RISK
ON THE MENU

An integrated recipe for
safer food at home.



WIEKE VAN DER VOSSEN-WIJMENGA

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Wieke P. van der Vossen-Wijmenga

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Chapter 1

General introduction

1.1 Food safety

Food safety has been a concern throughout human history. Long before scientific knowledge about microorganisms or chemical contaminants existed, people learned, often through trial and error, that food could cause illness (Smithers, 2024). Visible spoilage, unpleasant odours, or abnormal taste served as early warning signs, and food safety was largely assessed through sensory judgement and experience, a perspective that is echoed in one of the earliest Dutch food safety information materials for consumers (**Figure 1.1**). Today, food-related hazards are no longer identified through everyday experience alone. Harmful bacteria, viruses, parasites, and chemical contaminants cannot be detected by sight, smell, or taste, while their health effects may range from mild gastrointestinal illness to severe acute or chronic disease. As a result, food safety increasingly depends on scientific risk assessment, regulatory control, and informed behaviour rather than on direct sensory cues. Access to sufficient safe and nutritious food is essential for sustaining life and promoting good health. Contaminated food containing harmful bacteria, viruses, parasites, or chemical substances can cause more than 200 diseases, ranging from diarrhoea to cancer (Mead et al., 1999). Common foodborne pathogens include *Salmonella* spp., found in raw meat, eggs, and produce; *Listeria monocytogenes*, which poses a particular risk in ready-to-eat refrigerated foods; *Escherichia coli* O157:H7, known for causing severe illness through contaminated ground beef or leafy greens; and *Campylobacter* spp., often linked to undercooked poultry. Viruses such as norovirus and hepatitis A are also important pathogens, especially in foods handled after cooking or consumed raw, like shellfish or fresh produce. Globally, an estimated 600 million people, nearly 1 in 10, fall ill from unsafe food each year, resulting in 420,000 deaths and the loss of 33 million healthy life years (DALYs) (WHO, 2022). Food safety, nutrition, and food security are deeply interconnected. Unsafe food poses significant health risks, particularly for infants, young children, pregnant women, the elderly, and individuals with weakened immune systems. But this does not mean others are exempt of any risk. Beyond its impact on health, a safe food supply also strengthens national economies and supports trade by building trust between trading partners (WHO, 2022). Ensuring food safety requires strong engagement from governments, food producers, and consumers. It is a complex process that begins on the farm and extends through every stage of the food chain until it reaches the consumer. Different stakeholders work together to maintain a safe food supply and protect public health. Governments develop policies and enforce regulations, conduct inspections, and educate the public. Scientists research food safety hazards and risks and develop detection and control methods. The food industry adheres to standards and regulations to ensure safe processing, packaging, and labelling, supported by safety-by-design



BESTRIJD HET BEDERF

mijten vocht schimmel vliegen

motten schietmotten

meelwormen muizen

ratten torren kakkerlakken muizen

Door het ondoelmatig bewaren van levensmiddelen kan veel van hetgeen waarde heeft verloren gaan. In dezen tijd nu de grondstoffen schaarsch zijn, is het van het grootste belang, dat U Uw levensmiddelen, als U er nog een kleine voorraad van hebt, op de juiste wijze bewaart.

Het VOORLICHTINGSBUREAU van den VOEDINGSRAAD raadt U aan in het algemeen de volgende regels in acht te nemen:

1 Wanneer U nog wat voorraad hebt, gebruik dan geregeld van de oudste voorraad en voeg de nieuw gekochte waar toe.

1

2 Zorg, dat de bewaarplaats **droog koel** en **donker** is en goed geventileerd kan worden (De kelder en de provisiekast kunnen aan deze eischen voldoen, wanneer zij doelmatig geventileerd worden. Ongeschikte bewaarplaatsen zijn in het algemeen de keuken, een warme kamerkast, een kast tegen een vochtige buitenmuur).

3 Kies met overleg de bewaarplaats voor de verschillende artikelen (bijv. de inmaak in den kelder, bussen en verpakte levensmiddelen in een droge kast, gruttenswaren op zolder, mits U daar geen last hebt van muizen).

4 Pas een doelmatige verpakking toe bijv. grutterswaren in sloopjes, gedroogde groenten in blik, *enz.*

5 Plaats geen sterk riekende waar bij levensmiddelen, die gemakkelijk geur overnemen.

6 Plaats de waren zooveel mogelijk soort bij soort bijeen, goed gerangschikt en overzichtelijk.

7 Schrijf op alle artikelen den datum van aankoop.

8 Controleer de levensmiddelen regelmatig. Keur de waren

door **kijken** door **ruiken** door **proeven**

9 Verwijder wat bedorven is en regel het verbruik.
Pas op voor muizen en ongedierte, deze kunnen veel schade berokkenen.

10 Bedenk voor alles, dat de zuiverheid, vochtigheid en de temperatuur der lucht, de kwaliteit en de leeftijd van het product grooten invloed op de duurzaamheid uitoefenen

2

Figure 1.1. Brochure published in 1942 by the Information Office of the Nutrition Council, later the Netherlands Nutrition Centre (Voedingscentrum).

approaches, dedicated management, and targeted food safety policies. And consumers ensure food safety by following proper food handling practices. Yet, despite these joint efforts, the system does not always function flawlessly, as evidenced by the continued high number of foodborne infections (EC, 2025). Although the cause of foodborne incidents is not always known, experts agree that many foodborne infections occur in the domestic kitchen (De Jong et al., 2008, Van Asselt et al., 2009). In about 40 % of foodborne infection clusters reported to the Centre for Infectious Disease Control (CIb) in the Netherlands, the food preparation site was stated to be 'home' (Friesema et al., 2011). Also, the European Food Safety Authority (EFSA) and European Centre for Disease Preventions and Control (ECDC) stated that many of the strong-evidence outbreaks took place in a domestic setting (40.5 %) (EFSA and ECDC, 2019). To help reduce foodborne infections, effective food safety measures are required across the entire food chain, with governments and the food industry managing food safety risks, and consumers being mindful of food safety at every step, from purchasing and storing to preparing and cooking food.

1.2 Risk analysis framework

A structured and science-based approach to assess risks is essential for the effective coordination of food safety interventions and for supporting informed decision-making. One widely adopted framework that guides this process is risk analysis, which helps governments and organizations assess, manage, and communicate food safety risks in a transparent and consistent way. Risk analysis is defined by Codex Alimentarius Commission in the procedural manual as "a process consisting of three components: risk assessment, risk management and risk communication" (FAO and WHO, 2025).

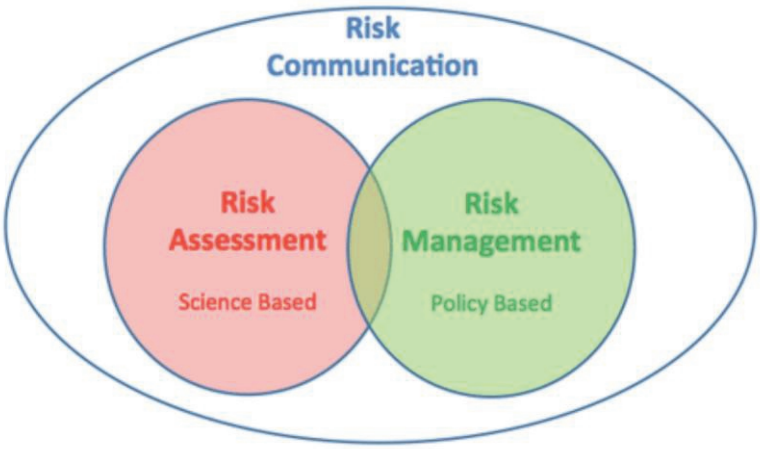


Figure 1.2. FAO/WHO risk analysis framework as described in FAO and WHO (2006) and published on the website www.fao.org.

- Risk Assessment: A scientifically based process consisting of the following steps: (i) hazard identification, (ii) exposure assessment, (iii) hazard characterization, and (iv) risk characterization.
- Risk Management: The process, distinct from risk assessment, of weighing policy alternatives, in consultation with all interested parties, considering risk assessment and other factors relevant for the health protection of consumers and for the promotion of fair-trade practices, and, if needed, selecting appropriate prevention and control options.
- Risk Communication: The interactive exchange of information and opinions throughout the risk analysis process concerning risk, risk-related factors and risk perceptions, among risk assessors, risk managers, consumers, industry, the academic community and other interested parties, including the explanation of risk assessment findings and the basis of risk management decisions.

The three components form an integrated and interdependent foundation of the risk analysis process (**Figure 1.2**). The success of risk analysis depends on how well the three parts work together. When risk managers connect risk assessment, risk management, and risk communication, the process becomes clearer, more based on science, and more effective (FAO and WHO, 2006).

1.3 Consumer perspective

While the risk analysis framework provides a scientific foundation for managing food safety, it cannot function effectively without understanding how consumers perceive risks. Scientific assessments characterize food safety risks, but it is public perception that often drives behaviour, shapes acceptance of policies, and determines the impact of communication strategies (WHO, 2022). For consumers, food safety is above all a matter of trust; trust that the food they eat is safe for themselves and their families. Whereas experts focus on pathogens and chemical contaminants, consumers interpret risk through the lens of personal experience, emotion, and intuition. Their perceptions are strongly shaped by factors such as media coverage (an example of a social media post is shown in **Figure 1.3**), familiarity, and individual beliefs (Abe et al., 2020; FSA, 2022a; NVWA, 2023a). Understanding how these perceptions translate into real-life food-handling behaviour is crucial for designing effective interventions.

1.3.1 Risk perception

Risk perception forms the basis of attitudes and behaviours. Effective communication must therefore address the psychological and social factors shaping these perceptions (WHO and FAO, 2016). A meta-analysis by Sheeran et al. (2014) found that increasing perceived risk or threat can significantly enhance behavioural intentions and lead to safer practices. However, cognitive biases such as optimistic bias, believing that negative events are less likely to happen to oneself, can distort food safety perceptions and encourage risky behaviour (Bearth et al., 2014; Da Cunha et al., 2015; Evans et al., 2020; Myintzaw et al., 2020; Sterniša et al., 2018). Consumers often perceive risks differently than experts. For example, chemical hazards are frequently seen as more dangerous than biological ones, even though biological hazards contribute more to the burden of disease (Kher et al., 2013; Van Kreijl et al., 2006). Risks perceived as involuntary or catastrophic, such as Genetically Modified Organisms (GMOs) or pesticide residues, are often overestimated, while more common risks like poor hygiene tend to be underestimated (Slovic, 1987; Frewer et al., 2007). Demographic factors also shape risk perception. Older adults and women tend to perceive risks higher, whereas individuals with higher education levels generally report lower perceived risk (Nardi et al., 2020; Zingg et al., 2013). Interestingly, scientific knowledge alone has limited influence; emotional and intuitive responses often outweigh rational



Figure 1.3. Fictional example of a typical online news headline about food contamination, inspired by common media reporting styles.

understanding (Rembischevski and Caldas, 2020). Cultural context plays a significant role as well. Van Dijk et al. (2008) found that communicating uncertainty increased trust in Germany but reduced it in the United Kingdom and Norway. This suggests that national or regional strategies may be more effective than one-size-fits-all approaches (Cope et al., 2010). Nevertheless, increasing cultural diversity within countries indicates that risk perceptions may also differ substantially between communities living in the same region. Therefore, understanding cultural heterogeneity within populations may become increasingly important for effective risk communication. Trust in institutions and information sources is critical. Food safety incidents, such as bovine spongiform encephalopathy (BSE), dioxin contamination, or the horsemeat scandal, can erode public trust in regulatory systems (Barnett and Breakwell, 2003; Brooks et al., 2017). Transparent, culturally sensitive communication is essential to maintain this trust. Finally, comparing consumer and expert perceptions reveals important gaps. Kampelmacher (1985) already pointed out that public concern often focuses on the presence of hazards, whereas experts assess actual health risks based on exposure and probability. Recent studies confirm that these perceptual differences persist. Understanding

these gaps is vital for designing effective communication and risk management strategies.

1.3.2 Risk behaviour

While risk perception shapes how consumers interpret food safety threats, it is their behaviour that ultimately determines exposure to those risks in everyday settings. Recognising this, the World Health Organization (WHO) developed the 'Five Keys to Safer Food', a globally applicable set of guidelines designed to promote safe food-handling practices at consumer level (WHO, 2006). The five principles of keeping clean, separating raw and cooked food, cooking thoroughly, keeping food at safe temperatures, and using safe water and raw materials offer a framework for reducing the risk of foodborne illness caused by bacteria, viruses, and parasites. These principles are visually summarised in **Figure 1.4**. The relevance of these principles becomes clear when examining specific pathogens. For instance, *L. monocytogenes*, known for its ability to grow at refrigeration temperatures, highlights the importance of keeping food cold. Refrigeration below 5 °C and avoiding extended storage of ready-to-eat foods are essential to prevent its proliferation. Similarly, *Campylobacter* spp., a leading cause of bacterial gastroenteritis, illustrates the need for multiple keys: keep clean, separate raw and cooked, and cook thoroughly. Found frequently in raw poultry, *Campylobacter* spp. can easily spread through cross-contamination or survive inadequate cooking, making hygiene and thorough heat treatment critical. However, safe food-handling behaviour is shaped by more than awareness of guidelines. It is influenced by a complex interplay of knowledge, attitudes, social norms, habits, and practical constraints (Ajzen, 1991). Even when consumers are informed about food safety risks, this does not always translate into consistent safe practices (Evans and Redmond, 2019). Time pressure, convenience, and routine often lead to lapses such as insufficient cooking, improper storage, or neglecting handwashing (Redmond and Griffith, 2003). Cultural traditions also play a role. Research by Møretrø et al. (2021) found significant differences in food-handling practices across countries, suggesting that interventions should account for cultural influences on food-related behaviour. However, in increasingly globalised and multicultural societies, cultural diversity is not limited to differences between countries. Many regions now consist of heterogeneous populations with diverse cultural backgrounds, traditions, and food practices. As a result, effective food safety interventions may need to consider variation both between and within countries, rather than relying solely on national-level approaches. Changing consumer behaviour is therefore not simply a matter of providing information; it requires strategies that engage emotional, social and contextual factors. Behavioural interventions such as nudging, visual cues, and interactive education have shown promise in promoting safer practices (Jevšnik, 2021). Ultimately,

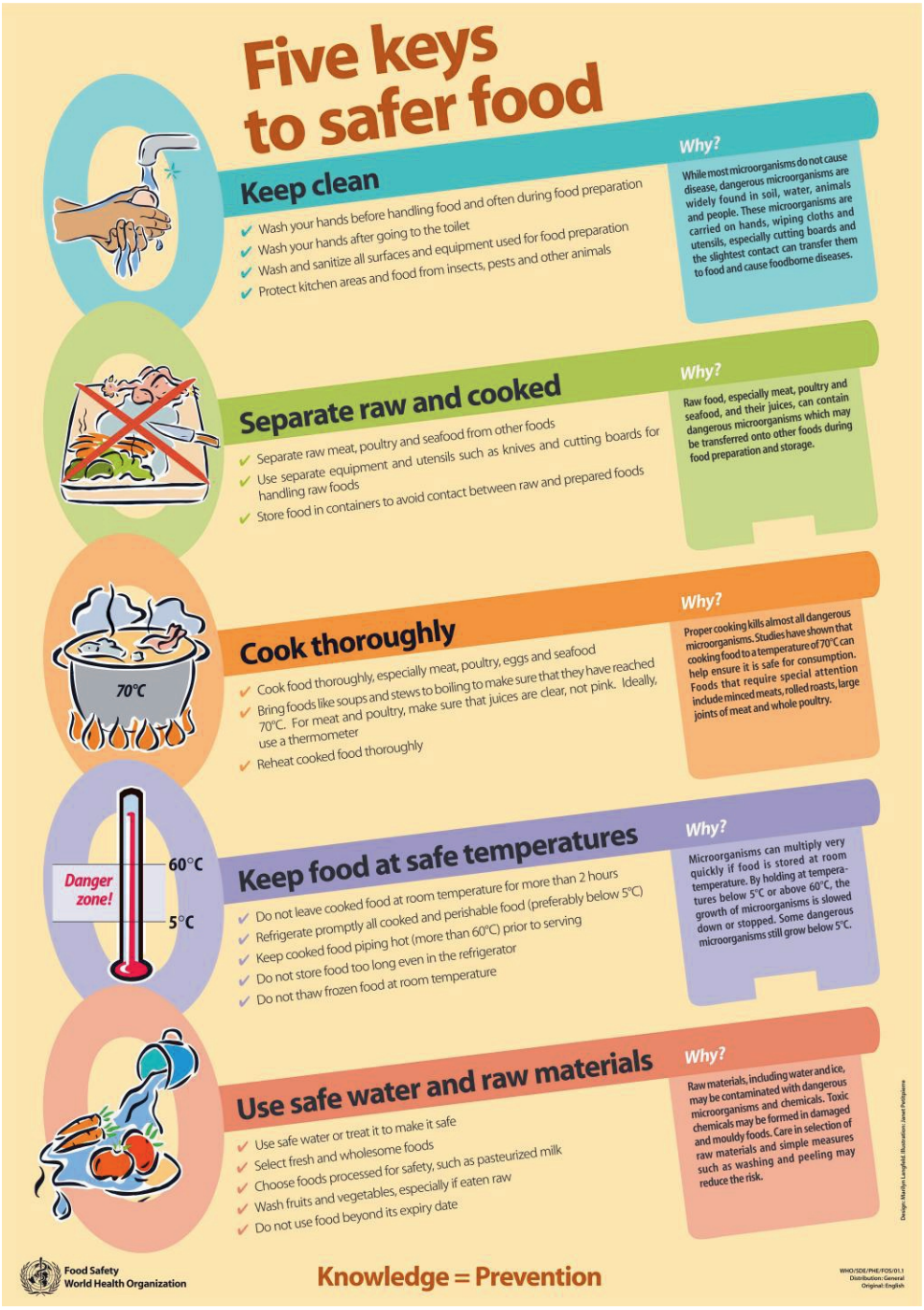


Figure 1.4. Five keys to safer food (WHO, 2006).

improving food safety at the consumer level demands a holistic approach, one that combines clear communication, behavioural insight, and cultural sensitivity. Only by addressing both perception and behaviour can food safety strategies achieve meaningful and lasting impact.

1.4 Expert perspective

Science plays a crucial role in identifying hazards within the food chain and assessing the associated risks and supporting risk managers in making informed decisions. The expert perspective on food safety is grounded in the objective evaluation of hazards, exposure, and the likelihood and severity of adverse health effects. This approach relies on data, models, and evidence-based methods, drawing from disciplines such as toxicology, microbiology, and epidemiology. It is inherently quantitative and seeks to inform risk managers with scientific evidence rather than value judgments.

1.4.1 Risk assessment

Quantitative microbiological risk assessment (QMRA) is a modelling approach used to estimate the risk of illness when a population is exposed to a pathogen. The process of QMRA involves four steps: i) hazard identification, ii) exposure assessment, iii) hazard characterization and iv) risk characterization (EC, 1997).

(i) Hazard identification

The hazard identification step is used to identify the pathogens and transmission routes that are relevant to address particular problem formulations or scenarios and modelling goals. It is the step that asks:

"What microbial hazard are we dealing with, and why does it matter?".

During this step, data from epidemiological studies, outbreak reports, and foodborne pathogen surveillance are often reviewed to support the selection of pathogens of concern (Hamilton et al., 2024). Comparative assessments of disease burden provide insight into the relative public health impact of different foodborne pathogens, both in terms of total annual burden and burden per case. **Figure 1.5** presents a visualization, constructed for this thesis, of the disease burden of 14 food-related pathogens in the Netherlands based on data reported by Benincà et al. (2024). It shows both the annual disease burden and the disease burden per case expressed in Disability-Adjusted Life Years (DALYs), displayed on both a linear and a logarithmic scale. These comparisons highlight marked differences between pathogens, particularly between those characterised by low incidence but high severity and those with high incidence but generally milder disease outcomes. In the case of *L. monocytogenes*, this pathogen is recognized as a significant hazard due to its ability to cause severe illness, particularly in vulnerable populations

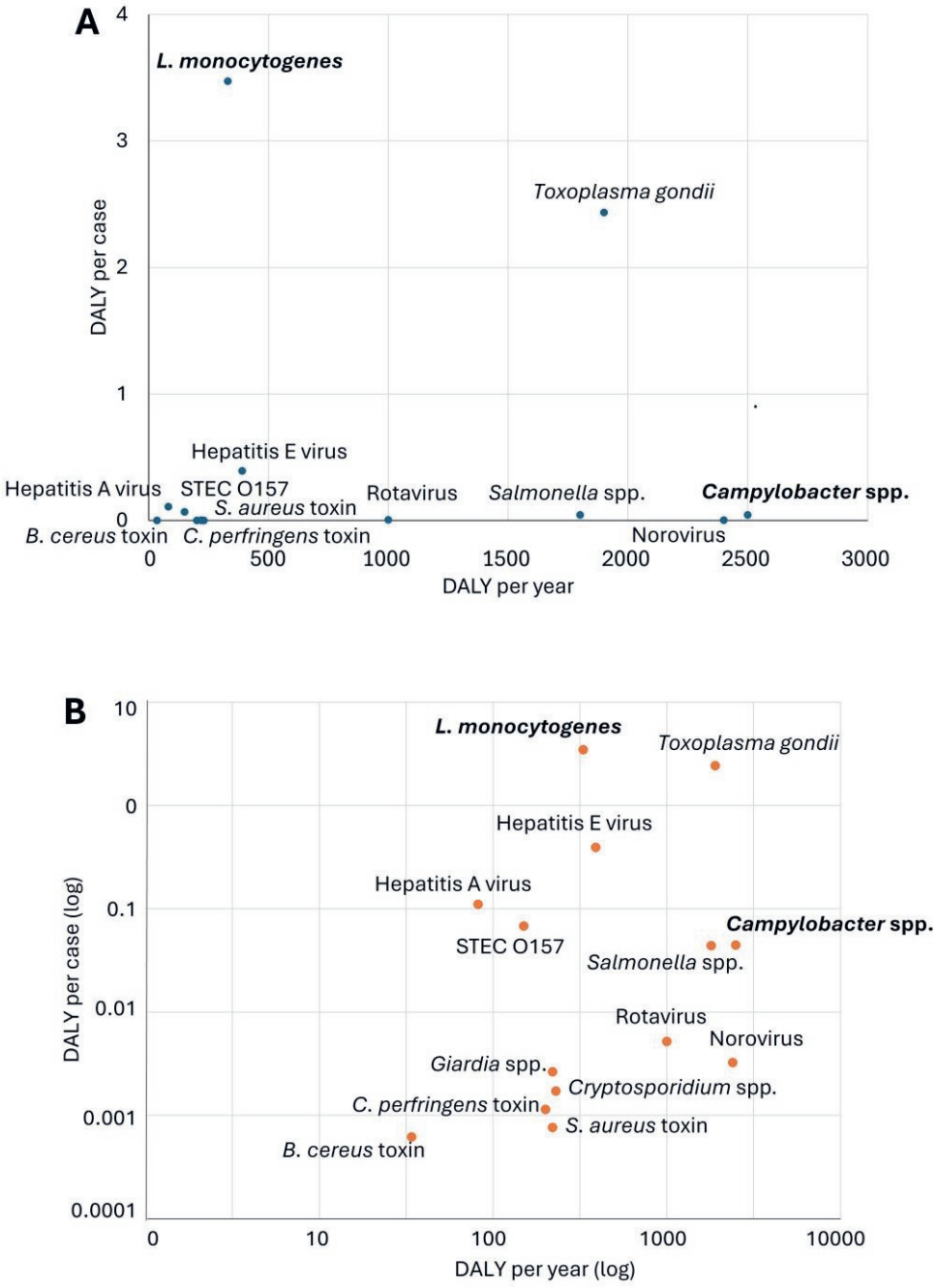


Figure 1.5. Disease burden of 14 food-related pathogens per year and per case in DALY, shown on both a linear [A] and a logarithmic scale [B]. Figure constructed by the author based on data from Benincà et al. (2024).

such as pregnant women, the elderly, and immunocompromised individuals, resulting in a high disease burden per case (Benincà et al., 2024; Buchanan et al., 2017). Although infections caused by *L. monocytogenes* are relatively rare compared to other foodborne pathogens, the consequences can be extremely serious, including septicaemia, meningitis, and stillbirth. This combination of low incidence but high severity makes *L. monocytogenes* a pathogen of particular concern in food safety risk assessments (EFSA BIOHAZ Panel, 2018). *Campylobacter* spp. are the most common cause of bacterial gastro-enteritis in humans and are associated with a high disease burden (Benincà et al., 2024; EFSA and ECDC, 2019). Infection is generally manifested as self-limiting diarrhoea that lasts three to five days, but may require hospital care in about 5–10 % of cases. Acute infection may lead to rare late-onset complications such as reactive arthritis or the Guillain-Barré syndrome and acute neuromuscular disease (Facciolà et al., 2017; Habib et al., 2020; ECDC, 2024). Extensive research in some countries identified raw chicken meat as a significant source of *Campylobacter* spp. infection (Havelaar et al., 2007; Nauta et al., 2009; Mughini Gras et al., 2012).

