SP components, are used for real-time monitoring of meat quality and subsequently inform the retailers and consumers about the freshness, microbiological, temperature, and shelf life status of the products. Barcodes and radio-frequency identification tags are employed in meat packaging for real-time information about the authenticity, and traceability of the products in the supply chain. Recently, innovations in SP technologies resulted in fast, sensitive, and effective detection, sensing, and record keeping of freshness, microbiological, and shelf life status of meat and meat products."	Real-time information for retailers -> Record-keeping of freshness	Information for retailers -> Documentation for follow-up	Ahmed et al. (2018)
	External food safety performance	"Information including food packing date, batch/lot number, package weight, nutritional information, cooking instructions and the website address of food manufacturer can ben encoded in the barcodes and they are even readable by smartphones; providing great convenience for both retailers and consumers." "Active and intelligent packaging offer great opportunities for enhancing meat safety, quality, and convenience, and consequently decrease the number of retailer and consumer complaints."	Information for retailers -> Less customer complaints	Information for retailers -> Less complaints	Fang et al. (2017)
Good practices & standards	Preventive measures	"It is crucial to adhere to the established standards in international table olive processing norms and respect the defined limits, especially concerning oxidized black olives." "The use of preservatives and heat treatments together with good manufacturing and hygiene practices are useful tools as control measures to reduce alterations in table olives."	Established standards -> Hygiene practices	Standards -> Hygiene management	Sab et al. (2024)
		"This analysis clearly shows that a timewise push to further improve hygiene standards will be needed in various countries for their food businesses to be able to achieve a high level of compliance with the progressively stringent EU Campylobacter process hygiene criterion"	Stringent criteria -> Improve hygiene	Standards -> Hygiene management	Zwietering et al. (2023)
		"The food and beverage industries operate their production units under stringent hygiene standards to verify high-quality products."	Stringent standards -> Hygiene	Standards -> Hygiene management	Achinas et al. (2019)
		"Cheese microbiota largely depends on the initial quality of milk used and on the hygiene procedures followed during manufacturing. The appropriated hygienic standards of the environment, pasteurization and the control of the chilling temperatures are of utmost importance to	Standards -> Hygiene procedures	Standards -> Hygiene management	Costanzo et al. (2018)

		avoid any potential contamination and growth of pathogenic and spoilage microorganisms"			
		"Hygienic production, harvesting and storage techniques have become obligatory standards for many products, including those intended for possible raw consumption such as meat, eggs, fruits, vegetables and nuts."	Obligatory standards -> Hygiene	Standards -> Hygiene management	Berge & Baars (2020)
		"This work demonstrates that global produce safety standards, with a particular emphasis on handwashing, effectively control norovirus contamination and mitigate risks to consumers." "Findings from our study demonstrate the primary importance of hand hygiene in preventing focal contamination with norovirus in important harvesting and packing agricultural settings."	Safety standards -> Importance of hand hygiene	Standards -> Hygiene management	Sobolik et al. (2021)
		"Ice cream is a complex food matrix, and a comprehensive approach to the whole production system is required to ensure high standards of quality and safety." "Appropriate training of the workforce in good hygiene and manufacturing practices is required, as well as ongoing maintenance of the plant and equipment, which should be easily cleaned and sanitized."	Standards of safety -> Good hygiene practices	Standards -> Hygiene management	Nalbone et al. (2022)
		"The legislation of the state of Minas Gerais is what determines the microbiological and physical-chemical parameters and standards of this cheese" "Therefore, in general, in relation to the analysis of coliforms, although the average results for non-conformity were small (Table 2), there was no trend for improvement in the AMC quality over the 11 years of study, which could be achieved by expanding the adoption of good agricultural and handling practices, such as care with animal and handler health, water quality, hygiene of facilities and equipment, amongst others."	Legally defined standards -> Good hygiene of facilities and equipment	Standards -> Hygiene management	Firmo et al. (2023)
	Monitoring	"Furthermore, standards are an important tool to trigger the maturation of the systems as companies that were lacking any pressure to comply to standards operated at a very basic level - with only few activities implemented." "This quantitative exposure ranking demonstrates that also niche products such as basil can have an potential impact on public	Standards -> Priority on monitoring	Standards -> Continuous monitoring	Jacxsens et al. (2017)