(ii) Exposure assessment

The aim of exposure assessment is to quantify the behaviour, prevalence, and final dose of pathogens along the food chain up to the point of consumption. It is the step that asks:

"How much of the pathogen do people actually ingest, and how often?"

In the exposure assessment step of the QMRA, the microbial kinetics of the identified hazards are quantitatively described for all subsequent steps of the product's value chain, using mathematical models. However, this system is inherently stochastic. For that reason, it is essential to include uncertainty and variability in the analysis (EFSA, 2018). In this context, variability refers to sources of variation that are inherent to the system (e.g., biological differences between microbial cells or human beings), whereas uncertainty is related to lack of or imprecise knowledge. This can be accomplished by a stochastic modelling approach where the relevant kinetic parameters are described using probability distributions (Garre et al., 2020; Nauta, 2000).

Importantly, the consumer phase plays a critical role in reducing, and sometimes increasing, the final dose of foodborne pathogens. For example, proper refrigeration is essential to limit the growth of *L. monocytogenes*, while thorough cooking and preventing cross-contamination are key to controlling *Campylobacter* spp. at home. QMRAs that incorporate the consumer phase have shown that practices such as refrigeration, cross-contamination and undercooking are important parameters to control (EFSA, 2018; FAO and WHO, 2009), as they significantly influence the final dose at the point of consumption. However, modelling consumer behaviour remains complex

due to the influence of both known and unknown factors, and it carries the potential to either overestimate or underestimate its true impact (Iulietto and Evers, 2023; Nauta, 2002; Pérez-Rodríguez et al., 2008). Beyond directly observable food-handling practices, risk perception is increasingly recognised as an important determinant of consumer behaviour and exposure. In QMRA, consumer behaviour is usually incorporated through measurable handling parameters, such as storage time, refrigerator temperature, cooking practices, and cross-contamination events. Risk perception itself is less often modelled quantitatively, but is commonly studied through behavioural frameworks such as the Health Belief Model and the Theory of Planned Behaviour. These approaches show that safe food-handling behaviour is shaped not only by knowledge, but also by perceived risk, habits, social influences, practical constraints, and trust in information sources. Integrating such behavioural insights into QMRA, where feasible through assumptions about quantitative behavioural parameters, can help define more realistic exposure scenarios and identify key targets for intervention (Da Cunha, 2025; Young and Waddell, 2016; Young et al., 2017).

(iii) Hazard characterization

Hazard characterization establishes the relationship between the ingested dose of a pathogen and the probability of illness. The dose-response relationship describes how the likelihood of illness changes with different exposure levels, taking into account factors such as host susceptibility and pathogen characteristics. It is the step that asks:

“How likely is someone to get sick if they’re exposed?”

Different models can be used depending on the pathogen and available data, but the choice of the model can have a significant impact on the final outcome (Buchanan et al., 2000).

(iv) Risk characterization

Risk characterization is the fourth and final step in QMRA. It integrates data from the previous steps, hazard characterization, and exposure assessment, to estimate the likelihood and severity of adverse health effects for the identified hazard. It is the final step that asks:

“What is the risk to human health, and how certain are we about it?”

To effectively translate QMRA results into actionable decisions, it is crucial to present the outcomes in a relevant and understandable manner for various stakeholders. One common way of communicating a risk is by expressing the probability of illness from consuming a food serving contaminated with a specific pathogen. This is usually represented as a distribution of the probability of illness, expressed as the risk per serving. This risk per serving can have large variability and the outcome can be low or extremely low. With

very large numbers of servings, even these extremely low risks per serving can result in a considerable number of illness cases.

In recent years, the field of risk-based modelling of microbial behaviour has advanced rapidly within the context of food safety (Hamilton et al., 2024). Enhancing QMRA through stronger expertise, interdisciplinary collaboration, and better links to policy and public health can play a vital role in preventing disease and increasing resilience.

1.5 Policy and Risk management perspective

The policy perspective in food safety focuses on managing risks based on the outcomes of scientific risk assessments, while also considering social, economic, ethical, and political factors. It is the role of risk managers, typically government authorities, to make informed decisions that protect public health in a proportionate and practical way. This includes setting standards, implementing control measures, and balancing competing interests such as consumer concerns, trade implications, and the needs of vulnerable populations. Unlike the purely scientific perspective, the policy perspective is decision-oriented and integrates broader societal values into the risk analysis process (CAC, 2007a). In this context, structured decision-support tools such as Multi-Criteria Decision Analysis (MCDA) can help risk managers evaluate and compare risk management options in a transparent way. MCDA allows scientific risk estimates to be considered alongside other relevant criteria, such as feasibility, costs, consumer perception, behavioural impact, and societal values. This is particularly relevant when interventions depend partly on consumer behaviour, because technically effective measures may not achieve their intended public health impact if they are poorly understood, distrusted, or difficult to implement in everyday life. In this way, MCDA can complement QMRA by supporting risk management decisions that account not only for estimated health risks, but also for consumer perceptions and likely behavioural responses (Ali et al., 2022; FAO, 2017). International organisations, such as WHO, FAO and EFSA, emphasize the need to translate QMRA outcomes into actionable public health insights (EFSA, 2021; WHO and FAO, 2016). They stress the importance of presenting risk information in a clear, understandable, and user-friendly manner, tailored to the target audience. However, in many risk assessments, outcomes are expressed as risk per serving; this metric is often difficult to interpret and poorly understood by non-expert audiences, limiting its usefulness for risk communication and policy decision-making. For this reason, number of illness cases or disease burden metrics such as Disability-Adjusted Life Years (DALYs), are increasingly used to support the prioritisation of interventions.

1.6 Risk communication

Risk communication is a critical component of the risk analysis framework and plays a central role in ensuring that the outcomes of QMRA are effectively translated into public understanding and action. Effective risk communication must be transparent, timely, and tailored to the needs and values of different audiences. Scientific uncertainty, for example, should not be hidden but clearly explained, as transparency can enhance credibility, though its impact may vary across cultural contexts (Van Dijk et al., 2008). Communication strategies should also consider the emotional and intuitive ways in which consumers perceive food risks, as discussed in section 1.2.1. Simply presenting technical data is often insufficient; messages must be framed in a way that resonates with the public's concerns, experiences, and level of scientific literacy.

In the context of microbial food safety, communication tools must be both informative and actionable. One practical example is the use of hygiene warning labels on food packaging, which is mandatory on the retail packages of raw poultry in the Netherlands since 2001 (Warenwet, 2023). This label aims to reduce the risk of foodborne illnesses by providing safe food-handling instructions, encouraging consumers to store, handle and prepare raw poultry safely. These labels can serve as direct, point-of-use interventions that reinforce key food safety behaviours at the moment of decision-making.

1.7 Aim and outline of this thesis

Human and microbiological behaviour interact in complex ways, and understanding this interaction is crucial for reducing the disease burden of foodborne infections. While there is considerable scientific literature on various aspects of food safety in the domestic kitchen, gaps remain, particularly in how behavioural and technical factors are linked and translated into effective interventions.

This thesis addresses these gaps by combining insights from consumer behaviour, microbiological risk assessment, disease burden, risk perception, and risk communication. The central aim is to explore the role of consumers in ensuring microbiological food safety and to generate evidence that supports the design of more targeted, practical, and effective public health strategies. To achieve this, the research adopts an interdisciplinary approach that integrates behavioural studies with quantitative microbiological risk assessment (QMRA).

Food-related risks are analysed from four key perspectives: risk perception, risk behaviour, risk assessment, and risk communication (see **Figure 1.6**).

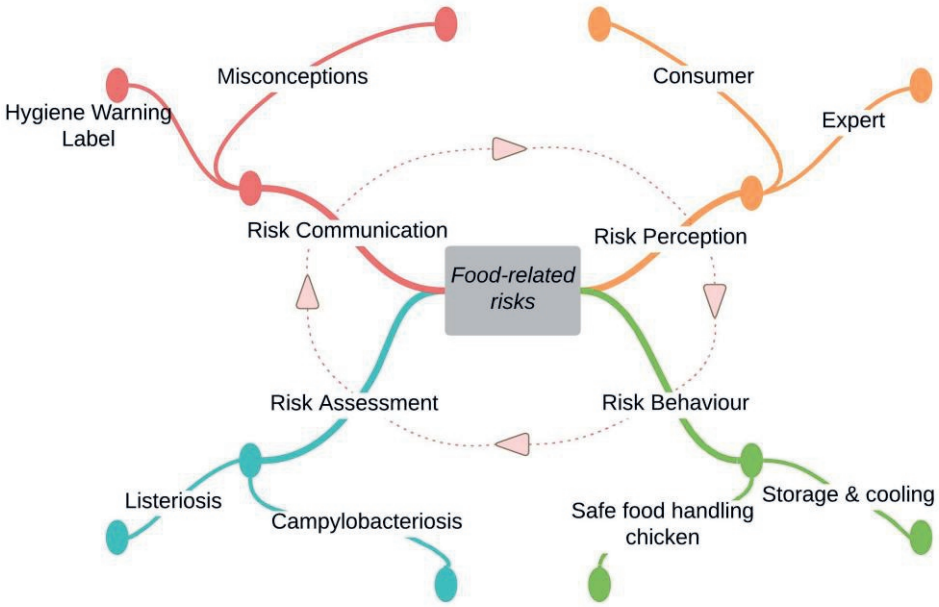


Figure 1.6. Conceptual overview of the four key perspectives on food-related risks addressed in this thesis.

These four perspectives form the conceptual framework that guides the structure and focus of this thesis. Each perspective highlights a different but complementary aspect of how food safety risks are understood, managed, and communicated.

- Risk perception is examined by comparing how consumers and experts assess food-related risks, and how these perceptions influence decisions and behaviours (**Chapters 2 and 5**). Consumer surveys from the Netherlands are used to explore changes in familiarity and concern over time.
- Risk behaviour is studied through surveys and experiments on food storage, cooling, and the handling of raw chicken in domestic kitchens (**Chapters 3 and 4**), offering insight into real-world practices that influence microbial risks.
- Risk assessment is conducted using QMRA models for *L. monocytogenes* in cooked ham and *Campylobacter* spp. in raw chicken. These models quantify how specific consumer practices affect health risks and help identify critical points for intervention (**Chapters 3 and 4**).
- Risk communication is addressed in **Chapter 5** by evaluating the effectiveness of a revised hygiene warning label on poultry packaging and its impact on consumers' food-handling practices, while also considering the role of consumer misconceptions that may hinder effective risk communication.

Each chapter addresses a key element of the integrated framework, showing how behavioural data and microbiological models can reinforce one another. Together, these chapters demonstrate that integrating behavioural science with QMRA strengthens both the scientific basis and practical applicability of food safety strategies. This holistic perspective offers a more complete understanding of consumer behaviour and its impact on foodborne risks. Ultimately, the thesis aims to support both consumers and risk managers in making better-informed decisions, contributing to the prevention of foodborne illness and the promotion of safer food practices.

Chapter 2

Perception of food-related risks: Difference between consumers and experts and changes over time

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Abstract

Understanding the consumers' perception of food-related risks is important in health and risk communication. Therefore, two surveys were conducted among consumers (n = 2005 in 2009 and n = 1014 in 2018) and experts (n = 62 in 2009 and n = 65 in 2018) in the Netherlands to evaluate their familiarity with and perception of food-related risks related to health, food safety and new technologies. In both surveys (2009 and 2018), experts scored unbalanced diet as highest risk followed by food poisoning, and chemicals formed during preparation. The consumers' risk scoring changed over the years and came more in line with the experts' scoring. Like the experts, consumers scored unbalanced diet as highest food risk in 2018, in contrast with 2009 when environmental contaminants were scored as the highest food risk by the consumers. Consumers perceived chemical risks and risks associated with new technologies significantly higher than experts in both years. Socio-demographic characteristics, like age and gender affected the risk scoring, because older consumers perceived risks higher than younger consumers and women higher than men. Consumers familiarity with the various food risks differed largely, with highest familiarity with the risks food poisoning and unbalanced diet. A shift towards higher risk perception and awareness of the risk of unbalanced diet by consumers is an important factor in fighting food-related diseases. This study provides insight into consumers' perception of food-related risks, which besides technical-scientific information, is essential to design a clear and targeted health- and risk communication strategy.

2.1 Introduction

How people perceive risks serves as the basis of their attitudes, intentions, and risk behaviours. Therefore, it is important for health- and risk communication to address the factors that influence people's perceptions (WHO and FAO, 2016). A quantitative synthesis of the literature demonstrated that when interventions successfully increased the perceptions of risk (or feelings of threat), behavioural intentions increased and health behaviour changed (Sheeran et al., 2014). Perception of risk also influences attitudes related to microbiological risks and food handling practices like handwashing and avoiding cross-contamination in the kitchen. Many studies demonstrated that optimistic bias, a cognitive bias that causes people to believe that they are less likely to experience a negative event than others, may distort food-safety risk perceptions, thereby encouraging risky food behaviours (Da Cunha et al., 2015; De Andrade et al., 2019; Evans et al., 2020; Rodrigues et al., 2020; Zanetta et al., 2022). In addition, risk perception studies are important for the understanding of public attitudes towards different technologies used in agriculture and food manufacturing, such as genetic modification or food irradiation (Frewer and Miles, 2001). The behaviour of consumers in relation to food safety and health can only be influenced by effective communication if there is a systematic understanding of how consumers perceive risks and benefits associated with different food (Frewer et al., 2007; Van Kreijl et al., 2006).

Consumers can respond very differently to various food safety issues compared to experts. For example, experts often wonder why consumers accept relatively high risks from unhealthy food choices, while at the same time they do not tolerate risks that experts may find relatively low, such as genetically modified organisms (GMO), nanotechnology, residues of pesticides or additives (Flynn et al., 1993; Frewer et al., 2007; Hartmann et al., 2018a; Rembischevski and Caldas, 2020; Savadori et al., 2004; Siegrist et al., 2007). Apparently, expert- and technical-scientific risk estimates do not necessarily match with how the risk is perceived by consumers. Technical-scientific risk estimates are often expressed in Disability Adjusted Life Years (DALY), where a DALY is a quantitative measure, which combines death and illness using a disability weighing factor for the seriousness of the disease. Research conducted by Slovic (1987) demonstrated that risks that are perceived as involuntary or that may have potentially catastrophic consequences are seen as a higher risk and have more impact on the public response than technical-scientific risk estimates. Hence, consumers are inclined to overestimate those risks with a low probability, but with very severe effects (Slovic, 1987; Van Kreijl et al., 2006). A large study of Kher et al. (2013) with consumer focus groups in Brazil, Poland, Ireland, the Netherlands, and France found that, in general, chemical hazards were perceived as of greater concern than biological hazards, which was opposite to the burden of disease expressed in DALYs (Van Kreijl et al., 2006). In fact, consumers associate chemical hazards strongly with severe consequences, long-term effects, and lack of personal control to prevent them (Kher et al., 2013).

Also, socio-demographic characteristics can influence risk perception. Nardi et al. (2020) investigated in a meta-analytic review the key drivers of food safety risk perception and the impact on consumer choices and their willingness to buy. The included studies revealed that age increased risk perception, meaning that the older people get, the higher they perceive the risk regarding food safety. With respect to gender, many studies concluded that women perceived risks higher than men (Nardi et al., 2020; Zingg et al., 2013). For education level a negative association with food safety risk perception was found, meaning that the higher people are educated, the lower they perceive risks regarding food safety. Rembischevski and Caldas (2020) found that the level of scientific knowledge about the risks usually has little impact on the risk perception. They concluded that the emotional- and intuitive sides of individuals more strongly contribute to the perception of food risks than the rational side where decisions are based on technical-scientific knowledge.

Differences in conception or misconceptions can also differ between cultures. Van Dijk et al. (2008) highlighted differences in consumer perceptions between four European countries (Germany, Greece, United Kingdom (UK) and Norway) and the importance of cultural variation on the impact of risk communication. For example, while communication of uncertainty resulted in more confidence in the expertise of food risk managers in Germany, this resulted in less confidence in the UK and Norway (Van Dijk et al., 2008). Furthermore, cross-cultural differences in consumer perception and information preferences suggested that a national or regional strategy for food risk communication may be more effective than one applied at a pan-European level (Cope et al., 2010; Frewer and Miles, 2001).

Trust in information sources influences the way risk information affects risk perceptions (Frewer and Miles, 2001; Siegrist et al., 2007) and food safety incidents can result in a decline in public trust in food safety regulations and management (Cope et al., 2010). Examples of such incidents include bovine spongiform encephalopathy (BSE) (Barnett and Breakwell, 2003), dioxins (Verbeke, 2001), and the horsemeat scandal in 2013, where horsemeat was sold as beef (Brooks et al., 2017). To keep public trust, the government plays an important role, not only by implementing an effective food safety policy, but also by providing reliable information to consumers (Nardi et al., 2020). Altogether, the knowledge of risk perception is important for the design of effective governmental risk management and communication strategies (Rembischevski and Caldas, 2020).

A method to study consumers' perception is to compare the consumer perception with the perception of experts. Already in 1985, Kampelmacher discussed the difference in perception between consumers and experts related to five food-related risks, namely unbalanced diet, food poisoning, naturally occurring toxins in food, environmental problems and additives or contaminants in food (Kampelmacher, 1985). He gave an overview of 'impressions and expressions' of consumers and experts in the Netherlands that he collected during his working

period as a professor, and the ranking of food-related risks by consumers and experts was based on qualitative experience research only (Kampelmacher, 1985). Because there was no quantitative based evaluation of the disparity in consumers'- and experts' risk perception in the Netherlands, we decided to investigate this. Knowing the difference in perception between consumers and experts can be helpful in designing clear and transparent risk communication strategies (Rembischevski and Caldas, 2020). Therefore, in this study we conducted two surveys to obtain a quantitative insight into the difference in risk perception between consumers and experts. To investigate if the risk perception of consumers changed over time, the levels of risk perception in 2009 and in 2018 were assessed. Furthermore, socio-demographic analyses were done to examine possible differences between age, gender, and education level. These quantitative insights are an important basis for further research to explore the underlying mechanism through which risk perception is formed and affects subsequent behaviour.

2.2 Materials and methods

2.2.1 Study design

To evaluate consumers' risk perception, a list of eight potential food-related risks was developed based on the risks as mentioned by Kampelmacher (1985) and a literature review (Frewer and Miles, 2001; Van Kreijl et al., 2006). Chemical and microbiological risks as well as risks associated with new technologies and the risk of an unbalanced diet were included (**Table 2.1**). The selected eight food risks for the survey in 2009 included risks that can and cannot be influenced by the consumers' handling at home (e.g., food poisoning can be influenced by consumers' handling at home, unlike residues of pesticides which cannot be influenced by consumers' handling at home). The wording in Dutch of the food risks was defined without giving it a positive or negative load to prevent that the wording would have an influence on the scoring. To evaluate changes in risk perception over the years, the survey was repeated in 2018. In this survey of 2018 two additional food risks were included, namely hormones/antibiotics in meat and chemicals coming from packaging of food (e.g., plastic softeners or bisphenol A).

For each of the risks, participants were asked to evaluate the relevance of the risk in relation to their health, using an increasing scale with the scoring: 1. No risk for my health; 2. Nearly no risk for my health; 3. Neutral; 4. A large risk for my health; 5. Very large risk for my health; No opinion/don't know. The questionnaire was pretested by twenty experts with an educational background in the field of nutrition or food science and with a working experience of at least 5 years within the Netherlands Nutrition Centre (Voedingscentrum) or TNO (the Netherlands Organization for applied scientific research). The experts assessed, by filling in a questionnaire, whether the question and the definition of risks were clear, and the selected risks were relevant. Comments were collected and questions were

adjusted where necessary. Besides risk perception, also scoring of familiarity with the identified food risk was included in the 2018 survey to investigate a possible correlation between (subjective) knowledge or familiarity with the risk and the perception of the risk. Participants were asked to assign a score to how familiar they were with the defined food risk, using an increasing scale with the scoring: 1. Not familiar with at all; 2. Not familiar with; 3. Neutral; 4. Familiar with; 5. Very much familiar with. The initial surveys were commissioned by the Netherlands Nutrition Centre (Voedingscentrum), an independent organization funded by the Ministry of Public Health, Welfare & Sport and the Ministry of Economic Affairs in 2009 and 2018 (Boon et al., 2019; Peters et al., 2009).

Table 2.1. List of food risks as literally mentioned in survey of 2009 and 2018 and the scale or rating

	Food risk	Scale [a]	2009	2018
1.	Unbalanced diet (e.g., too many calories, too much salt, too many snacks, not eating according to Dutch dietary Guidelines).	1-5	☑	☑
2.	Food poisoning (e.g., by uncareful storage and preparation of food).	1-5	☑	☑
3.	Toxins formed during preparation like PAHs, acrylamide (e.g., burned meat during BBQ, dark brown fried French fries).	1-5	☑	☑
4.	Environmental contaminants in food (e.g., dioxins and PCBs, heavy metals, etc.).	1-5	☑	☑
5.	Hormones or antibiotics in meat.	1-5		☑
6.	Toxins coming from packaging of food (e.g., plastic softeners or bisphenol A).	1-5		☑
7.	Residues of pesticides on vegetables and fruit.	1-5	☑	☑
8.	Additives (E-numbers) like colorants, flavourings, preservatives etc…	1-5	☑	☑
9.	Genetic Modified food (e.g., genetic engineering).	1-5	☑	☑
10.	Use of nanotechnology in food or packaging of food.	1-5	☑	☑

[a] Risks could be scored on a scale of 1 = no risk to 5 = very large risk.

2.2.2 Procedure and data-collection

Data collection was performed by two panel agencies, namely CentERdata (2009) and Flycatcher (2018). A sample of consumers in the Netherlands was recruited by the panel agencies. Demographic representativity of the sample was checked using the 'Golden Standard', a calibration instrument that has been developed by the Expertise Centre of Marketing Insight, Research and Analytics (MOA) in collaboration with Statistics Netherlands (CBS) (MOA, 2021), which confirmed that the ratio of male/female, the age distribution, the education level, and geographical distribution of the used panel members were comparable to the

information as provided by the Statistics Netherlands (CBS). Members of both panels registered voluntarily and gave explicit consent to be included in the panel. Panel members could terminate their panel membership at any time. After explaining the study details, participants partook in the survey which was anonymous and not invasive. Taken into account an expected response rate of 55–65 %, an initial group of consumers (n = 2372 in 2009 and n = 1758 in 2018) was randomly selected from the participant database of the panel agencies (based on socio-demographic representativeness, i.e., age (18 years or older), gender, educational level, currently living in the Netherlands, and geographics) and asked to participate in the study. Interested responders were informed about the purpose of the study. In case of a further positive response, detailed information (e.g., aim, client, estimated time required for completion, information about anonymity) was provided and the questionnaire was taken by a website survey, by phone, on paper or by email. Finally, this resulted in a sample size of consumers in 2009 (n = 2005) and in 2018 (n = 1014). Selected experts were professor or expert like Ph.D. in the field of nutrition, toxicology, food science, food microbiology or food technology with a working experience of at least 5 years at Dutch universities or national food institutes (i.e., TNO-Food (the Netherlands Organization for applied scientific research), Rikilt (currently Wageningen Food Safety Research), National Institute of Public Health and the Environment (RIVM) and the Netherlands Nutrition Centre (Voedingscentrum)). A majority of the above-mentioned group of experts that met the selection criteria were personally invited by email to participate in the survey. Between 55 and 60 % responded and this resulted in a sample size of experts in 2009 (n = 62) and in 2018 (n = 65).

2.2.3 Statistical analysis

Mean scores and standard deviations for risk perception and familiarity with the risk were calculated for consumers and experts in 2009 and 2018. Furthermore, homogeneity of variance was tested. A nonparametric Mann-Whitney U test (two sided) was used to test for significant differences of the mean between the scoring of risk perception of consumers and experts and differences between 2009 and 2018. The reason for choosing a nonparametric test was that the data was collected via an ordinal scale (scoring 1 to 5) and not normally distributed. Furthermore, this test is robust if variances are not fully homogeneous (Gibbons and Chakraborti, 1991). To reduce the number of false positives (type I error), the Bonferroni correction was applied. For this, the *p*-values were compared with the level of significance $\alpha = 0.05$, divided by the number of tests for each of the years, resulting in $\alpha = 0.005$. The correlation between familiarity with the risk and the perception of the risk was calculated by the Spearman's correlation coefficient (r_s). A chi-square statistic was used to calculate the *p*-value and verify associations. To understand if consumer characteristics (age, gender, education level) were associated with the perception of the risk, a multiple linear regression was conducted with age, gender, and education level (low, middle, high) as

independent variables and risk perception as the predicted dependent variable. For this, risk perception was calculated per respondent as a mean score over all ten food risks together. A residual plot (residuals vs predicted) and a Q-Q-plot was made to check the assumption of normality of this risk perception, calculated as a mean score over all ten food risks. For the individual food risks a nonparametric Mann-Whitney U test (two sided) was used to test for significant differences in age (50 years and below vs above 50 years), and gender (man vs woman). All data analyses were performed in JASP 0.14.1.0.

2.3 Results

A total of 2005 (=n) consumers and 62 (=n) experts completed the online survey in 2009, and 1014 (=n) consumers and 65 (=n) experts in 2018. The ratio of male/female, the age distribution, the education level and the geographical information of the panel are mentioned in **Appendix A**.

2.3.1 Risk perception of consumers versus experts

An overview of the mean scoring in risk perception of the food-related risks by consumers and experts in 2009 and 2018 is given in **Figure 2.1**. On average, consumers perceived the risk of unbalanced diet significantly lower than experts in 2009 and 2018. The risk of food poisoning and chemicals formed during preparation was not scored significantly different between experts and consumers in both years. Consumers perceived the risk of environmental contaminants, hormones/antibiotics in meat, chemicals from packaging materials, residues of pesticides, additives, and GMO significantly higher than the experts in both years. Especially residues of pesticides, additives and GMO were seen by experts as low (i.e., mean score lower than two), while consumers perceived these risks as neutral to large (i.e., mean score higher than three). The risk related to nanotechnology was the only risk, where the trend between risk perception of consumers versus experts changed over time, since in 2009 both consumers and experts scored this rather low (i.e., lower than three), while in 2018 the consumers scored the risk significantly higher than experts. Consumers scored the various food risks fairly evenly. For example, the difference between the food risk with the lowest score and the highest score was 0.52 in 2009 and 0.80 in 2018. Experts were more outspoken and scored the various food risks with greater differences. For example, the difference between the food risk with the lowest score and the highest score was 2.14 in 2009 and 2.86 in 2018 (see **Appendix B**). The scoring distribution of the food-related risks are shown in **Appendix C**. For unbalanced diet in 2009, 37 % of the consumers scored the risk as large to very large, while 73 % of the experts scored the risk as large to very large. In 2018 consumers scored the risk of unbalanced diet much higher, and the difference in risk perception between consumers and experts narrowed in 9 years' time, and was scored as large to very large, both by experts (91 %) and consumers (66 %) in 2018.

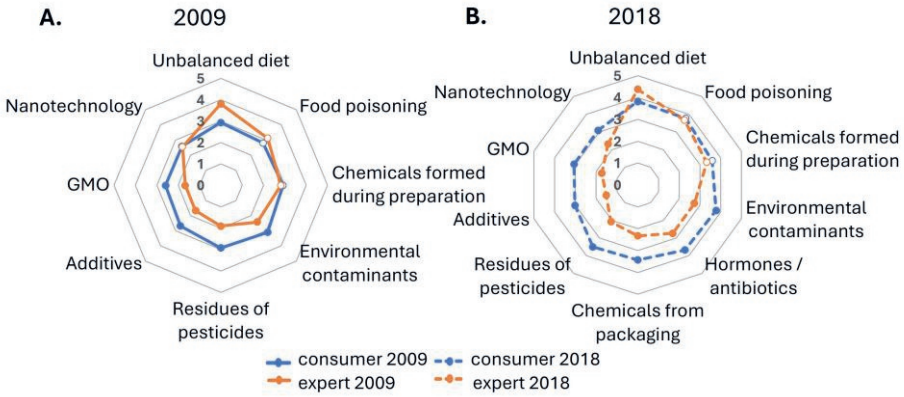


Figure 2.1. Risk perception in 2009 (panel A, filled lines) and 2018 (panel B, dashed lines). Risk perception is expressed as mean score of the consumers (blue) and experts (orange). Significant differences ($p < 0.005$) in mean score between experts and consumers are highlighted with a filled symbol.

2.3.2 Shift in risk perception over time: 2009 versus 2018

Table 2.2 shows the difference in risk perception between 2009 and 2018 for consumers and experts. Interestingly consumers scored all food risks significantly higher in 2018 compared to 2009. For unbalanced diet and food poisoning the difference in scoring was almost 1 scoring point (from neutral towards large risk). Experts scored unbalanced diet, food poisoning and chemicals formed during preparation significantly higher in 2018 compared to 2009. For environmental contaminants, residues of pesticides, additives, GMO, and nanotechnology no significant differences were seen between 2009 and 2018. In 2009 consumers perceived environmental contaminants as highest risk, but in 2018 this shifted towards unbalanced diet. Food poisoning shifted from the fifth highest score in 2009 towards the third highest score in 2018. For experts, the scoring of unbalanced diet (highest score), food poisoning (second highest score), chemicals formed during preparation (third highest score) was equal in 2009 and 2018. In general, the scoring of the highest risks by consumers came more in line with those of experts in 2018, compared to 2009.

Table 2.2. Mean scoring (standard deviation) of food risks by consumers and experts, and difference in scoring between 2009 and 2018

Food risk	Consumers			Experts		
	2009	2018	Difference (*p*)	2009	2018	Difference (*p*)
1. Unbalanced diet	2.94 (1.20)	3.82 (1.01)	0.88* (*p*<0.001)	3.81 (1.23)	4.38 (0.88)	0.57* (0.004)
2. Food poisoning	2.80 (1.28)	3.76 (1.14)	0.96* (*p*<0.001)	3.11 (1.14)	3.66 (1.03)	0.55* (0.004)
3. Chemicals during preparation	2.91 (1.15)	3.59 (1.00)	0.68* (*p*<0.001)	2.81 (1.04)	3.33 (0.95)	0.52* (0.004)
4. Environmental contaminants	3.10 (1.16)	3.78 (1.01)	0.68* (*p*<0.001)	2.42 (0.90)	2.73 (1.01)	0.31 (0.080)
5. Residues of pesticides	2.92 (1.10)	3.50 (1.00)	0.58* (*p*<0.001)	1.89 (0.87)	2.08 (1.00)	0.19 (0.346)
6. Additives	2.69 (1.01)	3.02 (1.06)	0.33* (*p*<0.001)	1.67 (0.91)	1.52 (0.79)	-0.15 (0.295)
7. GMO	2.59 (1.05)	3.07 (1.08)	0.48* (*p*<0.001)	1.67 (1.09)	1.73 (1.74)	0.06 (0.135)
8. Nano-technology	2.58 (0.96)	3.09 (1.05)	0.51* (*p*<0.001)	2.54 (1.26)	2.31 (0.92)	-0.23 (0.543)

Asterisk (*) means significant difference of the mean ($p < 0.005$).

2.3.3 Familiarity with the risk versus perception of the risk

In 2018, besides risk perception also familiarity with the identified food risks was included in the survey. **Table 2.3** shows the mean scoring of familiarity with the food risk and the mean scoring of perception of the food risk for consumers and experts. Consumers scored lower on familiarity than experts for all ten risks (on average 0.6 point lower than experts). Consumers scored themselves most familiar with the risk of food poisoning, unbalanced diet, and additives. For consumers, a weak positive, but significant correlation was seen for all risks, based on the Spearman's correlation analyses (**Table 2.3**), and confirmed by chi-square statistic to verify associations (data not shown). This may suggest that the more familiar consumers were with the risk, the higher they perceived the risk. This correlation was the lowest for GMO (r_s = 0.143, $p < 0.005$) and the highest for unbalanced diet (r_s = 0.338, $p < 0.005$). It should be kept in mind that the sample size of consumers is considerable. This results more easily in significant *p*-values while the data show that the correlations between familiarity and perception of the food-related risks are weak. For experts, there was a significant negative correlation between familiarity and perception for GMO (r_s = -0.580, $p < 0.005$), and residues of pesticides (r_s = -0.366, $p < 0.005$). For the other eight food risks the correlation was not significant. It should be noted that the experts' sample size (n = 65) was much smaller than the consumers' sample size (n = 1014), which means that correlations are less likely resulting in significance.

Table 2.3. Average scoring of familiarity with the food risk and perception of the food risk, and the correlation between familiarity with the food risk and the perception of the food risk, for consumers and experts in 2018

Food risk	Consumer			Expert		
	Familiarity with risk	Perception of risk	Correlation (r_s)[a]	Familiarity with risk	Perception of risk	Correlation (r_s)[a]
1. Unbalanced diet	3.92	3.82	0.338*	4.59	4.38	0.319
2. Food poisoning	3.97	3.76	0.249*	4.22	3.66	0.121
3. Chemicals during preparation	3.12	3.59	0.267*	4.05	3.33	0.041
4. Environmental contaminants	2.99	3.78	0.238*	3.69	2.73	-0.099
5. Hormones/ antibiotics in meat	3.36	3.68	0.285*	3.63	2.73	-0.246
6. Chemicals from packaging	2.68	3.44	0.218*	3.35	2.33	-0.212
7. Residues of pesticides	3.44	3.50	0.272*	3.80	2.08	-0.366*
8. Additives	3.49	3.02	0.213*	4.05	1.52	-0.206
9. GMO	2.78	3.07	0.143*	3.49	1.73	-0.580*
10.Nano-technology	2.26	3.09	0.282*	2.86	2.31	-0.033

[a] Results of the Spearman's correlation is indicated with r_s. Asterix (*) means a significant correlation ($p < 0.005$).

Table 2.3 shows that consumers' score on the familiarity ranged from 2.26 for nanotechnology to 3.92 for unbalanced diet, while the score on risk perception ranged from 3.02 for additives to 3.82 for unbalanced diet. This indicates that despite large differences in familiarity, there is less difference in consumers' risk perception. Experts, however, were more outspoken in assessing the risk, which is to be expected based on their expertise. The experts' score on familiarity ranged from 2.86 for nanotechnology to 4.59 for unbalanced diet, while the score on risk perception ranged from 1.52 for additives to 4.38 for unbalanced diet.

2.3.4 Socio-demographic differences

The Q-Q plot of the average scoring of all ten food risks together confirmed that the assumption of normality was not violated, and a multiple linear regression analysis could be applied. This multiple linear regression analysis with age, gender and education level as independent variables and risk perception as the predicted dependent variable showed that education level had no significant impact on the risk perception. For this reason, education level was excluded in the multiple linear regression model. The multiple linear regression analyses showed that age and gender together explained a very small (adjusted R^2 of 0.016 and 0.040 respectively for 2009 and 2018) but significant ($p < 0.001$ for both 2009 and 2018) amount of variance in scoring of risk perception calculated over all ten food risks. Age was

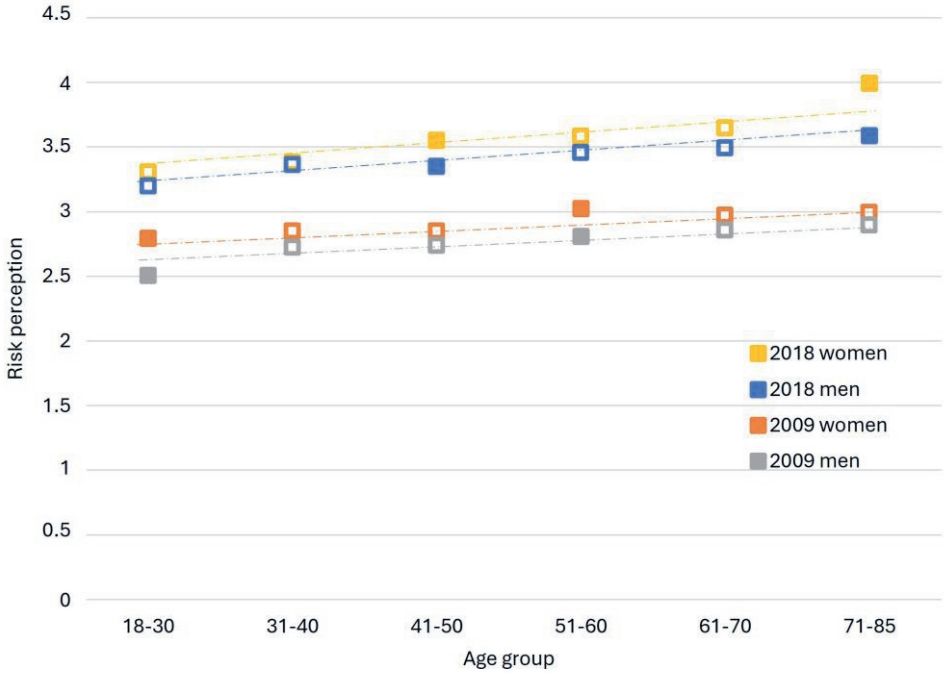


Figure 2.2. Risk perception per age group in 2009 for women (orange) and men (grey), and in 2018 for women (yellow) and men (blue). Risk perception is calculated as a mean score over all ten food-related risks. Significant differences ($p < 0.005$) in mean score per age group between men and women are highlighted with a filled square.

positively affecting risk perception. The older the consumers were, the higher the consumers perceived the risk. For each year of increase in age, the multiple regression model showed that risk perception increased with 0.005 point ($p < 0.001$) in 2009, and 0.009 point ($p < 0.001$) in 2018. This is a very small effect of age (per year) on risk perception, but still relevant. Comparing the younger generation (20 years) with the older generation (80 years), this means an increase of 0.54 points in risk perception in 2018, which is around 10 % on a scale from 1 to 5. The multiple regression model showed that women significantly perceived risks higher than men. In 2009 this difference was on average 0.156 point ($p < 0.001$) and 0.165 point ($p < 0.001$) in 2018. This is confirmed by a nonparametric Mann-Whitney U test (two sided) (see **Appendix D**). **Figure 2.2** shows the scoring of risk perception per age group for women and men in 2009 and 2018. Calculated over all age groups a significant distinction could be seen between men and women ($p < 0.005$), and this gender effect was also observed for several age groups (**Figure 2.2**). Looking at the individual risks, differences of the effect of age and gender on the scoring of risk perception can be seen. For food-related risks like additives, GMO and nanotechnology, age and gender significantly influenced the scoring of risk

perception, while for unbalanced diet and food poisoning the effects of age and gender were not noticeable and not significant in 2009 as well as in 2018 (see **Appendix D**).

2.4 Discussion

Consumers may respond very differently to food safety issues than experts, therefore, risk estimates based on experts' opinion or technical scientific information do not necessarily indicate how the risk is perceived by consumers. Knowing the difference in perception between consumers and experts can be helpful in designing clear and transparent risk communication strategies (Rembischevski and Caldas, 2020). In this study the risk perception of consumers and experts was examined in 2009 and 2018 to evaluate differences in risk perception by consumers and experts, and to assess to which extent risk perception changed over time. Experts scored unbalanced diet as the highest food-related risk followed by food poisoning, and chemicals formed during preparation, in both 2009 and 2018. This ranking of risks by experts corresponded with the ranking of disease burden when expressed in DALYs as calculated by the Dutch National Institute of Public Health and Environment (RIVM, 2018). The DALYs due to an unhealthy diet were calculated around 400,000 DALYs, foodborne infections around 4,000 DALYs, and contaminants between 300 and 1,000 DALYs.

Furthermore, the experts and the calculation by the Dutch National Institute of Public Health and Environment (RIVM) both underlined the small (sometimes negligible) risks of additives, GMO and pesticide residues (Lagerweij et al., 2020; RIVM, 2018; Van Kreijl et al., 2006). The consumers' perception changed over the years. Consumers scored unbalanced diet as highest food risk in 2018, in contrast with 2009, where environmental contaminants were scored as the highest food risk. Food poisoning was scored as fifth highest food risk in 2009 and moved towards the third highest food risk in 2018. Although the scoring of the food risks was not completely the same for consumers compared to experts in 2018, it clearly came more in line with the experts' view. Overall, chemical-related risks like environmental contaminants or residues of pesticides shifted to a lower position and unbalanced diet and food poisoning shifted to a higher position over time. Abe et al. (2020) examined changes in risk perception of food safety between 2004 and 2018 in Japan. They concluded that hazards such as contaminants (e.g., heavy metals) and residues of pesticides caused high levels of concern among the public in 2004. In contrast in later years, hazards such as food poisoning by harmful microorganisms, and antimicrobial resistance and so-called 'health foods' ranked higher, indicating that concerns also shifted over time from chemical hazards towards biological hazards and healthy foods (Abe et al., 2020). Notably, unbalanced diet was the only food risk that experts perceived significantly higher than consumers, but the difference in risk perception narrowed down between consumers and experts in 2018. This indicates that in almost ten years' time,

consumers' awareness has risen about the unhealthy eating habit and its relationship with health. In the Netherlands, an unhealthy dietary pattern is responsible for a large proportion of the ill-health and deaths due to cardiovascular diseases, diabetes, and cancer (Ocké et al., 2017). Half of the Dutch population is overweight, and this rate is even higher in lower socio-economic groups. Food Consumption data showed that the intake of salt, sugar, calories, and unfavourable fat is for most consumers higher than recommended (Schuurman et al., 2020). Underestimating the risk of unbalanced diet may make consumers less susceptible for communication about healthy eating habits, and therefore an increased risk perception of unbalanced diet is a positive signal. Socio-demographic characteristics, such as age, gender and education level had no significant effect on the perception of the risk of unbalanced diet. Apparently, people from all groups (including consumers with a lower education) became more aware of the risk of an unbalanced diet. Improved risk perception is important, but on its own not enough to make a healthy food choice. Consumers often fail to classify and recognise unhealthy food items (Marsola et al., 2021). Furthermore, many food choices are made unconsciously (Dijksterhuis et al., 2005). Social factors (e.g., habits and food preferences) and physical environmental factors (e.g., temptations in the local food environment) play a major role in food choice, while rational factors, such as intentions based on knowledge and motivation play a less prominent role (Caspi et al., 2012; Dijksterhuis et al., 2005; Drewnowski and Monsivais, 2020; Geurts et al., 2017; Sleddens et al., 2015; Van der Velde et al., 2019). Therefore, good risk and health communication as well as changing the food environment is important in improving dietary patterns. Consumers perceived seven out of ten food-related risks significantly higher than experts, namely environmental contaminants, residues of pesticides, residues of hormones/antibiotics in meat, chemicals coming from packaging materials, additives, GMO, and nanotechnology. This outcome is consistent with previous research that showed that involuntary exposure to (chemical) risks seems more threatening to consumers, and concerns arise about the long-term effects (Hartmann et al., 2018a; Kher et al., 2013; Siegrist et al., 2018). Experts have a distinctly different point of view of these risks and perceive most of these risks as low to very low. Indeed, the Dutch National Institute for Public Health and Environment pointed out in an overview report 'What is on our plate?: Safe, healthy and sustainable diets in the Netherlands', that food in the Netherlands is mostly safe: most chemicals in food pose a negligible risk to public health (Ocké et al., 2017). The concerns about food poisoning and harmful chemicals formed during preparation were scored equally by consumers and experts. Consumers can influence the exposure towards these two food-related risks by their own food handling at home. For example, pathogenic bacteria can cause illness, if the food is not handled correctly by the consumer like improper storage or cross-contamination. And chemicals like acrylamide and Polycyclic Aromatic Hydrocarbons (PAHs) can be formed during improper heating at home, like too much browning of fried potatoes. These events can be seen as personally