		health equal or higher than lettuce, resulting in a priority in monitoring and surveillance"			
		"It is crucial to adhere to the established standards in international table olive processing norms and respect the defined limits, especially concerning oxidized black olives." "In summary, this study provides a snapshot of the quality of table olives available in the outlets surveyed and underscores the importance of strict microbiological control, quality, and appropriate production practices in the table olive industry in Algeria."	Established standards -> Strict microbiological control	Standards -> Improve microbiological analysis	Sab et al. (2024)
		"Extensive review recapitulates overall food-pathogen testing research market trends, as well as commercialization of biosensors for the food safety industry as legislation creates novel standards for microbial monitoring."	Legislation defined standards -> Microbial monitoring	Standards -> Continuous monitoring	Vallinayagam et al. (2022)
		"It is also important to consider that during the coronavirus (SARS-CoV-2) pandemic, new legislation on microbiological standards for food came into force in Brazil, which is of importance to all segments of the food and food service industry. This update of the sanitary legislation has increased the challenge and responsibility of those involved in the food production chain, including microbiological analysis laboratories, in proving the safety of food, as well as the adequacy of production processes."	New microbiological standards -> Challenge for microbiological analysis	Standards -> Improve microbiological analysis	Da Silva et al. (2023)
		"As a result, food authorities are closely monitoring the food industry to ensure that products meet the required standards of quality. " "The scope of the proposed paragraph is to discuss the application and advantages of hyperspectral and multispectral imaging combined with chemometric tools in detecting food adulteration, assessing food composition, monitoring food quality, and classifying different food products."	Required standards of quality -> Monitoring food quality	Standards -> Continuous monitoring	Kharbach et al. (2023)
		"Commercially produced complementary foods (CPCF) were investigated and computed in accordance with the standards." "Thus, regular monitoring of the raw material and processing trends and the inclusion of animal sources in the raw material are suggested for having well-enriched complementary foods"	Accordance to standards -> Regular monitoring	Standards -> Continuous monitoring	Mario et al. (2024)

		Periodic monitoring of produce at various levels of production and sale is required to achieve satisfactory levels of microbial load as specified by Food Safety and Standards Authority of India (FSSAI).	Standards -> Periodic monitoring	Standards -> Continuous monitoring	Saksena et al. (2019)
		"This study recommends conducting regular assessments of cottage industry products, especially in cases where quality control standards are less stringent than those in large-scale doenjang industries, to ensure product safety. Also, it is advisable to carry out these analyses in the very large sample size to establish a strong concluding remark."	Quality control standards -> more samples	Standards -> Improve microbiological analysis	Bahuguna et al. (2023)
	Operation	"Therefore, if pollen is intended for human consumption, appropriate hygiene standards must be applied to all bee pollen production operations."	Standards -> Hygienic working	Standards -> Adapt operations	Fernandez et al. (2023)
		"They establish export protocols and guidelines, including ideal temperature ranges for each perishable product, and ensure exporters adhere to quality standards." "Utilising this knowledge, stakeholders can optimise operations and formulate guidelines tailored to high-risk seasons for fruit handling and transportation."	Quality standards -> Optimize operations	Standards -> Ease of operation	Du Plessis et al. (2023)
		"This work describes μMET, a novel microfluidic device for precise microbial enumeration tests (MET), essential in pharmaceutical, cosmetic, and food industries for ensuring microbiological safety standards." "Notably, bright-field μMET eliminates the need for fluorescent staining, streamlining operations with deep-learning algorithms for bacterial counts."	Microbiological safety standards -> Streamlining operations	Standards -> Ease of operation	Wu et al. (2024)
	Verification	"Extensive review recapitulates overall food-pathogen testing research market trends, as well as commercialization of biosensors for the food safety industry as legislation creates novel standards for microbial monitoring." "The preface of biosensors has assisted food industries for monitoring and verification of raw materials, food processing, and composition of the food and assessment of product freshness."	Legislation defined standards -> Verification	Standards -> Verification of strategies	Vallinayagam et al. (2022)
		"It is also important to consider that during the coronavirus (SARS-CoV-2) pandemic, new legislation on microbiological standards for food came into force in Brazil, which is of importance to all segments of the food and food service industry." "The application of the design thinking	New microbiological standards -> Process verification	Standards -> Verification of strategies	Da Silva et al. (2023)

		method and the use of the online platform establish an appropriate environment for a collective sampling solution for process verification."			
	External food safety performance	"Food manufacturers who hold GFSI scheme certification can demonstrate their compliance with food safety and quality standards more easily and thus protect and improve the reputation and income of their business globally." "Many external food safety and quality audits are now conducted by, or on behalf of, one of the four main Global Food Safety Initiative (GFSI) approved food safety schemes ,these being"	Standard certification -> quality audits	Standard certification -> Additional audits	Smith (2019)
Official controls & communication	Monitoring	"Overall, the majority of the FBOs believed that application of an FSMS helps to overcome official controls, to produce healthy foods, to better manage the production process, and for staff training;" "The cost of FSMS(mainly due to microbiological analysis) and the time it takes were the main reasons for FBO resistance to its application."	Official controls -> Microbiological analysis needed	Official controls -> Improve microbiological analysis	Ceballos et al. (2020)
	External food safety performance	"The main reported purpose of categorising abattoirs is to adapt the frequency of official controls. Major differences in the described categorisation systems were found between countries, particularly in their complexity and the criteria used. The number of included criteria ranged from 1 to 10, the main ones being the outcomes of the CA's official audits"	Different countries of control -> More audits	Different countries of control -> Additional audits	Salines et al. (2023)
Food legislation	Preventive measures	"European food legislation has established microbiological criteria to ensure consumer protection. Salmonella is listed under both process hygiene criteria and food safety criteria."	Food legislation criteria -> Hygiene	Food legislation requirement -> Hygiene management	Bianchi et al. (2023)
	Monitoring	"Because of these well-established food safety risks, food legislation such as that in Europe stipulates that BMS production areas are monitored for faecal contamination and classified accordingly."	Food legislation requirement -> Monitoring	Food legislation requirement -> Continuous monitoring	Walker et al. (2018)