controllable. In 2009 consumers perceived the risk of environmental contaminants as the main food-related risk, however, in 2018 this shifted to the second most important risk. Although in this survey it was not asked which type of food products the respondents had in mind when the risk was scored, it is known that fish is perceived as very susceptible for environmental contamination like methyl mercury and dioxins (Ocké et al., 2017). Verbeke et al. (2005) looked at risk perception and fish consumption in Belgium, and concluded that consumers are more aware of the content and effect of harmful substances than of beneficial nutrients in fish. These findings exemplify the conflict in consumers' minds between benefits and risks of fish consumption. Earlier research performed in five European countries (Belgium, the Netherlands, Denmark, Spain and Poland) revealed that, in general, consumers have a low risk perception in relation to seafood, but that consumers in Belgium and the Netherlands have a slightly higher risk perception compared to the other countries (Pieniak et al., 2008). Consumption of seafood is more traditional in the southern European countries which may explain the higher score on benefit perception and lower score on risk perception. In these countries risk–benefit evaluations tend to be leaning toward acceptance of all that is traditional (Pieniak et al., 2008). In the Netherlands on average 43 % of the total population eats the recommended amount of fish (lowest consumption among children and highest among elderly), which is lower than southern European countries (Guillen et al., 2019; Schuurman et al., 2020). Consumers perceived the risk of residues of pesticides as neutral in 2009 (mean score 2.92) towards a somewhat larger risk for their health in 2018 (mean score 3.50). In the consumer monitor of the Dutch Food Safety Authority (NVWA) (2008–2018) and in the Eurobarometer on food safety in de EU (2010 and 2019) it can be seen that Dutch consumers have concerns about pesticides on food (EFSA, 2019; NVWA, 2018a). An unfavourable effect of these concerns about pesticides could be that consumers eat less vegetables and fruit. The National Food Consumption Survey showed that nine out of ten consumers do not eat the recommended amount of vegetables and fruit in the Netherlands, while there is convincing evidence that eating at least 200 g of vegetables and 200 g of fruit a day can reduce the risk of coronary heart disease and stroke, diabetes, colorectal cancer and lung cancer (Health Council of the Netherlands, 2015; Schuurman et al., 2020). If and to what extent risk perception of residues of pesticides influences the consumption of vegetables and fruit is unknown. Nardi et al. (2020) found that healthy food products with a shorter shelf life had a higher perception of benefits, and a lower perception of risks compared to food products with a long shelf life. Also, people have more trust and are less risk-averse towards food of a vegetable origin compared to animal origin. In Germany, a computer-assisted telephone survey showed that of the consumers who eat mostly organically grown fruit and vegetables, about 70 % rated the risks of pesticides use higher than the benefits of eating vegetables, compared to 53 % of the consumers who eat mostly conventionally grown fruit and vegetables. Organic consumers were significantly more concerned about pesticide residues in the food than conventional

consumers (Koch et al., 2017). This could mean that consumers who are more concerned and more risk-averse shift from conventional towards organic grown vegetables and fruit, where less pesticides or pesticides made from elements of natural origin are used. Two technologies were included in the survey, namely use of genetic engineering (GMO) and use of nanotechnology in food or packaging of food. Especially for GMO, consumers perceived the risk much higher than experts. In 2018 this also applied to nanotechnology, although it must be noticed that a lot of consumers (around 29 %) were not able to score this risk, because they were not familiar with the risk. The use of nanotechnology was less well known by consumers than the use of GMO. The perception of these type of technologies might be especially sensitive to the expertise factor because of the specialized knowledge associated with these type of risks. Unfamiliar, uncertain, unknown, uncontrollable, and severe consequences are some factors associated with risk perception, and new technologies score high on several of these parameters and are consequently regarded with suspicion and perceived as risky by consumers (Siegrist and Hartmann, 2020; Ueland et al., 2012). Factors influencing consumers' perception of novel food technologies during the early stage of development and introduction can result in a higher acceptance of such technologies (Siegrist and Hartmann, 2020). This survey showed that, in general, older respondents perceived the food-related risks slightly higher than younger respondents, and women tend to perceive risks higher than men. This is in line with earlier studies on risk perception (Abe et al., 2020; Finucane et al., 2000; Nardi et al., 2020; Zingg et al., 2013). However, looking at individual risks, differences could be seen. Data from our study suggested that the older generation and women generally expressed more concern towards chemical related risks and new technologies. This difference did not apply for unbalanced diet and food poisoning where no significant differences between the gender- and age groups were visible. Insight in differences in risk perception between socio-demographic groups is essential to design clear and targeted communication strategies. While our study provided quantitative data on food-related risk perception of consumers and experts over time (in 2009 and 2018), we did not determine the cause of this and we did not assess consumers' underlying concerns in relation to food hazards. Previous research has shown that these are not confined to human health but extend to animal welfare and the environment (Miles and Frewer, 2001). Further research must be designed to address these causes, and these must be considered in any adequate communication strategy. Communication and providing information about specific food risks can influence risk perception (Rembischevski and Caldas, 2020). It can be noted that in the last decade the Dutch government (Dutch Ministry of Health, Welfare, and Sport, 2018), global organizations such as the World Health Organization (WHO, 2018), and the media reported more often about the importance of balanced diet than before, which may have contributed to changes in consumers' risk perception. Also, food labelling can be seen as a communication tool for the management of perceived risks for consumers (Hartmann et al., 2018b; Tonkin et al., 2016). A practical implication from this study

can be to further look at food labelling as a tool for consumers to manage perceived risks like food poisoning (e.g., a hygiene warning label on the packaging of poultry). Following up studies are needed to further explore how perception of risks can be changed through communication (e.g., food labelling) and eventually may underlie changes in behaviour.

2.5 Conclusion

This study showed that consumers' awareness of unbalanced diet as food risk increased over time, and in 2018 consumers scored unbalanced diet as highest food-related risk, just as experts. Chemical risks and risks of new technologies were perceived significantly higher by consumers than by experts. This was especially the case for the older generation and women. Consumers were most familiar with the risk of food poisoning, unbalanced diet, and additives and least familiar with nanotechnology. This study provides insights into the differences in risk perception between consumers and experts and the changes over time. Recognition of differences is an important element in order to design clear and transparent risk communication strategies.

2.6 Acknowledgement

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2.7 Supplementary material

2.7.1 Appendix A. Demographic data used in survey of 2009 and 2018

Table A1. Demographic data in number (n) and percentage (%) of 2009 panel (n = 2005) and 2018 panel (n = 1014)

	2009 CentERdata panel, n (%)	2018 Flycatcher panel, n (%)
Gender [a]		
Male	1062 (53)	498 (49)
Female	943 (47)	516 (51)
Age [a]		
18-29	176 (9)	137 (14)
30-49	704 (35)	279 (28)
50-65	708 (35)	326 (32)
Above 65	417 (21)	261 (26)
Education level [a]		
Low	642 (32)	314 (31)
Middle	662 (33)	399 (39)
High	702 (35)	301 (30)
Geographical [a]		
Groningen	80 (4)	33 (3)
Friesland	100 (5)	41 (4)
Drenthe	60 (3)	30 (3)
Overijssel	140 (7)	71 (7)
Flevoland	40 (2)	21 (2)
Gelderland	241 (12)	115 (11)
Utrecht	140 (7)	83 (8)
Noord-Holland	280 (14)	161 (16)
Zuid-Holland	402 (20)	231 (23)
Zeeland	63 (3)	25 (3)
Noord-Brabant	317 (16)	141 (14)
Limburg	139 (7)	61 (6)

[a] Age, gender, highest level of education and geographical information were assessed. Based on the Dutch educational system (Statistics Netherlands CBS, 2021) three educational levels were defined: high (university, college, higher vocational, general secondary, and intermediate vocational education), middle (general intermediate, and lower vocational education), and low (elementary education or less).

2.7.2 Appendix B. Scoring of risk perception of food-related risks by consumers and experts in 2009 and 2018

Table B1. Mean scoring (M) and standard deviation (SD) of risk perception of food-related risks by consumers and experts in 2009 and 2018

Food-related risk	2009 consumers	2009 experts	2018 consumers	2018 experts
1. Food poisoning	2.80 (1.28)	3.11 (1.15)	3.76 (1.14)	3.66 (1.04)
2. Unbalanced diet	2.94 (1.20)	3.81 (1.24)	3.82 (1.01)	4.38 (0.88)
3. Residues of pesticides	2.92 (1.10)	1.89 (0.87)	3.50 (1.00)	2.08 (1.00)
4. Environmental contaminants	3.10 (1.16)	2.42 (0.90)	3.78 (1.01)	2.73 (1.01)
5. Chemicals formed during preparation	2.91 (1.15)	2.81 (1.04)	3.59 (1.00)	3.33 (0.95)
6. Genetic Modified food	2.59 (1.05)	1.67 (1.09)	3.07 (1.08)	1.73 (1.74)
7. Additives (E-numbers)	2.69 (1.01)	1.67 (0.91)	3.02 (1.06)	1.52 (0.79)
8. Use of nanotechnology	2.58 (0.96)	2.54 (1.26)	3.09 (1.05)	2.31 (0.92)
9. Chemicals coming from packaging	-	-	3.44 (1.03)	2.33 (0.84)
10. Hormones or antibiotics in meat	-	-	3.68 (1.00)	2.73 (0.89)

2.7.3 Appendix C. Distribution of consumers' and experts' risk perception in 2009 and 2018

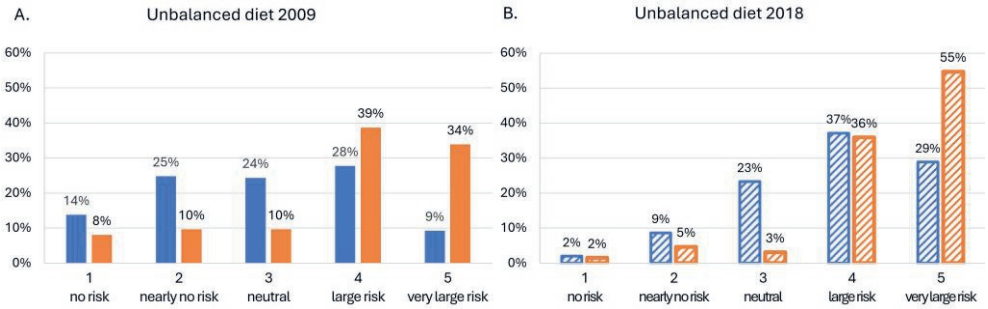


Figure C1. Distribution of consumers' and experts' risk perception for unbalanced diet in 2009 (panel A) and 2018 (panel B). Risk perception is expressed as percentage of consumers (blue) or experts (orange) with the same scoring.

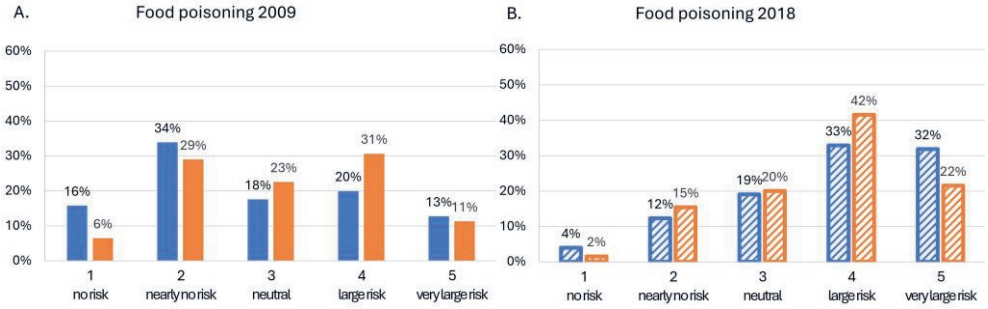


Figure C2. Distribution of consumers' and experts' risk perception for food poisoning in 2009 (panel A) and 2018 (panel B). Risk perception is expressed as percentage of consumers (blue) or experts (orange) with the same scoring.

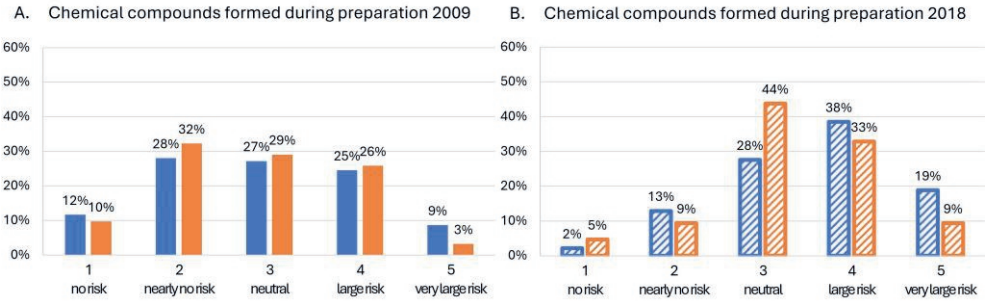


Figure C3. Distribution of consumers' and experts' risk perception for chemicals formed during preparation in 2009 (panel A) and 2018 (panel B). Risk perception is expressed as percentage of consumers (blue) or experts (orange) with the same scoring.

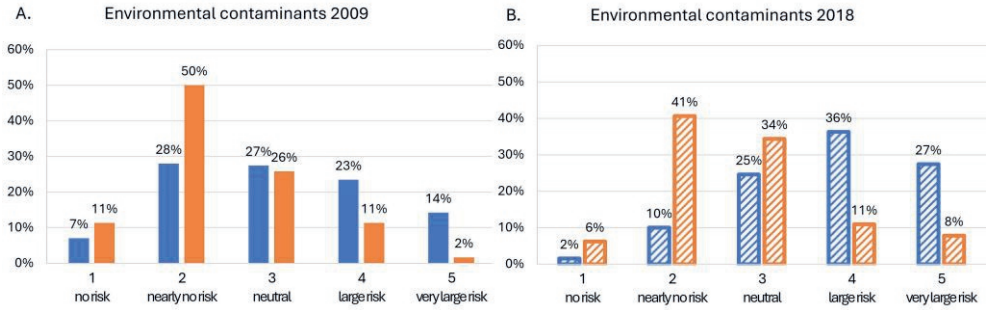


Figure C4. Distribution of consumers' and experts' risk perception for environmental contaminants in 2009 (panel A) and 2018 (panel B). Risk perception is expressed as percentage of consumers (blue) or experts (orange) with the same scoring.

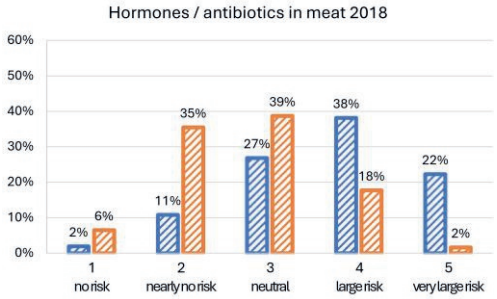


Figure C5. Distribution of consumers' and experts' risk perception for hormones / antibiotics in meat in 2018. Risk perception is expressed as percentage of consumers (blue) or experts (orange) with the same scoring.

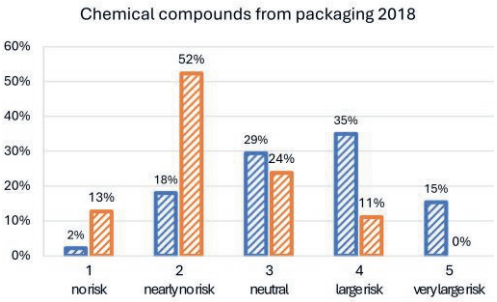


Figure C6. Distribution of consumers' and experts' risk perception for chemicals coming from packaging materials in 2018. Risk perception is expressed as percentage of consumers (blue) or experts (orange) with the same scoring.

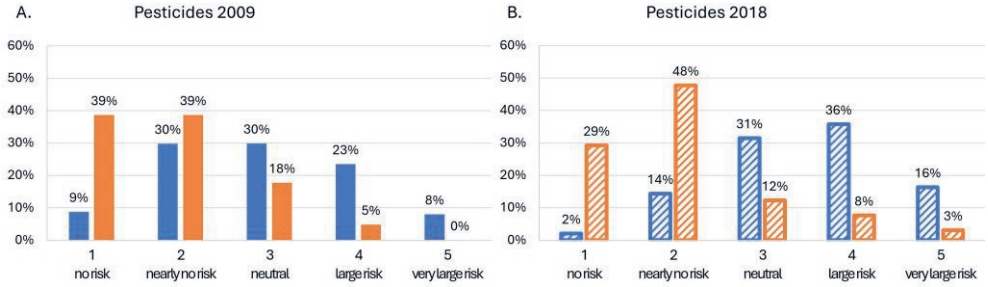


Figure C7. Distribution of consumers' and experts' risk perception for residues of pesticides in 2009 (panel A) and 2018 (panel B). Risk perception is expressed as percentage of consumers (blue) or experts (orange) with the same scoring.

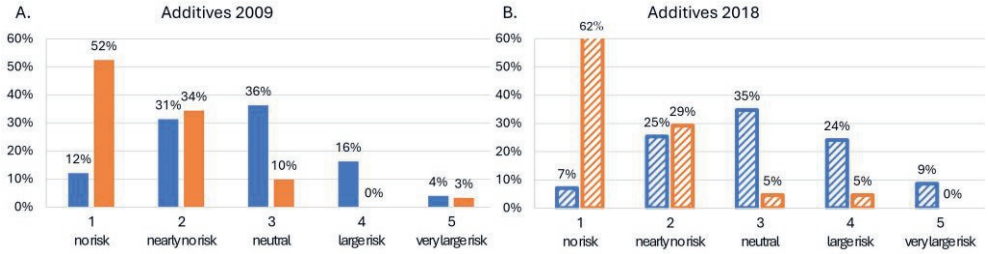


Figure C8. Distribution of consumers' and experts' risk perception for additives in 2009 (panel A) and 2018 (panel B). Risk perception is expressed as percentage of consumers (blue) or experts (orange) with the same scoring.

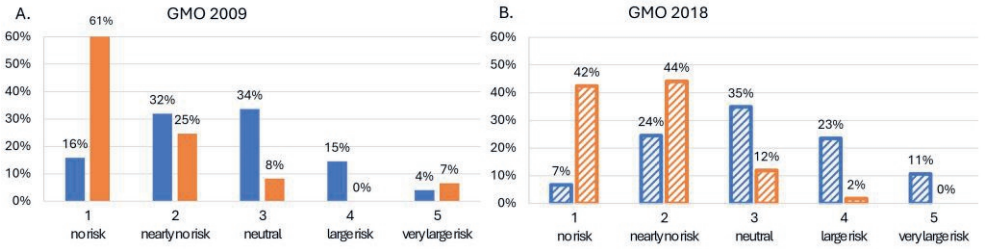


Figure C9. Distribution of consumers' and experts' risk perception for GMO in 2009 (panel A) and 2018 (panel B). Risk perception is expressed as percentage of consumers (blue) or experts (orange) with the same scoring.

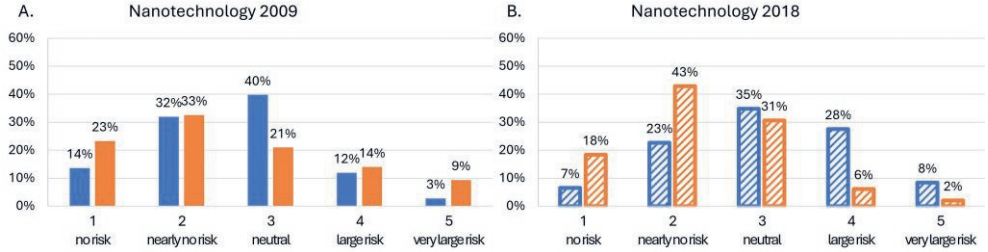


Figure C10. Distribution of consumers' and experts' risk perception for nanotechnology in 2009 (panel A) and 2018 (panel B). Risk perception is expressed as percentage of consumers (blue) or experts (orange) with the same scoring.

2.7.4 Appendix D. Impact of age and gender on scoring of consumers' risk perception

Table D1. Scoring of food-related risks by consumers 2009 of different ages (50 years or younger vs older than 50 years) and gender (man vs woman). Mean values, (standard deviation, SD), differences of the mean, and the *p*-values of the difference of the mean

Food-related risk	Age			Gender		
	≤ 50 yrs	> 50 yrs	Difference (*p*)	Man	Woman	Difference (*p*)
Mean of all food risks	2.76 (0.79)	2.91 (0.91)	0.15* (*p*<0.001)	2.77 (0.85)	2.92 (0.87)	0.15* (*p*<0.001)
Unbalanced diet	2.97 (1.10)	2.92 (1.29)	-0.05 (0.33)	2.94 (1.18)	2.94 (1.23)	0.00 (0.84)
Food poisoning	2.82 (1.20)	2.78 (1.35)	-0.04 (0.21)	2.79 (1.27)	2.81 (1.30)	-0.02 (0.82)
Chemicals during preparation	2.84 (1.06)	2.97 (1.22)	0.13 (0.014)	2.89 (1.12)	2.92 (1.19)	0.03 (0.50)
Environmental contaminants	2.93 (1.12)	3.25 (1.18)	0.32* (*p*<0.001)	3.04 (1.20)	3.16 (1.12)	0.12 (0.01)
Residues of pesticides	2.77 (1.03)	3.05 (1.14)	0.28* (*p*<0.001)	2.85 (1.10)	3.00 (1.09)	0.15* (0.001)
Additives	2.58 (0.99)	2.78 (1.14)	0.20* (*p*<0.001)	2.57 (1.00)	2.82 (1.01)	0.25* (*p*<0.001)
GMO	2.53 (0.99)	2.64 (1.09)	0.11 (0.035)	2.44 (1.02)	2.76 (1.04)	0.32* (*p*<0.001)
Nano-technology	2.49 (0.95)	2.66 (0.97)	0.17* (*p*<0.001)	2.47 (0.97)	2.73 (0.93)	0.26* (*p*<0.001)

Asterisk (*) means significant difference ($p < 0.005$) using the nonparametric Mann-Whitney U test (two sided).

Table D2. Scoring of food-related risks by consumers 2018 of different ages (50 years or younger vs older than 50 years) and gender (man vs woman). Mean values, (standard deviation, SD), differences of the mean, and the *p*-values of the difference of the mean

Food-related risk	Age			Gender		
	≤ 50 yrs	> 50 yrs	Difference (*p*)	Man	Woman	Difference (*p*)
Mean of all food risks	3.37 (0.73)	3.59 (0.79)	0.22* (*p*<0.001)	3.43 (0.74)	3.55 (0.79)	0.12* (0.004)
Unbalanced diet	3.85 (0.97)	3.80 (1.04)	-0.05 (0.57)	3.79 (0.97)	3.86 (1.05)	0.03 (0.11)
Food poisoning	3.71 (1.11)	3.81 (1.16)	0.10 (0.08)	3.71 (1.10)	3.81 (1.17)	0.10 (0.06)
Chemicals during preparation	3.48 (0.98)	3.67 (1.02)	0.19* (0.002)	3.55 (1.01)	3.63 (1.00)	0.08 (0.36)
Environmental contaminants	3.63 (1.00)	3.89 (1.00)	0.26* (*p*<0.001)	3.79 (0.98)	3.77 (1.04)	-0.02 (0.91)
Hormones/ antibiotics in meat	3.56 (1.01)	3.78 (0.98)	0.22* (0.001)	3.57 (1.00)	3.79 (0.98)	0.22* (*p*<0.001)
Chemicals from packaging	3.31 (1.03)	3.53 (1.01)	0.22* (0.001)	3.40 (1.02)	3.48 (1.02)	0.08 (0.21)
Residues of pesticides	3.32 (0.98)	3.64 (0.99)	0.32* (*p*<0.001)	3.48 (0.98)	3.52 (1.01)	0.04 (0.42)
Additives	2.81 (1.09)	3.18 (1.01)	0.37* (*p*<0.001)	2.92 (1.04)	3.11 (1.07)	0.19* (0.004)
GMO	2.89 (1.09)	3.22 (1.05)	0.33* (*p*<0.001)	2.96 (1.09)	3.19 (1.06)	0.23* (*p*<0.001)
Nano-technology	2.87 (1.06)	3.25 (1.01)	0.38* (*p*<0.001)	3.02 (1.03)	3.16 (1.06)	0.14 (0.074)

Asterisk (*) means significant difference ($p<0.005$) using the nonparametric Mann-Whitney U test (two sided).

Chapter 3

Temperature status of domestic refrigerators and its effect on the risk of listeriosis from ready-to-eat (RTE) cooked meat products

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Abstract

Inadequate domestic refrigeration is frequently cited as a factor that contributes to foodborne poisoning and infection, and consumer behaviour in this regard can vary largely. This study provides insight into the temperature profiles of domestic refrigerators in the Netherlands and the impact on the number of listeriosis cases related to ready-to-eat (RTE) cooked meat products. A survey was conducted among Dutch consumers (n = 1020) to assess their knowledge and behaviour related to refrigerators. Out of these participants, 534 measured their refrigerator's temperature, revealing an average temperature of 5.7 °C (standard deviation (SD) of 2.2 °C) with a maximum of 17 °C. Elderly people (65 years and older) had refrigerators with temperatures that were on average 0.6 °C higher than those of younger people (35 years or younger). The 24-hour temperature profiles of an additional set of actively surveyed refrigerators (n = 50) showed that the temperature measured on the upper shelf was significantly higher (mean 7.7 °C, SD 2.7 °C) than the temperature measured on the bottom shelf (5.7 °C, SD 2.1 °C). Quantitative Microbiological Risk Assessment (QMRA) predicted that the primary factors contributing to the risk of listeriosis were the initial concentration and the time and temperature during household storage. Scenario analysis revealed that storing opened RTE cooked meat products at home for either < 7 days or at temperatures < 7 °C resulted in a significant reduction of over 80 % in predicted illness cases. Among all illness cases, the elderly represented nearly 90 %. When assessing the impact of the disease in terms of Years of Life Lost (YLL), the contribution of the elderly was 59 %. Targeted communication, particularly directed towards the elderly, on the importance of storing RTE cooked meat products at the recommended temperature on the bottom or middle shelf as well as consuming within two to three days after opening, holds the potential to significantly reduce the number of cases.

3.1 Introduction

Insufficient food temperature control is one of the most common causes of foodborne illness according to the official standards of the Codex Alimentarius Commission (CAC, 2003). The World Health Organization (WHO) also states, in its five keys to safer food, that all cooked and perishable food should be quickly refrigerated below 5 °C (WHO, 2006). Recommended refrigerator temperatures vary throughout the world, but the maximum recommended temperatures are mostly below 7 °C (FDA, 2022; FSA, 2022b; Terpstra et al., 2005), with many countries recommending below 5 °C. In the Netherlands, it is recommended that the temperature of the domestic refrigerator should be 4 °C (Van der Vossen and Van Dooren, 2012).

The safety of many foods is dependent on ensuring the cold chain until the time of consumption. One of the weakest links is the consumer part of the chain as the temperatures of domestic refrigerators may be above the recommended temperature. A review of 23 available survey studies in mostly European countries from 1991 to 2016 showed mean, minimum and maximum temperatures ranging from 5 to 8.1 °C, -7.9 to 3.8 °C and 11.4 to 20.7 °C, respectively (EFSA BIOHAZ Panel, 2018). The temperature in domestic refrigerators varies among consumers and over time, but can vary also within the refrigerators. Studies reporting simultaneous recordings of temperature at different positions in the refrigerators using data loggers (temperature measurement every 1 to 10 min) showed lower mean temperature values on the bottom shelves than top shelves (Jofré et al., 2019; Koutsoumanis et al., 2010). Available data indicate that the domestic refrigerators mean temperature, as well as the fluctuation within the refrigerator, is affected by their type and age (Dumitrașcu et al., 2020; EFSA BIOHAZ Panel, 2018; George et al., 2010). Several surveys have shown that few householders know the actual temperature of their refrigerators. A fridge thermometer is not often used by consumers to check the temperature of the refrigerator (James et al., 2017; Janjiç et al., 2016; George et al., 2010). More often, personal judgement and tactile senses are used when it comes to evaluation of the temperature of the refrigerator (George et al., 2010). However, the subjective experience of tactile coldness can easily be misleading. Borda et al. (2020) showed that the probability to give the exact temperature value after touching a surface or food kept at 8 °C is very low. Consumers demonstrated limited ability to assess the food and surface temperature by tactile senses when the skin touches refrigerated foods. The estimated temperature is highly related to the thermal properties of the packaging materials, for example an aluminium can is estimated colder than a PET bottle when kept at refrigeration temperature. Food handling behaviour may also differ among age groups. EFSA BIOHAZ Panel (2018) noted that unsafe practices, including prolonged storage time and too high temperatures, are not uncommon among elderly. However, there is a wide variation in behaviour among elderly,

which makes it challenging to generalise about knowledge and food handling behaviours (Dumitrașcu et al., 2020).

Temperature abuse during storage can support the growth of *Listeria monocytogenes* to levels that largely increase the health risk (Mataragas et al., 2006). *L. monocytogenes* remains a significant public health concern, despite not being among the most commonly reported causes of food-borne illnesses (Buchanan et al., 2017). The capacity of *L. monocytogenes* to grow under extreme conditions such as low temperature, low pH and high salt concentrations, is among the most important factors affecting the risk of human listeriosis associated with the consumption of ready-to-eat (RTE) foods. These foods are of particular concern, because of the lack of a cooking step to inactivate *L. monocytogenes* prior to consumption (Georgalis et al., 2020). Cooked meat and heat-treated sausages with extended shelf lives were the RTE food subcategories with the most consumed servings per person and per year in the European Union (EU) (EFSA BIOHAZ Panel, 2018). Cooked meat products were associated with the largest number of listeriosis cases per year (Sampedro et al., 2022; Hadjicharalambous et al., 2019). Risk assessment for *L. monocytogenes* in deli meats predicted that 63 % – 84 % of human listeriosis cases and deaths attributable to deli meats are due to retail-sliced products (FSIS, 2010; Gombas et al., 2003; Pradhan et al., 2011). Contaminated RTE meat products constitute a high risk for the susceptible populations, such as pregnant women, the elderly and immune-compromised persons (FAO and WHO, 2022; Mataragas et al., 2008; Sampedro et al., 2022). Since the start of EU-wide surveillance, most listeriosis cases have been reported in the elderly, in particular those over 64 years of age. At the EU level, the proportion of listeriosis cases in this age group steadily increased from 56.1 % in 2008 to 72.5 % in 2020; in the age group over 84, there was an increase from 7.3 % to 17.1 % in the same time period (EFSA and ECDC, 2021).

Quantitative microbiological risk assessment (QMRA) is a modelling approach used to estimate the risk of illness when a population is exposed to a pathogen. The process of QMRA involves four steps: i) hazard identification, ii) exposure assessment, iii) hazard characterization and iv) risk characterization (EC, 1997). In the exposure assessment step of the QMRA, the microbial kinetics of the identified hazards are quantitatively described for all subsequent steps of the product's value chain, using mathematical models. However, this system is inherently stochastic. For that reason, it is essential to include uncertainty and variability in the analysis (EFSA, 2018). In this context, variability refers to sources of variation that are inherent to the system (e.g., biological differences between microbial cells or human beings), whereas uncertainty is related to lack of or imprecise knowledge. This can be accomplished by a stochastic modelling approach where the relevant kinetic parameters are described using probability distributions (Garre et al., 2020; Nauta, 2000). QMRA's that have incorporated the consumer phase indicate that storage time and storage temperature in the consumer phase are important parameters to control (Hadjicharalambous et al., 2019; Mataragas et al.,

2010). These consumer practices have a crucial impact on the final dose of exposure. Neves et al. (2018) concluded that, for adequate risk assessments, it may be necessary to include the variation in consumer practices (e.g., variation in storage time and temperature), because this variation is expected to be large. However, lack of information about these consumer practices makes it difficult to draw quantitative conclusions on the variation in food handling practices and how this may contribute to the number of human listeriosis cases (FAO and WHO, 2022). However, EFSA estimated, based on predictions of the QMRA model, that the expected number of invasive listeriosis cases per year is reduced by 37 % in the absence of growth after retail (i.e., at the consumer phase) (EFSA BIOHAZ Panel, 2018). Another risk assessment that focussed on *L. monocytogenes* in deli meats estimated an up to a million-fold increase in risk due to consumer mishandling, and storage practices appeared to be more important in terms of risk than cross contamination (Yang et al., 2006).

To date, still little is known about the consumer practices regarding refrigeration of RTE food and its impact on the number of listeriosis cases. Therefore, in this study we conducted a survey to obtain quantitative insight into the knowledge and behaviour of Dutch consumers regarding refrigeration, as well as quantitative information about the temperature profiles in domestic refrigerators. The outcomes of this survey were used to quantitatively estimate the number of listeriosis cases per year due to the consumption of RTE cooked meat products among different risk groups of the Dutch population. The most risky food-handling practices were identified. These results help in designing risk communication messages that target most risky food-handling behaviour.

3.2 Materials and methods

3.2.1. Consumer knowledge and temperature data collection of domestic refrigerators

A questionnaire was developed to evaluate consumers' knowledge and behaviour regarding the temperature of their refrigerator (**Table 3.1**). The included questions covered four topics: (i) socio-demographic information regarding the respondents, (ii) general information about their refrigerator, such as type, age, and digital temperature indication (iii) users' habits regarding checking and changing the temperature, and (iv) consumers' knowledge regarding the temperature setting. Data collection was performed by the panel agency Flycatcher. Selected consumers were asked by e-mail to participate in the survey. The goal was to sample 1000 consumers to obtain a representative result.

Table 3.1. List of questions as mentioned in consumer survey about refrigerators' temperature

Questions of consumer survey
1. Does your refrigerator have a (digital) temperature display?
2. What temperature is indicated on the temperature display?
3. Do you know, without measuring the temperature of your refrigerator, what the temperature of your refrigerator is?
4. What do you think the temperature of your refrigerator is? (in case of no temperature display)?
5. Do you, or someone else, ever change the temperature of your refrigerator?
6. Do you ever check the temperature of your refrigerator?
7. How do you check the temperature of your refrigerator?
8. If your refrigerator is not at the right temperature, what do you usually do?
9. What type of refrigerator do you have?
10. How do you change the temperature of your refrigerator?
11. If you want to make the refrigerator colder, what do you usually do?
12. How old is your refrigerator?
13. What is in your opinion the ideal temperature of a refrigerator?
14. What is the temperature you just measured in your refrigerator? [a]

[a] Question 14 was asked to 536 participants measuring the temperature of their refrigerator.

In case of a positive response a questionnaire was taken by a website survey. This message included detailed information about the purpose of the study (e.g., aim, estimated time required for completion, information about anonymity). Inclusion criteria were being aged 18 years or older and currently living in the Netherlands. Consumers who participated (n = 1020), completed the first part of the questionnaire (questions 1–13) and were asked to participate in the follow-up study to measure the temperature of their refrigerator. These participants (n = 536) received a fridge thermometer (Hendi 271117, temperature range -40 °C to 40 °C, accuracy 1 °C) by post mail. The participants were instructed to place the thermometer in a glass (150 mL) of cold water from the tap at the bottom shelf of the refrigerator. The thermometer was read after being kept in a closed refrigerator for at least 2 h (preferably read in the morning after an overnight). Two hours proved to be sufficient to reduce the temperature of the cold tap water to the stable temperature of the refrigerator. The results were recorded in question number 14 of the questionnaire. Mean scores, standard deviations, and 75^{th} and 95^{th} percentiles were calculated for the measured temperature of the household refrigerators. A Shapiro-Wilk test was performed to check whether the data was normally distributed. The correlation between the ideal mentioned temperature (question 13) and the measured temperature (question 14) was calculated by the Spearman's correlation coefficient (r_s), and chi-square statistic was used to calculate the p-value with a level of significance α is 0.05. To understand if consumer characteristics (age, gender, education level) were associated with different temperatures, a multiple linear regression was conducted with age,

gender, and education level (low, middle, high) as independent variables and measured temperature as the predicted dependent variable.

3.2.2 24-hour temperature measurement

Following the collection of information on the temperature status of 536 domestic refrigerators at the bottom shelf, a more detailed follow-up study was performed to investigate the temperature distribution inside a set of domestic refrigerators. The temperature was assessed at three different locations in the refrigerator (upper, middle and bottom shelf) in 50 households (17 student homes, 16 family homes, 15 elderly homes, 2 single persons). The temperature was monitored in a container (2.5 · 2.5 · 5 cm) filled with water (60 mL) for a minimum period of 24 h with a temperature datalogger (DS1921G-F5# Thermochron iButton, accuracy 0.5 °C and programmed to record the temperature at 10 minute intervals). Recorded values were downloaded from the dataloggers using 1-WireViewer and analysed with Microsoft Excel 365 (Microsoft, Redmond, USA). A Mann-Whitney test (level of significance α is 0.05) was used to check differences between the temperature distribution of the different locations in the refrigerator (upper, middle or bottom shelf), and differences between the temperature distribution of households. Relevant information was collected from the participants in an interview, such as the method and place of storage of RTE cooked meat products. To check whether water reacts the same to temperature changes in the refrigerator as RTE cooked meat products, data loggers were placed inside pâté and in a container with water (n = 50 measurements). Both products were stored side-by-side in the same place in the refrigerator (upper, middle or bottom shelf) and the temperature was monitored for 24 h. A Mann-Whitney test (level of significance α is 0.05) was used to check differences between the temperature distribution of pâté and water.

3.2.3 Quantitative microbiological risk assessment

A QMRA was performed with emphasis on consumer handling and storage of RTE cooked meat products before consumption. Stages of manufacturing and distribution of the product before the retail phase were not included. A stochastic model was developed that describes the prevalence and growth of *L. monocytogenes* on RTE cooked meat products, considering the effects of temperature and time, during transport from supermarket to home and storage at home. The QMRA modules were based on information derived from the consumer survey, refrigerator survey and previous risk assessments.

3.2.3.1 Prevalence

Information from the EU-wide baseline survey 2010–2011 was used to estimate the frequency of contamination (i.e., prevalence) (EFSA BIOHAZ Panel, 2018). The EU prevalence of *L. monocytogenes* contaminated RTE heat-treated meat products was 2.07 % (CI: 1.63 % - 2.64 %) (72 positive samples out of 3470, at the end of shelf-life). A food sample was considered contaminated with *L. monocytogenes* if

either the detection test result was positive (detected in 25 g of sample) and/or the enumeration test result was positive, i.e., having at least one colony on a plate of the first decimal dilution (resulting in a count of at least 10 CFU/g in the original sample). The prevalence was described by a PertAlt distribution, assuming a most likely value of 2.07 %, $P^{2.5}$ of 1.63 %, $P^{97.5}$ of 2.64 %, and always between 0 % and 100 % (EFSA BIOHAZ Panel, 2018).

3.2.3.2 Initial concentration

The initial concentration (i.e., at point of sale, in case of being contaminated) was estimated using information from the EU-wide baseline survey 2010–2011. A beta-general distribution was chosen to describe the initial concentration, assuming α equal to 0.502 and β equal to 2.908 and a minimum of -1.69 log CFU/g and a maximum of 6 log CFU/g (EFSA BIOHAZ Panel, 2018).

3.2.3.3 Consumer handling

Accurate data about temperature profiles during transport from retail to home were not available. Possas et al. (2019) assumed that the transport from retail to home can last a minimum of 15 min and a maximum of 2 h. A uniform distribution was used with a minimum of 0.25 h and a maximum of 2 h (Possas et al., 2019). The temperature during transport is largely unknown, but in general, foods are not refrigerated during transport by the consumer and at this phase there is an increase in temperature which depends on many uncertain and variable factors. A beta-pert distribution was used to describe the temperatures during transport from retail to home with minimum 4 °C, most likely 10 °C and maximum 25 °C, as proposed by expert opinion published by Nauta et al. (2003). Although it is unlikely that the temperature will rise from refrigeration temperature to a maximum of 25 °C within 2 h, on a hot day, it could potentially happen due to the thinness of a package of ham and the potential for a rapid temperature increase. Household storage times were determined from a consumer survey, executed in 2021 (Voedingscentrum, 2021). In this survey 1690 participants were asked to answer the question 'within how many days do you eat opened cooked deli-meat'. Possible answers were: 1. Within one day (0.5); 2. within two days (1); 3. within three to four days (3.5); 4. within five to six days (5.5); 5. for a week or longer (9); 6. until durability date (an equal allocation of days between 4 and 14); 7. I use my senses (an equal allocation of days between 4 and 14). The number of days used to determine the distribution is shown in brackets. A pert distribution was used to describe storage time with a most likely of 1.52 days, a minimum of 0 days and a maximum of 18 days, which was the maximum storage time according to the survey. Refrigerated storage temperatures at the household were used from the survey among the 534 households. A normal distribution was fitted to describe the temperature data with a mean (μ) of 5.68 °C and a standard deviation (σ) of 2.23 °C. A minimum of 0 °C (below zero products will freeze) and a maximum of 18 °C was chosen (the maximum temperature of the refrigerators in the survey).

3.2.3.4 Consumption data

Data about individual consumption patterns (typical serving size) of cooked deli-meat of the Dutch population were retrieved from the Dutch National Food Consumption Survey 2012–2016 (Van Rossum et al., 2020). The food group 'Cold processed meat' was chosen, and deli-meats which were cooked or boiled (e.g., pâté or ham), pre-packaged and pre-sliced were chosen as representative for RTE cooked meat (**Appendix A**). A pert distribution was chosen with a mean serving size of 30 g per consumption day, a minimum of 8.1 g, a most likely of 20 g and a maximum of 100 g. On average people consumed 48 % of the days 'cold processed cooked meat' (=175 days (servings) per year). A normal distribution was chosen with μ is 175 servings and σ is 50 servings.

3.2.3.5 Growth model for Listeria monocytogenes

Maximum growth rates μ_{max} of RTE pâté and cooked ham were retrieved from Combase at www.combase.cc (USDA, 2023). For a reliable estimation of growth parameters, experimental growth curves were only used for estimation of the maximum growth rate if they met the following criteria: (i) if there was exponential growth, there should be at least four data points in the exponential phase, (ii) parameters of the product like a_w, pH, NaCl and sodium nitrite concentration should be reported, (iii) no specific package conditions like vacuum or modified atmosphere. For pâté the selection criteria 'organism: '*Listeria monocytogenes/innocua*'; food category: 'other or unknown type of meat'; food name: 'pâté' were used. In total, maximum growth rates (log/h) from 143 pâtés were collected in a temperature range of 0 °C and 15 °C, with a_w 0.989–0.991, pH 6.2–6.3, NaCl 1.6 % - 2.0 %, and sodium nitrite 81.3–102 ppm. For ham the selection criteria 'organism: '*Listeria monocytogenes/innocua*'; food category: 'pork'; food name: 'ham' were used. In total, maximum growth rates (log/h) from 192 hams were collected in a temperature range of 0 °C and 15 °C, with a_w 0.988–0.995, pH 6.1–6.4, NaCl 1.0 %–2.2 %, and sodium nitrite 84–110 ppm. The square root model described by Ratkowsky et al. (1982) was used to describe μ_{max} as function of temperature (T).

$$\sqrt{\mu_{max}} = b \cdot (T - T_{min}) \quad [1]$$

where μ_{max} is the maximum growth rate (log/h); b is the regression parameter determined during the modelling process the modelling process ($\sqrt{}$(log/h/°C)); T is the storage temperature (°C); and T_{min} is the theoretical lower temperature at which the estimated maximum growth rate of *L. monocytogenes* first becomes 0. A linear regression line was plotted for pâté and cooked ham, and the mean, standard error, 95 % confidence and 95 % prediction interval and the correlation coefficient (R^2) of the model were calculated (**Appendix B**). To express the variability of μ_{max} , the deviation of the $\sqrt{\mu_{max}}$ (delta$\sqrt{\mu_{max}}$) was represented by a normal distribution

with mean of 0 and standard deviation represented by the standard error of the model fit, which was found independent of temperature on this square root scale. This delta$\sqrt{\mu_{max}}$ was added to the square root model, i.e.,

$$\sqrt{\mu_{max}} = b \cdot (T - T_{min}) + delta\sqrt{\mu_{max}} \quad [2]$$

This approach differed from the method described in the FDA & FSIS risk assessment, which utilizes a baseline exponential growth rate at 5 °C with its deviation, and from that the growth rate is converted to the actual temperature with $\mu_{max} = (\mu_{max,5} + delta\mu_{max}) * [(T - T_{min}) / (5 - T_{min})]^2$ (FDA and FSIS, 2003). The approach described in the FDA and FSIS risk assessment was not used because simulations showed that the variability of $\sqrt{\mu_{max}}$ increased with increasing temperature above 5 °C. However, our study and other studies showed that the variability of $\sqrt{\mu_{max}}$ remains constant and is independent of temperature (Abe et al., 2023; Aryani et al., 2016; Le Marc et al., 2021). Note that the use of delta$\sqrt{\mu_{max}}$ may yield a negative value for $\sqrt{\mu_{max}}$. Squaring this negative value would still produce a positive μ_{max}, which is incorrect. To address this issue, first $\sqrt{\mu_{max}}$ was calculated. If the result was negative, the μ_{max} was set at zero, and when it was positive, the $\sqrt{\mu_{max}}$ was squared and used in the simulations. A more detailed description of the followed approach can be found in **Appendix C**. To verify the results, the outcome of the square root model was compared with maximum growth rates as described in the literature, but not present in Combase. Maximum population densities of *L. monocytogenes* were derived from Combase, involving 179 hams, with a recorded increase of 0.5 log CFU/g. A pert distribution was selected with a minimum of 3.6 log CFU/g, a most likely of 8.2 log CFU/g, and a maximum of 8.5 log CFU/g (Szczawiński et al., 2017; Zhang et al., 2012).

3.2.3.6 Hazard characterization

An exponential dose-response model was used to estimate the probability of illness given a dose:

$$P_{ill}(D;r) = 1 - e^{(-r \cdot D)} \quad [3]$$

where D represents the ingested dose and r is the dose-response parameter, representing the probability of illness per CFU. Two different r values were considered: r is 2.37×10^{-14} for the low-risk population and r is 1.06×10^{-12} for the susceptible population as suggested by the World Health Organization/Food and Agricultural Organization of the United Nations (WHO and FAO, 2004). The QMRA was based on the Dutch population. According to Statistics Netherlands (CBS) the total number of inhabitants was 17,475,415 dated January 1st, 2021 (Statistics Netherlands CBS, 2021). The fraction of the total population being at risk, i.e., 'susceptible or high-risk' is considered 20 % of the total population as described by Mataragas et al. (2010).

Included groups were:

- Aged population (65 years or older). It is estimated that 95 % of the high-risk group consists of elderly people (Statistics Netherlands CBS, 2021).
- Pregnant women. It is estimated that 5 % of the high-risk group consists of pregnant women (Friesema et al., 2022).

Immunocompromised people and new-born infants who are susceptible for *L. monocytogenes* were excluded, because they constitute a relatively small group and new-born infants do not consume cooked deli meats. Cross-contamination during transport from supermarket to home and during household storage was not included in the QMRA, because storage practices appeared to be much more important in terms of risk for deli-meats than cross-contamination (Yang et al., 2006).

3.2.3.7 Risk characterization

Monte Carlo simulations were performed to determine the distribution of P_{ill} using @Risk simulation software (@Risk 8.2 for Excel, Palisade, Ithaca, USA), as an add-in to Microsoft Excel, with 1,000,000 iterations. For each iteration, the risk per serving for the high-risk population ($R_{serv,hr}$) and the low-risk population ($R_{serv,lr}$), respectively was calculated by multiplying P_{ill} with the prevalence. The number of cases per year was calculated by multiplying the average arithmetic risk per serving ($R_{serv,\,hr}$ and $R_{serv,\,lr}$) with the average number of servings per year per person (Nr_{serv}) and with the number of persons in the high-risk (Pop_{hr}) and low-risk population (Pop_{lr}), respectively. The number of cases for the total population ($Nr_{cases\ avg,\,tot}$) was calculated by summating the number of cases of the high-risk population ($Nr_{cases\ avg,\,hr}$) and the low-risk population ($Nr_{cases\ avg,\,lr}$). The number of cases was also calculated performing a Bernoulli trial with 1,000,000 iterations using the P_{ill} distribution. A value of 1 indicated an illness case, whereas a value of 0 indicated no illness case. The total number of cases was then calculated by summing up all cases of the 1,000,000 iterations and multiplying this by the average prevalence, the average number of servings and the high-risk population and low-risk population per 1,000,000, respectively. This was repeated 100 times to calculate the estimated mean and the standard deviation of the number of cases. To validate the developed QMRA model, the outputs were compared with the epidemiological data for listeriosis in the Netherlands. An overview of the QMRA model and the parameters' values and/or distributions is shown in **Table 3.2**.

3.2.3.8 Sensitivity analysis

Three types of sensitivity analyses were conducted on the stochastic model (**Table 3.2**) to identify the most crucial factors influencing the probability of illness (P_{ill}) and the number of cases. A tornado chart was created to illustrate the impact of different sources of variability on the final output (P_{ill}), using Spearman's rank

correlation coefficient. Additionally five simulations (each with 1,000,000 iterations) were performed, and iterations that resulted in illness cases (denoted by a value of 1 from the Bernoulli trial) were analysed to evaluate the underlying input values. These input values were illustrated in the distribution figures as a bar code plotting. In addition, a deterministic approach was used to determine the effect of worst-case scenarios of the input variables on the final output. For this an input variable was set at a high value (e.g., P^{95} for a normal distribution) while keeping the rest of the input variables at the mean value, and then comparing the resulting risk per serving to the risk per serving in the default scenario (i.e., all input variables set to the mean value).

3.2.3.9 Intervention scenarios

To evaluate the impact of input variables on the number of listeriosis cases, 'what if' scenario analyses were conducted. The baseline model (**Table 3.2**) was modified by truncating the following input variables at various maximum limits: (i) initial concentration (maximum: 5, 4, 3 and 2 log CFU/g), (ii) storage time (maximum: 14, 10, 7, and 4 days), (iii) refrigerator temperature (maximum: 14, 10, 7, and 4 °C), (iv) a combination of storage time and refrigerator temperature (maximum: 12 days and 12 °C, 10 days and 10 °C, 7 days and 7 °C, and 4 days and 4 °C). The model was re-run for each scenario with 1,000,000 iterations. Furthermore, it was evaluated how variations in storage practices between high-risk populations and low-risk populations affected the number of listeriosis cases and the Years of Life Lost (YLL). According to the World Health Organization, 98 % of the Disability-Adjusted Life Years (DALY) estimates for listeriosis are due to YLL, which highlight the high case-fatality rate of listeriosis (FAO and WHO, 2022). The YLL were estimated based on the following assumptions: i) 95 % of the high-risk population cases consists of elderly of 65 years and older (Statistics Netherlands CBS, 2021), and 5 % of the high-risk population cases were pregnant women that gave birth to an infected baby (Friesema et al., 2022); ii) a case-fatality ratio of 0.15 was applied for perinatal listeriosis (pregnant women) and 0.25 for acquired listeriosis (in elderly and low-risk population) (De Noordhout et al., 2014; WHO and FAO, 2004); and iii) the YLL per case was estimated to be 85 years for perinatal listeriosis (life expectancy in the Netherlands (Statistics Netherlands CBS, 2021)), 10 years for acquired listeriosis in elderly above 65 years old (the median age of reported listeriosis cases in the Netherlands in 2020 was 75 years (Friesema et al., 2022)), and 43 years for acquired listeriosis for the low-risk population (the average age of people in the Netherlands is 42 years (Statistics Netherlands CBS, 2021)). The YLL of the total population was calculated using the following formula:

$$YLL_{total} = \sum_{1}^{i} number\ of\ cases_i * case\ fatality\ ratio_i * YLL_i \quad [4]$$

where *i* represents the persons of 65 years and older, the pregnant women (neonates), and the low-risk population.

Table 3.2. Overview of input variables for the QMRA model for 'Consumption, dose-response and risk of infection module'

ID	*Input variable*	*Distribution or formula*	*Unit*	*Data source/ reference*
Growth of *L. monocytogenes*				
$\sqrt{\mu_{max}}$	Growth rate (square root) of *L. monocytogenes* in cooked ham	$b \cdot (T - T_{min})$	$\sqrt{\log/h}$	Fitted with data from Combase (b: 0.015; T_{min}: -0.75 °C)
$delta\sqrt{\mu_{max}}$	Deviation of the growth rate (square root) due to variability	Normal (0; 0.0286)	$\sqrt{\log/h}$	Calculated from linear regression (square root model)
C_{max}	Maximum concentration of *L. monocytogenes* in ham	Pert (3.6; 8.2; 8.5)	log CFU/g	Fitted with C_{max} data from Combase
Initial concentration and prevalence				
C_0	Initial concentration	BetaGeneral (0.502; 2.908; -1.69; 6)	log CFU/g	EFSA (2018)
Prev	Prevalence at end of shelf life	PertAlt (2.07%; 1.63%; 2.64%)	%	EFSA (2018)
Transport to home				
$time_{tr}$	Transport time from retail to home	Uniform (0.25, 2)	h	Possas et al. (2019)
T_{tr}	Transport temperature from retail to home	BetaPert (4; 10; 25)	°C	Nauta et al. (2003)
$\mu_{max,tr}$	Growth rate during transport to home	If $(b \cdot (T_{tr} - T_{min}) + delta\sqrt{\mu_{max}}) < 0$ then 0, else: $(b \cdot (T_{tr} - T_{min}) + delta\sqrt{\mu_{max}})^2$	log/h	Calculated
C_{tr}	Concentration at end of transport towards home	Min $(C_0 + \mu_{max,tr} \cdot time_{tr}, C_{max})$	log CFU/g	Calculated

Consumer storage				
$time_h$	Household storage time	Pert (0; 1.52; 18.3)	days	Own survey with max 21 days
T_h	Household temperature refrigerator	Normal (5.68; 2.23)	°C	Own survey with min: 0 °C and max: 18 °C
$\mu_{max,h}$	Growth rate during home storage	If $(b \cdot (T_h - T_{min}) + delta\sqrt{\mu_{max}}) < 0$ then 0, else: $(b \cdot (T_h - T_{min}) + delta\sqrt{\mu_{max}})^2$	log/h	Calculated
C_{cons}	Concentration at consumption	Min $(C_{tr} + \mu_{max,h} \cdot time_h \cdot 24, C_{max})$	log CFU/g	Calculated
Consumption data				
S_{size}	Serving size (mass of cold processed meat per serving)	Pert (8.1; 20.0; 100.0)	g	Van Rossum et al. (2020)
Nr_{serv}	Number of servings (consumption days) per year per person	Normal (175, 50)	servings	Van Rossum et al. (2020) with max: 350 servings
Dose-response model				
D	Ingested dose (number of cells consumed per single serving)	$10^{Ccons} \cdot S_{size}$	CFU	Calculated
$P_{ill,\ hr}$	Probability of illness per contaminated serving for high-risk population	$1 - e^{(-r_hr \cdot D)}$		WHO and FAO (2004) with $r_{_hr}$: $1.06 * 10^{-12}$
$R_{serv,\ hr}$	Risk per serving for high-risk population	$P_{ill,hr} \cdot Prev$		Calculated
$P_{ill,\ lr}$	Probability of illness per contaminated serving for low-risk population	$1 - e^{(-r_lr \cdot D)}$		WHO and FAO (2004) with $r_{_lr}$: $2.37 * 10^{-14}$
$R_{serv,\ lr}$	Risk per serving for low-risk population	$P_{ill,\ lr} \cdot Prev$		Calculated

Population				
Pop_{tot}	Total population	17,475,415	persons	Statistics Netherlands CBS (January 1st, 2021)
Pop_{hr}	High-risk population	$0.2 \cdot Pop_{tot}$	persons	Calculated (Mataragas et al., 2010)
Pop_{lr}	Low-risk population	$0.8 \cdot Pop_{tot}$	persons	Calculated (Mataragas et al., 2010)
Illness occurrence				
$Nr_{cases\ avg,\ hr}$	Nr of illness cases per year (average) for the high-risk population	$\overline{R_{serv,hr}} \cdot \overline{Nr_{serv}} \cdot Pop_{hr}$	cases per year	Calculated with $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$ and n = 1,000,000 iterations
$Nr_{cases\ avg,\ lr}$	Nr of illness cases per year (average) for the low-risk population	$\overline{R_{serv,lr}} \cdot \overline{Nr_{serv}} \cdot Pop_{lr}$	cases per year	Calculated with $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$ and n = 1,000,000 iterations
$Nr_{cases\ avg,\ tot}$	Nr of illness cases per year (average) for the total population	$Nr_{cases\ avg,hr} + Nr_{cases\ avg,lr}$	cases per year	Calculated
$Nr_{cases\ bern,\ hr}$	Nr of illness cases per year (Bernoulli) for the high-risk population	Bernoulli ($<P_{ill,hr}$), if illness = 1, if not = 0	cases per year	Calculated by summation with n = 1,000,000 iterations, and multiplied by Nr_{serv} and corrected by Pop_{hr}.
$Nr_{cases\ bern,\ lr}$	Nr of illness cases per year (Bernoulli) for the low-risk population	Bernoulli ($<P_{ill,lr}$), if illness = 1, if not = 0	cases per year	Calculated by summation with n = 1,000,000 iterations, and multiplied by Nr_{serv} and corrected by Pop_{lr}.
$Nr_{cases\ bern,\ tot}$	Nr of illness cases per year (Bernoulli) for the total population	$Nr_{cases\ bern,hr} + Nr_{cases\ bern,lr}$	cases per year	Calculated

The following variations in household storage temperatures were included: a) default with 5.7 °C for both high-risk and low-risk population (baseline as shown in **Table 3.2**); b) difference between storage temperature of older individuals of 6.1 ◦C (persons 65 years and older) and younger individuals of 5.5 °C (low-risk population and pregnant women), based on the results of the consumer survey; c) storage temperature of the upper shelf of 7.7 °C for both high-risk and low-risk population, as determined in the 24-hour temperature measurements; and d) extreme storage temperature of the upper shelf of 13.4 °C for both high-risk and low-risk population, as determined in the 24-hour temperature measurements. To estimate the number of listeriosis cases and the YLL, the model was re-run with 1,000,000 iterations for each variation. The ratio for each variation was determined by dividing the listeriosis cases of the specific scenario by the listeriosis cases of the default scenario.

3.3 Results

In total 1020 consumers participated and completed the first part of the questionnaire (questions 1–13) and 536 consumers also measured the temperature of their refrigerator and completed the second part of the questionnaire (questions 14). Two results of the measured temperatures were invalid (temperature refrigerator of - 9 and - 13 °C), leaving 534 participants with valid temperature results.

3.3.1 Consumer knowledge and domestic refrigerators temperature analysis

The analysis of the measured temperatures of 534 domestic refrigerators (bottom shelf) showed a mean temperature of 5.7 °C (SD 2.2 °C). The measured temperatures varied from - 1 °C to 17 °C, with 66.8 % of the refrigerators with a temperature of 6 °C or lower. Following a normal distribution, the 75th percentile was determined at 7.2 °C and the 95th percentile at 9.4 °C. An overview of the distribution and the cumulative frequency is given in **Figure 3.1**. The survey showed that around 28 % of the consumers indicated 4 °C as the temperature a refrigerator should have, which is the recommended temperature in the Netherlands. Around 8 % of the respondents indicated a temperature below 4 °C, 22 % at 5 °C, 16 % at 6 °C, 18 % at 7 °C, and 8 % of the respondents at 8 °C. Based on Spearman's correlation analyses, and confirmed by the chi-square statistic, a positive and significant correlation was seen between the mentioned temperature the refrigerator should have and the measured temperature of the refrigerator (r_s = 0.667, $p < 0.01$). This means that consumers who indicated a lower recommended temperature, also measured a lower temperature of their refrigerator. Most of the respondents never checked the temperature of the refrigerator (61 %), 37 % of the participants occasionally, and 2 % regularly. Of those who indicated that they checked the temperature, approximately half of the respondents checked it with a

thermometer (45 % measuring the air temperature and 6 % the temperature in a glass of water), making it in total 20 % of all respondents checking the refrigerator with a thermometer. Multiple linear regression analyses with age, gender, and education level as independent variables and the measured or indicated recommended temperature as the predicted dependent variable showed no significant impact of gender (men, women) and education (low, middle, high). Age had a significant impact on both the measured temperature and on the indicated recommended temperature. The measured temperature of the refrigerators of older consumers (65 years and older) were on average 0.6 °C higher than that of younger consumers below 35 years of age, i.e., 6.1 °C and 5.5 °C respectively. Older consumers significantly indicated a higher recommended temperature than younger consumers (5.9 °C versus 5.0 °C). Younger consumers were better aware of the recommended temperature of 4 °C. Notably, the refrigerators with the highest measured temperature (16 and 17 °C) were both owned by old participants (79 and 86 years old). Statistical analysis showed that refrigerator's type and refrigerator's age did not significantly affect the measured temperature.

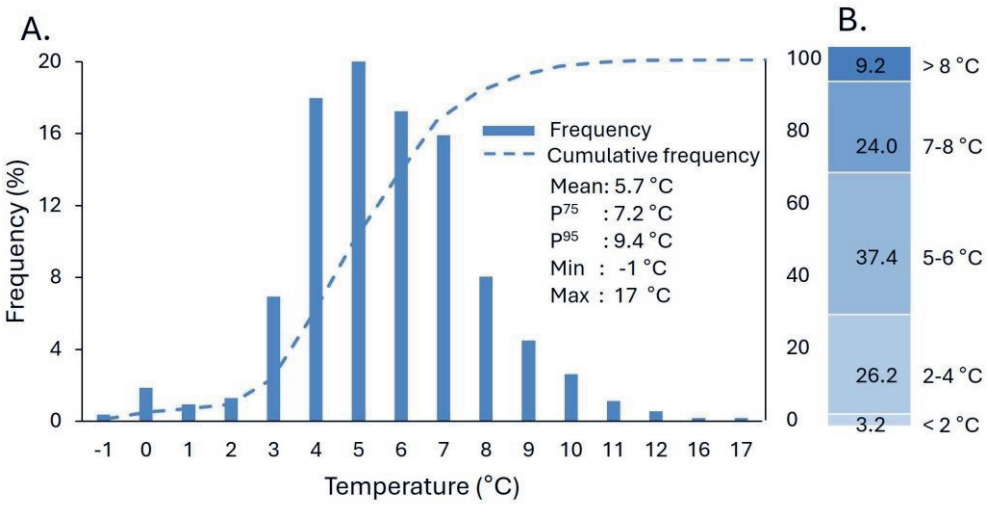


Figure 3.1. Frequency (%) and cumulative frequency (%) of the 534 domestic refrigerators with mean temperature, P^{75}, P^{95}, minimum and maximum (A). Percentage of refrigerators with temperature below 2 °C, from 2 to 4 °C, from 5 to 6 °C, from 7 to 8 °C and above 8 °C (B).

3.3.2 24-hour temperature profiles

The analysis of the 24-hour temperature profiles of 50 surveyed refrigerators showed differences in temperature inside the household refrigerators (**Figure 3.2**). The highest temperature was measured on the upper shelf (mean 7.7 °C, SD 2.7 °C) and the lowest temperature was measured on the bottom shelf (mean 5.7 °C, SD 2.1 °C). This result is almost perfectly equal (5.7 °C, SD 2.2 °C) to the results from the 534 measurements of the consumer survey. The difference was significant between the upper shelf and the middle and bottom shelf ($p < 0.05$). No significant difference was found between the middle and the bottom shelf. In general, a cyclical fluctuation of the temperature was noticed, and depending on the brand and the on-off cycles of the compressor, less or more fluctuation was noticeable per refrigerator. Seven out of fifty refrigerators showed the lowest temperatures on the upper shelf, which was the opposite from the other refrigerators. These seven refrigerators were a specific type of refrigerator with a small freezer unit at the top of the refrigerator. This freezer unit lowered the temperature of the upper shelf. As also found in the consumer survey, refrigerator's brand and refrigerator's age did not significantly affect the measured temperature. The refrigerators at the homes of the elderly were significantly warmer than the refrigerators at the other homes (student, family, single person) ($p < 0.05$).

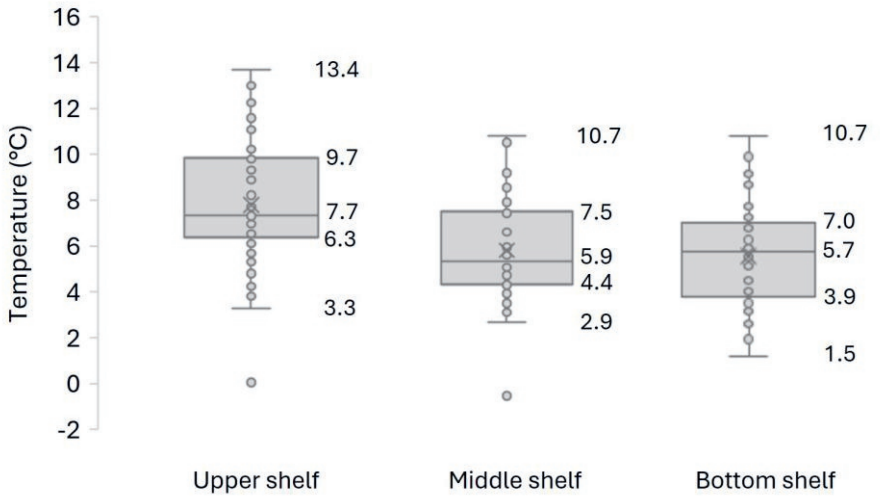


Figure 3.2. The temperature distribution of the upper shelf, middle shelf and bottom shelf within household refrigerators (n = 50) with the mean (x), median temperature, and the 5th, 25th, 75th and 95th percentile.

Especially the top shelf of the elderly was warmer than the top shelf of the other homes (0.9 °C warmer with an average of 8.3 °C).Information retrieved from the interviews showed that 34 % of the participants stored meat products on the bottom shelf, 30 % on the middle shelf, and 36 % on the top shelf or on every shelf where space is available. No significant difference was found between 24-hour temperature measurement of pâté and water (p = 0.734). Water turned out to be a good predictor of the temperature course of pâté meat products in the refrigerator. It should be noticed that in pâté it takes a longer time to go from room temperature to refrigerator temperature than in water. This can be explained by the fact that in more solid material no circular flow develops during cooling and the internal heat transfer is lower (Kandhai et al., 2009). A reliable temperature measurement of cooked ham and water could not be conducted due to the challenge of consistently finding a suitable measuring point within the thin slices of the cooked ham using the data logger.

3.3.3 Maximum growth rates of *L. monocytogenes* in pâté and ham

In **Figure 3.3** the maximum growth rates in 143 different pâté meat products and 192 different cooked ham meat products are shown that were extracted from Combase. A square root model was fitted to the data to determine the maximum growth rate (μ_{max}) of *L. monocytogenes* and its variation in pâté and cooked ham meat products as function of temperature. The maximum growth rates found in the literature, and which were not included in Combase (Beumer et al., 1996; Farber et al., 1995; Glass and Doyle, 1989; Hayrapetyan et al., 2012; Hudson and Mott, 1993; Hunt et al., 2018), fitted within the prediction intervals of the respective product types. In addition, more variability was visible in the cooked ham meat products than in pâté. This may be due to more variability in the components of ham (e.g., more variation in salt content) and therefore the ability of *L. monocytogenes* to grow also varies. In the QMRA model, the growth rate of cooked ham meat product was chosen to represent the RTE cooked meat products. This decision was based on the fact that in the Netherlands, the consumption of cooked ham meat products is more than seven times higher than that of pâté (Van Rossum et al., 2020). Furthermore, the composition of cooked ham is more similar to the other RTE cooked meat products mentioned in **Appendix A** than pâté. A lag phase was not included in the primary growth model. According to the data reported in Combase, with a maximum culturing and pre-culturing temperature of 15 °C, in 132 out of the 192 hams, the lag time was not significantly different from zero. For those studies reporting a lag time, it ranged from 2 h to 522 h, with an average lag time of 95 h. Therefore, since in most cases (approximately 68 %) the lag phase was zero, and in cases where a lag phase did exist, the assumption was made that the lag time would have passed by the time the consumer purchases the product. This approach opts for the safe side.

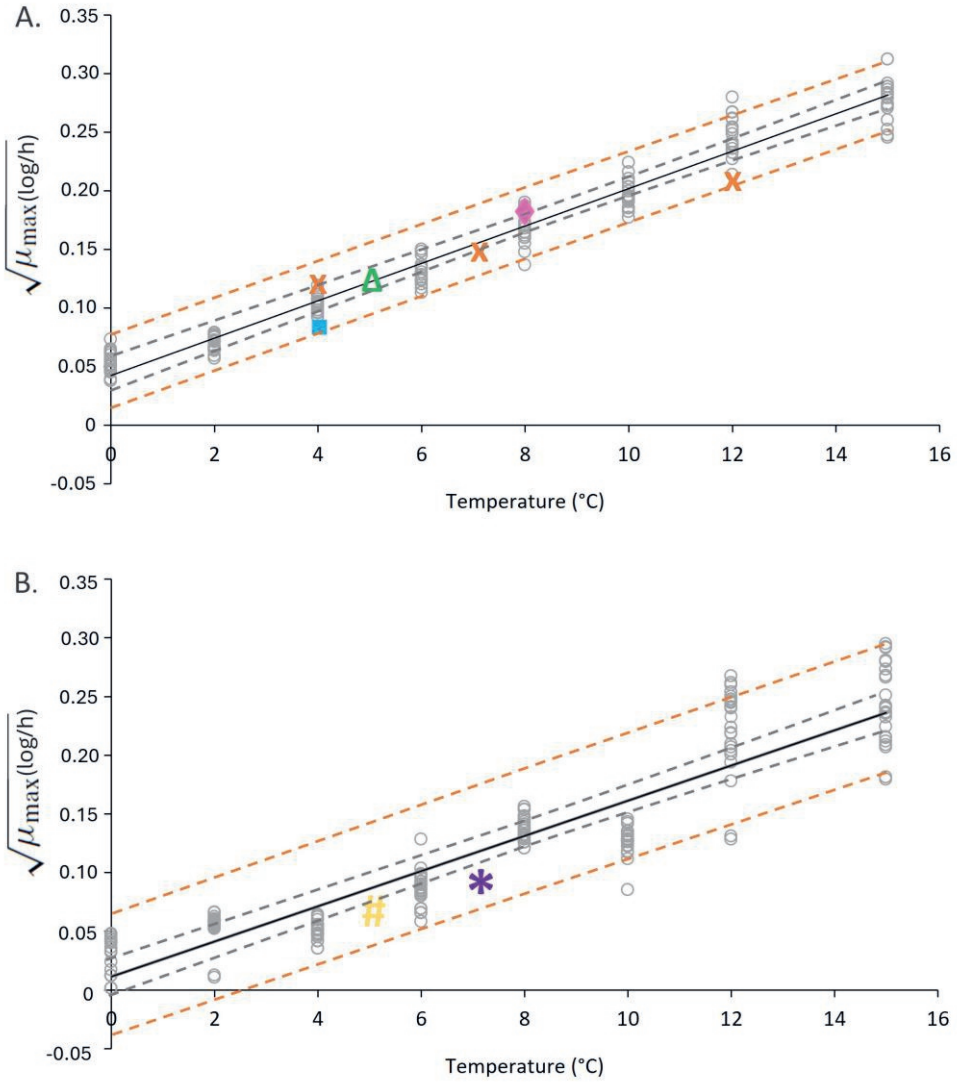


Figure 3.3. Square root plot of maximum growth rate ($\sqrt{\mu_{max}}$) of *L. monocytogenes* in pâté meat products (A) and cooked ham meat products (B) as function of temperature. Open dots represent the maximum growth rates extracted from Combase, solid line indicates the square root function (A: $\sqrt{\mu_{max}} = 0.0159 \cdot (T + 2.67)$; B: $\sqrt{\mu_{max}} = 0.0150 \cdot (T + 0.75)$), grey dashed lines indicate the upper and lower 95 % confidence intervals of the model and orange dashed lines indicate the upper and lower 95 % prediction interval. Calculated with a standard error of 0.0144 for pâté and 0.0286 for cooked ham. The coloured symbols represent growth rates from literature (Hayrapetyan et al., 2012; Hudson and Mott, 1993; Farber et al., 1995; Hunt et al., 2018; Beumer et al., 1996; Glass and Doyle, 1989).

3.3.4 Quantitative microbiological risk assessment (QMRA)

The QMRA model predicted an average number of 191 illness cases per year (SD 54) for the total population. As expected, the high-risk populations displayed a significant higher risk of listeriosis compared to the low-risk population (175 cases versus 16 cases). With 1,000,000 iterations the Bernouilli trial gave on average the same results as the calculation with the arithmetic mean.

3.3.4.1 Sensitivity analysis

To evaluate the influence of input variability on the outcome variability, a sensitivity analysis was conducted, and the results are visualized in a tornado plot (**Figure 3.4**). Variability in the initial concentration of *L. monocytogenes* has the largest impact on the variability in the probability of illness (P_{ill}) associated with the consumption of RTE cooked meat products. Household storage time and household storage temperature were also found to be significant contributors, followed by the variability on the growth rate of *L. monocytogenes* and the serving size. Using a deterministic approach with fixed input variables at their respective minimum and maximum, also showed that the initial concentration, household storage time, household storage temperature and variability in the growth rate had the largest impact on the final output (**Appendix D**). This confirmed the output of the sensitivity analysis as shown in **Figure 3.4**.

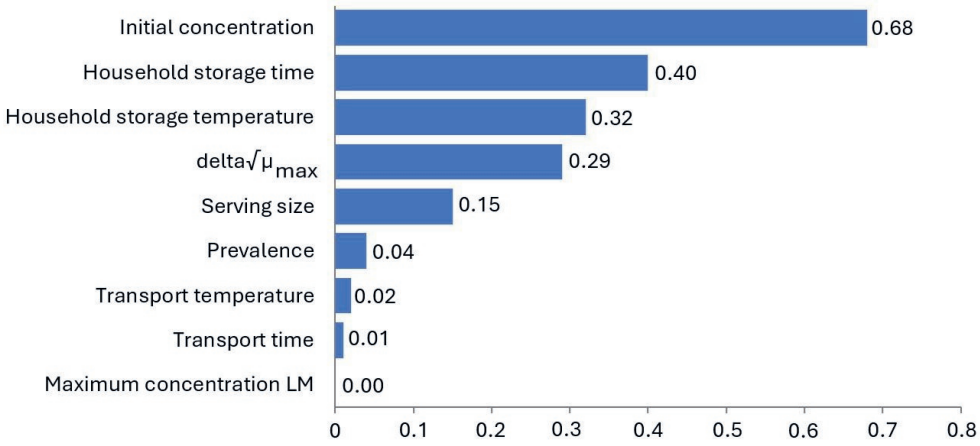


Figure 3.4. Sensitivity analysis showing the correlation coefficients (Spearman's rank) of the variability of the input factors on the variability of the probability of illness (P_{ill}).

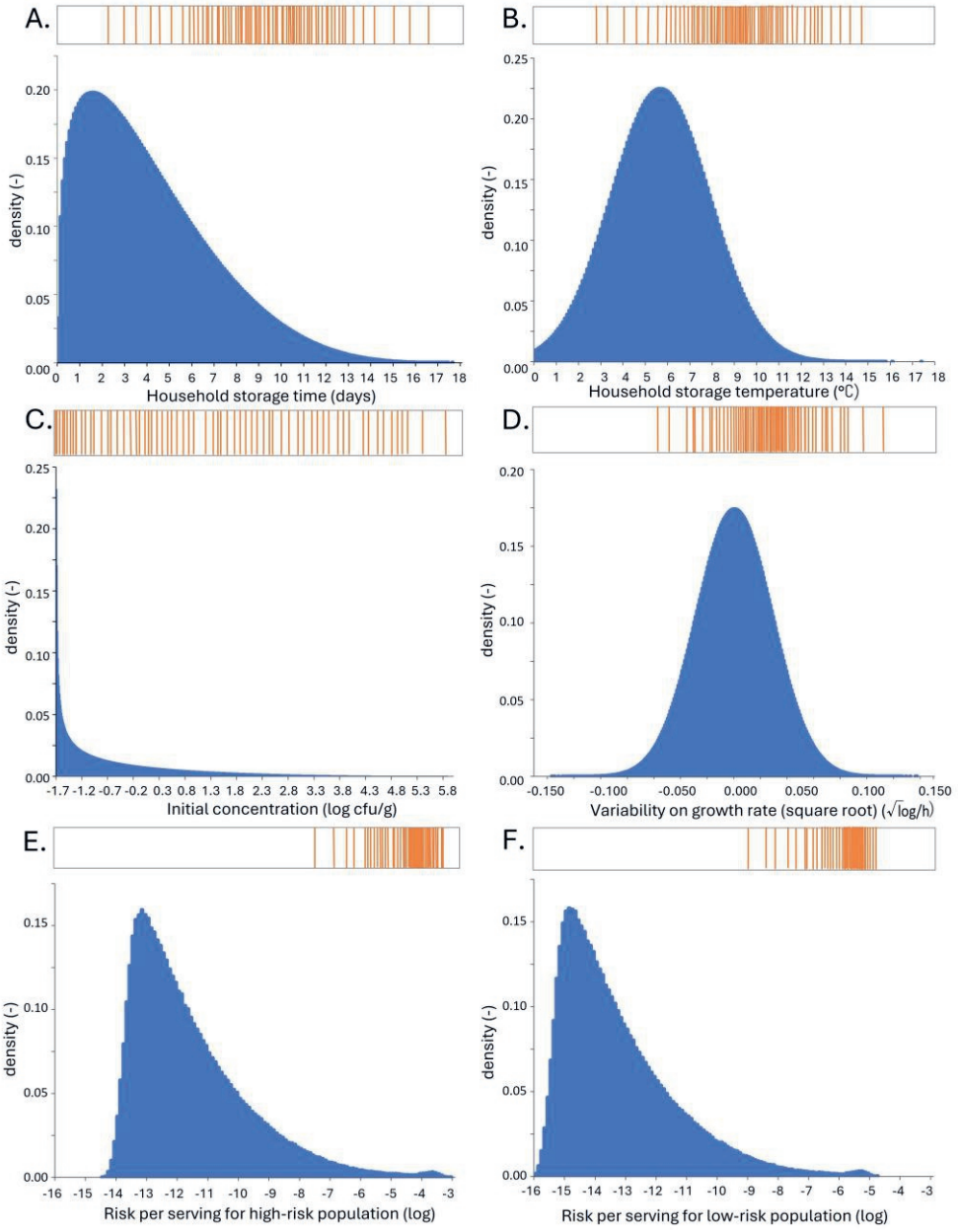


Figure 3.5. The distribution of the household storage time (A), household storage temperature (B), initial concentration (C), variability on growth rate (square root) (D), risk per serving for the high-risk population (E), and risk per serving for the low-risk population (F) of 1,000,000 iterations (blue distribution chart) and the corresponding input values from five simulations that resulted in an illness case (orange barcode chart). The orange bars represent all the cases from both the high-risk and the low-risk group in all the panels.

To further explore the factors that contributed to illness cases, the input values of the most important variables that resulted in an illness case were visualized with a barcode of (orange) lines plotted in the input distributions in **Figure 3.5**, following the approach proposed by Abe et al. (2023). Based on model simulations, the average storage time for illness cases was 9.7 days (SD 2.6 days), and the average refrigerator's temperature for these cases was 9.1 °C (SD 1.9 °C). Most of the cases were attributable to storage for >7 days or at refrigerator's temperature above 7 °C. Conversely, the distribution of illness cases for initial concentration was more evenly spread (mean 1.3 log CFU/g; SD 2.1). For growth rate variability, the cases of illness were associated with a positive deviation of the mean (mean 0.0356 $\sqrt{\log/h}$; SD 0.0263). **Figure 3.5E** and **F** show that cases of illness were linked to a relatively very high risk per serving, where the risk per serving was higher for the high-risk population (mean - 4.2 log; SD 0.6) than for the low-risk population (mean - 5.9 log; SD 0.6), and considerably higher than the mean risk per serving for all 1,000,000 iterations (- 13.1 log (SD 1.8) and - 14.7 log (SD 1.8) for high- and low-risk populations, respectively).

3.3.4.2 Scenarios

A scenario analysis was conducted to determine the impact of various input variables on the estimation of the risk of listeriosis from RTE cooked meat products. Four input variables were selected for assessing potential interventions to reduce the number of listeriosis cases: (i) initial concentration, (ii) household storage time, (iii) household storage temperature, and (iv) combination of household storage time and temperature (**Figure 3.6**). The grey boxplot refers to the default scenario (**Table 3.2**), while the red, green, blue, and yellow boxplots represent different scenarios with truncated input values. The analysis showed that a maximum temperature of 4 °C or a maximum storage time of 4 days reduced the estimated number of cases of listeriosis to almost zero. A maximum storage time of 7 days or a maximum storage temperature of 7 °C also reduced the number of cases significantly (83 % and 80 % respectively). A reduction was also visible by reducing the maximum initial concentration, but to a smaller extent than reducing the household storage time and temperature. Improving both household storage time and temperature resulted in even more significant decrease of annual cases of listeriosis. These results demonstrate that consumer behaviour, such as reducing storage time and controlling refrigerator temperature at home, can significantly reduce the risk of listeriosis. Additional scenario analyses were performed to account for differences in household storage practices among high-risk and low-risk consumer groups (**Appendix E**). Comparing the default scenario, where the mean temperature of the refrigerator was 5.7 °C for all consumer groups, with the scenario where the mean temperature of the refrigerator was 6.1 °C for the

Box 3.1 Recalculation of the mean and standard deviation (SD) (not published in IJFM 413, 110516)

In addition to the calculations of the mean and SD of the number of illness cases as described in **Section 3.2.3.7**, a recalculation of the mean and SD was performed using a similar methodology as applied in the *Campylobacter* study (**Chapter 4**). In **Figure 3.6A**, the mean and SD were estimated using 100 Bernoulli trials of 1 million iterations. This approach reflects the variability in a sample of one million contaminated servings, corrected for the total number of contaminated servings in the population per year. In the additional, more extensive simulation, the variability associated with all contaminated servings consumed annually in the population was also directly estimated. The number of contaminated servings consumed per year was estimated as the product of the total population, the prevalence, and the average number of servings. This resulted in approximately 64 million contaminated servings per year. The annual number of illness cases was therefore simulated using 64 Bernoulli trials of 1,000,000 iterations, representing the total number of contaminated servings consumed in the population. The total number of illness cases per year was obtained by summing the illness outcomes across all 64 trials. To estimate the mean and SD of the annual number of cases, this procedure was repeated 50 times, representing 50 simulated years. The results are presented in **Figure 3.6B**. The estimated mean number of cases is approximately equal to that obtained using the method applied in **Figure 3.6A**, e.g., 191 cases per year for the default scenario. However, the variability of the default scenario is substantially lower, e.g., an SD of 8 instead of 54 cases. The new approach better reflects the variation across years and is more consistent with the expected variation at the population level over the years. For comparison, the National Institute for Public Health and Environment reported an average of 92 cases with an SD of 15 cases of listeriosis per year from 2011 to 2020 (Friesema et al., 2022).

elderly and 5.5 °C for the younger generation, resulted in an overall 1.3-fold increase of illness cases. This increase was primarily observed in the elderly, with a significant higher number of cases, while the younger generation showed a slightly lower number of cases. Furthermore, comparing the default scenario with the scenario where the mean temperature of the refrigerator was set at 7.7 °C (average temperature of the upper shelf) for all consumer groups, resulted in a 3.3-fold increase in number of illness cases. Moreover, comparing the default scenario with the scenario where the temperature of the refrigerator was set at 13.4 °C (extreme temperature measured at the 24-hour temperature measurements) for all consumer groups, resulted in a 30-fold increase in the number of illness cases.

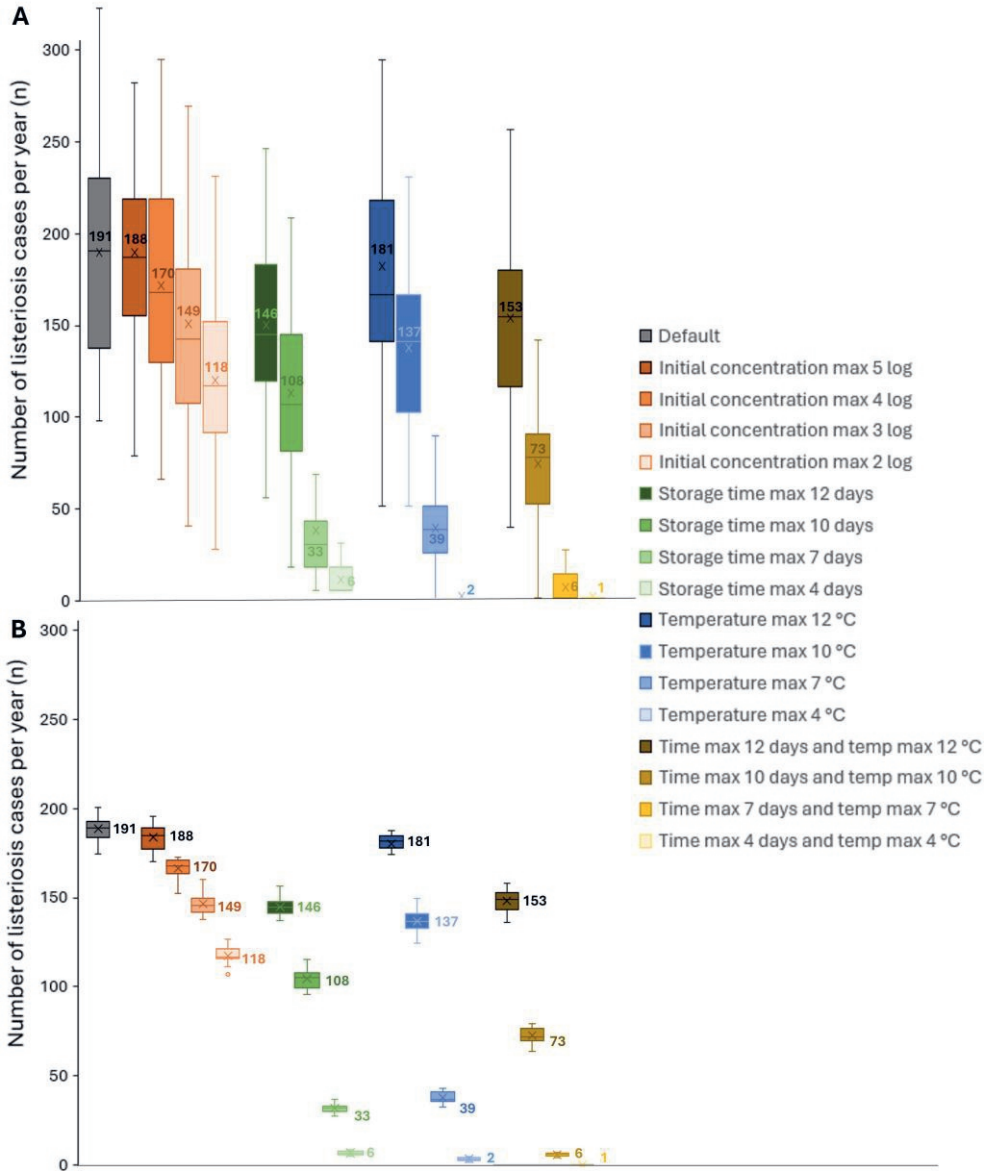


Figure 3.6A. Number of listeriosis cases per year with four scenarios: initial concentrations (max 5, 4, 3, 2 log CFU/g, red), household storage times (max 12, 10, 7, 4 days, green), household storage temperatures (max 12, 10, 7, 4 °C, blue), and combined storage time-temperature (yellow), compared with the default (grey). Boxplots show mean (x), median (line), P^{25} (bottom boxplot), P^{75} (upper boxplot), minimum and maximum (see **Section 3.2.3.7**). All other variables follow the default scenario. **Figure 3.6B** applies the same approach as **Figure 3.6A**, using a methodology similar to the *Campylobacter* study [see **Text Box 3.1**] (not published in IJFM 413, 110516).

It is important to note that it is unrealistic to assume that all individuals store their RTE cooked meat products at such high temperatures. However, it is important to consider this factor of increase for individuals who do store their RTE cooked meat products at elevated temperatures.

3.4 Discussion

Consumers play an important role in risk reduction associated with *L. monocytogenes*, as individuals make food handling decisions in purchasing, storage and cooking practices in their homes. One of the most commonly reported consumer food safety practices that increases the concentration of *L. monocytogenes* are not using proper refrigeration storage (FAO and WHO, 2022). The current study analysed the knowledge and practice of household refrigeration of Dutch consumers. A mean temperature of 5.7 °C was found, which is within the range of temperatures appropriate for the preservation of perishable RTE products (≤6 °C) as recommended by the Codex Alimentarius (CAC, 2007c). However, 33.7 % of the refrigerators had a temperature above the recommended value of 6 °C (**Figure 3.1**), the 75th percentile being at 7.2 °C, and the 95th percentile being at 9.4 °C. These results are in agreement with the outputs of a review by James et al. (2017) showing that the temperature performance of household refrigerators has not remarkably changed over the last decades, with mean air temperatures ranging from 3.5 to 9.3 °C in different European countries. Despite the temperature recommendations included in numerous food safety campaigns among consumers, the storage temperature of chilled foods is frequently above 6 °C. The reasons for the difference between recommendations and actual practices are unclear. A lack of knowledge of the recommended temperature may be a contributing factor. The current study demonstrated that a majority (72 %) of the Dutch consumers is not familiar with the recommended temperature of 4 °C. Consumers who were familiar with the recommended temperature, have a significantly lower temperature of household refrigerator and this temperature came more in line with the recommendation. This could indicate that knowledge does have an effect on the behaviour regarding refrigeration. Especially younger consumers were more aware of the recommended temperature. Another contributing factor could be a lack of perceived importance or risk control benefit. Optimistic bias, a cognitive bias that causes people to believe that they are less likely to experience a negative event than others, may encourage people to risky food behaviours (Clayton and Griffith, 2004; Da Cunha et al., 2015; Evans et al., 2020; Rodrigues et al., 2020). In this study most respondents never checked the temperature of the refrigerator (61 %), indicating a lack of perceived importance or risk control. The measured temperature of the refrigerator of older consumers (above 65 years old) was higher than that of younger consumers. Also the outliers of measured temperatures of 16 °C and 17 °C were measured at households of older consumers (above 80 years old). Looking at the risk of serious health impact due to listeriosis, this is also the group of people who have an increased risk. For

example, in the cantaloupe outbreak in the United States of America, the median age of patients who became ill was 78 years; the median age of persons who died was 81 years (McLauchlin et al., 2004). The surveillance data in the Netherlands showed that the highest mean annual number of listeriosis cases was recorded for the age group above 65 years old. The median age of the reported cases in 2020 was 75 years old, with 62 % being male (Friesema et al., 2022). Since the beginning of EU-level surveillance, most listeriosis cases have been reported in elderly people, in particular those over 64 years of age (EFSA BIOHAZ Panel, 2018). The population of older susceptible consumers is increasing and may represent up to 30 % of the general population in the future (Farber et al., 2021). The importance of good temperature and time control is an important control measure to reduce the risk of getting listeriosis, especially for the older generation. The temperature measured inside the different compartments of the refrigerators varied. The 24-hour temperature profile of the surveyed refrigerators in this study showed that the temperature measured on the upper shelf was significantly higher (7.7 °C) than the temperature measured on the bottom shelf (5.7 °C). Both the 24-hour temperature measurement with 50 refrigerators and the temperature measurement of the consumer survey with 534 refrigerators had, on average, the same temperature on the bottom shelf (5.7 °C (SD 2.1 °C) and 5.7 °C (SD 2.2 °C), respectively). The large difference of temperature between the upper and lower shelf indicates that for the best temperature measurement in the refrigerator, two or three temperature points (top, middle, and bottom) may be needed, as also suggested in other studies (George et al., 2010; Laguerre et al., 2002). But the question is whether consumers are prepared to use multiple thermometers to check the temperature of their refrigerator. The survey showed that only a minority of the consumers check the temperature of the refrigerator (39 %). And if they did, it was only with one thermometer at one point in the refrigerator. This suggests that a more intelligent system for monitoring refrigerator temperatures is needed; one that provides more interactions with, and feedback to, the householder. To meet the recommendation of the Codex Alimentarius (CAC, 2007c) that perishable RTE products should be stored below 6 °C, consumers should be informed to store these products on the bottom or middle shelf. The survey showed that two thirds of the participants stored meat products indeed on the bottom or middle shelf (32 out of 50 participants), but more research is needed to evaluate how this varies among different countries. Jofré et al. (2019) noticed that most of the interviewed consumers in Spain claimed to store cooked meat products in the refrigerator core (94 %), especially on the upper shelves. Although the general advice towards consumers should be to store RTE cooked meat products on the bottom or middle shelf, there can be some exceptions. The survey showed that refrigerators with a freezer unit on top of the fridge showed the lowest temperatures on the upper shelf, which was the opposite from the other refrigerators. RTE cooked meat products are associated with the highest number of listeriosis cases (FDA and FSIS, 2003; Sampedro et al., 2022). Deli meats were ranked as very high risk by the U.S. Food and Drug Administration, both per serving and per annum. This high risk ranking is

due to their relatively high contamination levels, their ability to support growth of *L. monocytogenes* under refrigerated storage, their prolonged storage, and their high consumption frequency (FDA and FSIS, 2003). To assess the ability of *L. monocytogenes* to grow under refrigerated conditions in cooked meat products, growth rates are required. The growth of *L. monocytogenes* is described by the relationship between growth rate and temperature represented by a square root linear regression model (Ratkowsky et al., 1982). Many growth rates were collected from Combase, and it was possible to generate a linear regression model for pâté (R^2 = 0.97) and cooked ham (R^2 = 0.86). The constituents (e.g., the use of growth inhibitors or salt) and the type of packaging or package atmosphere are important parameters for the growth of *L. monocytogenes*. Several studies showed that modified atmosphere packaging slows down the growth of *L. monocytogenes* compared to air packaging or vacuum packaging (Devlieghere et al., 2001; EFSA BIOHAZ Panel, 2018). However, since the packaging is typically opened at home, this QMRA analysis only considered results without specific packaging conditions. This approach is considered a worst-case scenario because even during the transportation from the supermarket to home and the first few days at home, the package may remain sealed under conditions that partly inhibit the growth of *L. monocytogenes*, such as modified atmosphere packaging. Additionally, RTE cooked ham was selected as a representative for RTE cooked meat products in the QMRA model. It is important to note that in reality, there is a lot of variation in RTE cooked meat products due to differences in composition, processing and packaging. A quantitative microbiological risk assessment (QMRA) was performed to estimate the risk per serving and predict the annual number of listeriosis cases. The model predicted an average number of 191 cases of illness per year for the total population through the consumption of RTE cooked meat products, which translates to 1.09 cases per 100,000 individuals. In comparison, the National Institute for Public Health and Environment reported an average of 92 cases of listeriosis per year in total (0.53 cases per 100,000 individuals) through the mandatory notification system in the Netherlands from 2011 to 2020 (Friesema et al., 2022). The QMRA model thus predicted a higher incidence of listeriosis cases than what was observed through epidemiological data. This may be due to the fact that risk assessment models tend to rely on worst-case scenarios, assumptions, and estimates. For example, the model does not take into account the variability of the virulence of *L. monocytogenes* strains, variability of susceptibility within the population, or changes in susceptibility to *L. monocytogenes* infection over time. Additionally, products that are stored for longer periods at higher temperatures (which are associated with higher predicted risk) are more likely to be spoiled and not consumed. Also, the presence of background flora (e.g., lactic acid bacteria) is considered an additional factor that affects the growth of *L. monocytogenes*, since lactic acid bacteria act as competitors and may suppress the pathogen when they reach a critical density population (Lardeux et al., 2015; Mejlholm and Dalgaard, 2015; Tsaloumi et al., 2021). Furthermore, not all packages will be opened immediately upon arrival at home, but some may remain closed in the refrigerator

for a few days. On the other hand, discrepancies between the model predictions and reported incidence rates may also be attributed to underdiagnosis within microbiological surveillance systems, as has been observed for listeriosis. Scallan et al. (2011) estimated that there was a 2.1-fold factor of underdiagnosis for listeriosis. Taken all these factors into account, caution is required when interpreting the absolute results of QMRA models, and the limitations of the model inputs and assumptions should be taken into consideration. However, the outcomes derived from the QMRA model, and especially the relative effects, can be useful in evaluating key input variables and anticipating potential consequences of various scenarios related to the risk of listeriosis. The sensitivity analysis showed that initial concentration, storage time and temperature at home were important factors that contributed to the risk of listeriosis. Most of the predicted illness cases were attributed to the storage of RTE cooked meat products for >7 days and/or at a temperature of 7 °C or above. Besides home storage, also initial concentration was an important factor that contributed to the risk of listeriosis. This was to be expected since a high initial concentration is also more likely to end up in a final concentration that can make people sick. A scenario where the RTE cooked meat products that are contaminated with *L. monocytogenes* do not exceed the 100 CFU/g at the point of sale, predicted a reduction of the illness cases by 50 %. This suggests that approximately half of the current occurrences of listeriosis cases are likely caused by foods that have a level of *L. monocytogenes* exceeding the legal limit, even already at the point of sale. The QMRA model showed that the high-risk population accounted for >90 % of predicted illness cases (175 cases of the 191 cases in total). When assessing the impact of disease in terms of Years of Life Lost (YLL), the contribution of the elderly was 60 %. Both outcomes indicate a significant contribution of the elderly group. Targeted risk communication about the risk of listeriosis is available in many countries, as well as in the Netherlands, for immunocompromised persons and pregnant women. Specific advice is given about (avoiding) risky foods and control measures that can reduce risks in the home kitchen (Health Council of the Netherlands, 2021). For the elderly, targeted communication to reduce the risk of listeriosis is much less available and less common. Yet, the QMRA model showed that the vast majority of illness cases and YLL are in this group and it is expected that this will even further increase (EFSA BIOHAZ Panel, 2018). The rapid aging population in the Netherlands and Europe, and the increase in chronic age-related diseases contributes to this high predicted number of illnesses (Statistics Netherlands CBS, 2021). In addition, specific food-handling behaviours which are more common among the older generation than the younger generation (e.g., a lack of adherence to use-by dates and ineffective refrigerated storage of RTE foods) increase this risk (FAO and WHO, 2022). Our study showed that especially the more extreme high storage conditions were found in refrigerators of elderly and this indicates that there is a need for more targeted communication about good storage practices that can be taken in the home kitchen. Especially prevention of outliers can have a serious effect. Specific advice can be given to the elderly, such as

setting a maximum temperature for the home refrigerator, storing RTE cooked meat products on the bottom or middle shelf of the refrigerator, and establishing a maximum storage time for opened RTE cooked meat product. From the distribution data, as shown in **Figure 3.5A**, it can be seen that the first cases of illness occur after a storage time of 2 to 3 days. This aligns with the Dutch Health Council's recommendation for pregnant women, suggesting consumption of products capable of supporting *L. monocytogenes* growth within the stated shelf life date and, once opened, within 2 to 3 days (Health Council of the Netherlands, 2021). However, the exact duration for storing opened RTE cooked meat products can vary due to factors like storage temperature, the presence of preservatives or inhibitors, and the timing of product opening (Couvert et al., 2017; Devlieghere et al., 2001). Manufacturers should be encouraged to conduct appropriate challenge tests to more accurately determine the post-opening storage duration based on specific product characteristics, as also stipulated in Regulation (EU) No 1169/2011 (2011). Also awareness of risky products needs to be improved as mentioned in a meeting report about *L. monocytogenes* in RTE foods (FAO and WHO, 2022). Further research is necessary to understand how targeted communication can be effectively organized. Reducing the risk of listeriosis is a shared responsibility. Consumers must be involved, yet the manufacturer remains also an important stakeholder in reducing the risk of listeriosis for the simple reason that if *L. monocytogenes* is not present in the product, it cannot lead to any disease. In conclusion, while the mean temperature of household refrigeration of Dutch consumers is appropriate for preserving perishable ready-to-eat products, a significant proportion of refrigerators had temperatures above the recommended value. A lack of knowledge, optimistic bias, and a lack of perceived importance of risk control may contribute to this difference. To reduce the risk of listeriosis, the importance of storing RTE foods at the recommended temperature on the bottom or middle shelf as well as consuming them within a few days after opening, should be highlighted. Raising awareness among stakeholders, especially towards older consumers who are at higher risk, is essential in decreasing the disease burden.

3.5 Data availability

The used QMRA model, along with the outcomes of one simulation with 10,000 iterations and another simulation with 1,000,000 iterations, is available at https://doi.org/10.4121/98b4d5dd-7b07-48c0-bbc7-62a2f10944b1.

3.6 Acknowledgment

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3.7 Supplementary material

3.7.1 Appendix A. List of RTE cooked meat products

Table A1. List of food products which were chosen from the Dutch National Food Consumption Survey 2012-2016 (available at https://statline.rivm.nl) as representative for RTE cooked meat like pâté or ham to estimate the consumption frequency and serving size

Pork fricandeau fried	Beef salted cooked
Ham lean boiled	Pork rolled (processed meat)
Gammon boiled deboned	Processed meat prod excl liver
Ham shoulder medium fat boiled	Sausage luncheon meat lean
Sandwich meat chicken	Sausage cooked
Liver pork boiled	Sausage grill
Sausage luncheon meat	Sausage grill chicken
Pork side cured and smoked	Sausage grill w cheese
Corned beef	Liver sausage
Minced meat loaf fried	Liver sausage coarse hausmacher
Ham lean grilled	Sausage w smoked bacon-bits
Sandwich meat turkey	Liver pate sausage
Liver ox boiled	Sausage tongue
Liver pate/Berliner liver sausage	Brawn, pork pickled in vinegar
Liver pate	Luncheon meat tinned
Pate	
Pate spreadable lean	

3.7.2 Appendix B. Maximum growth rates, lag time and maximum concentrations for cooked ham and maximum growth rates for pâté with the mean, standard error, 95 % confidence and 95 % prediction interval and the correlation coefficient (R^2)

The complete dataset of this Appendix is provided in https://doi.org/10.1016/j.ijfoodmicro.2023.110516.

3.7.3 Appendix C. Including variability of μ_{max} in the QMRA analysis.

To express the variability of μ_{max} , the deviation of the $\sqrt{\mu_{max}}$ ($delta\sqrt{\mu_{max}}$) was represented by a normal distribution with mean of 0 and standard deviation represented by the standard error of the model fit, which was independent of temperature (see **Figure 3.3**). This $delta\sqrt{\mu_{max}}$ was added to the square root model:

$$\sqrt{\mu_{max}} = b \cdot (T - T_{min}) + delta\sqrt{\mu_{max}} \quad [C1]$$

This approach differed from the method described in the FDA/FSIS risk assessment, which utilizes a baseline exponential growth rate at 5 °C (FDA and FSIS, 2003) by translating all growth rates to one reference temperature, where

$$\sqrt{\mu_{max,5}} = b \cdot (5 - T_{min}), \text{ or } b = \sqrt{\mu_{max,5}} / (5 - T_{min}) \quad [C2]$$

resulting in

$$\sqrt{\mu_{max}} = \sqrt{\mu_{max,5}} \cdot (T - T_{min}) / (5 - T_{min}) \quad [C3]$$

And

$$\sqrt{\mu_{max,5}} = \sqrt{\mu_{max}} \cdot (5 - T_{min}) / (T - T_{min}) \quad [C4]$$

Equation C4 was used to transform all growth rate data to a $\sqrt{\mu_{max,5}}$ and equation C3 to determine then in the simulations the growth rates at other temperatures. The deviation of μ_{max} ($delta\ \mu_{max}$) was added to square root of the baseline exponential growth rate at 5 °C ($\mu_{max,5}$).

$$\mu_{max} = (\mu_{max,5} + delta\ \mu_{max}) \cdot [(T - T_{min}) / (5 - T_{min})]^2 \quad [C5]$$

Figure C visualizes the confidence and prediction band of the square root model used in our study (**Figure C1**) and the square root model described in the FDA & FSIS risk assessment (**Figure C2**). It can be seen that the prediction band is widening in the method used by the FDA and FSIS risk assessment. The higher the temperature, the higher the variability. However, our study and other studies showed that variability for $\sqrt{\mu_{max}}$ remains constant as function of temperature and is independent of temperature, and the confidence and prediction band aligns parallel to the regression line of the model fit (Abe et al., 2023; Aryani et al., 2016; Le Marc et al., 2021). Based on these findings, we calculated $\sqrt{\mu_{max}}$ and accumulated the deviation of $\sqrt{\mu_{max}}$, as this method ensures a constant level of variability.

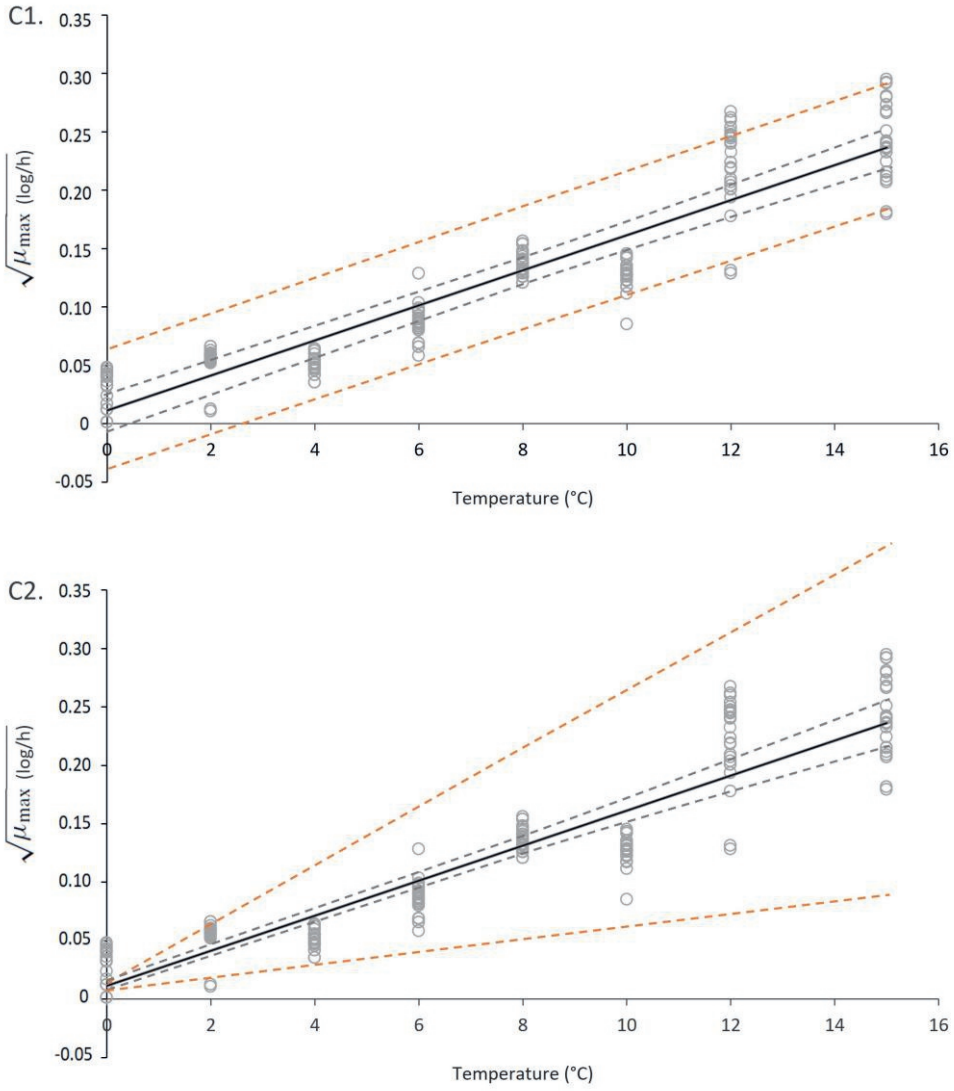


Figure C. Square root plot of maximum growth rate ($\sqrt{\mu_{max}}$) of *L. monocytogenes* in cooked ham meat products as function of temperature, as determined in our study (**Figure C1**) and the square root model described in the FDA/FSIS risk assessment (**Figure C2**). The solid line indicates the square root function, grey dashed lines indicate the upper and lower 95 % confidence intervals of the model and orange dashed lines indicate the upper and lower 95 % prediction interval; calculated with a standard deviation of 0.0286 for cooked ham. For visualisation purposes the deltaμ_{max} for the FDA/FSIS model was determined, so that at 5 °C the bands in C1 and C2 are exactly equal, using $\sqrt{\mu_{max}} = (\sqrt{\mu_{max,5}} + delta\sqrt{\mu_{max,5}}) \cdot (T - T_{min}) / (5 - T_{min})$.

Simulations of using our method (**Figure C1**) or the method used by the FDA/FSIS (**Figure C2**) in the QMRA analysis showed that the number of illnesses doubled when the method as described in the FDA/FSIS risk assessment was used, compared to our method (388 versus 191, respectively). This would also mean that by adding the error term to the reference μ_{max} and then multiplying this with the temperature effect, the error increases above the reference temperature (i.e. 5 °C), and decreases below the reference temperature.
In conclusion, it can be stated that a constant variability in the square root of the growth rate can be incorporated into the square root model in the following manner:

$$\sqrt{\mu_{max}} = b \cdot (T - T_{min}) + delta\sqrt{\mu_{max}}, \text{ and} \quad [C6]$$

$$\mu_{max} = (b \cdot (T - T_{min}) + delta\sqrt{\mu_{max}})^2 \quad [C7]$$

or

$$\sqrt{\mu_{max}} = \sqrt{\mu_{max,5}} \cdot (T - T_{min}) / (5 - T_{min}) + delta\sqrt{\mu_{max}}, \text{ and} \quad [C8]$$

$$\mu_{max} = (\sqrt{\mu_{max,5}} \cdot (T - T_{min}) / (5 - T_{min}) + delta\sqrt{\mu_{max}})^2 \quad [C9]$$

But if the error is included as in C5, the error is also multiplied by the temperature effect and not constant.
Another issue arose that the use of $delta\sqrt{\mu_{max}}$ may yield a negative value for $\sqrt{\mu_{max}}$. Squaring this negative value would still produce a positive μ_{max}, which is incorrect. To address this issue, first $\sqrt{\mu_{max}}$ was calculated. If the result was negative the μ_{max} was set at zero, and when it was positive, the $\sqrt{\mu_{max}}$ was squared and used in the simulations.

$$\text{If } \sqrt{\mu_{max}} = (b \cdot (T_h - T_{min}) + delta\sqrt{\mu_{max}}) < 0 \text{ then } \mu_{max} = 0; \quad [C10]$$

$$\text{else } \mu_{max} = (b \cdot (T_h - T_{min}) + delta\sqrt{\mu_{max}})^2 \quad [C11]$$

3.7.4 Appendix D. Influence of an extreme high value of the individual input variable on the final risk output by using the deterministic model

Table D1. Deterministic approach to evaluate the influence of an extreme value of an individual input variable on the risk per serving while keeping the rest of the variables at the mean value

ID	*Input variable*	*Extreme*	*Unit*	*Default*	*delta* $\sqrt{\mu}_{max}$	C_0	*Prev*	$Time_{tr}$	T_{tr}	$Time_h$	T_h	S_{size}	Nr_{serv}
	Growth of *L. monocytogenes*												
$\sqrt{\mu}_{max}$	Growth rate (square root) in cooked ham		$\sqrt{log/h}$										
$delta\sqrt{\mu}_{max}$	Deviation of the growth rate (square root) due to variability	**0.0570**	$\sqrt{log/h}$	0.0000	**0.0570**	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Initial concentration and prevalence												
C_0	Initial concentration	**2.50**	log cfu/g	-0.56	-0.56	**2.50**	-0.56	-0.56	-0.56	-0,56	-0.56	-0.56	-0.56
Prev	Prevalence at end of shelf life	**0.0264**	%	0.0209	0.0209	0.0209	**0.0264**	0.0209	0.0209	0.0209	0.0209	0.0209	0.0209
	Transport to home												
$time_{tr}$	Transport time from retail to home	**2**	h	1.125	1.125	1.125	1.125	**2**	1.125	1.125	1.125	1.125	1.125
T_{tr}	Transport temperature from retail to home	**20**	°C	11.5	11.5	11.5	11.5	11.5	**20**	11.5	11.5	11.5	11.5
$\mu_{max,tr}$	Growth rate during transport to home	**0.0969**	log/h	0.0338	0.0388	0.0338	0.0338	0.0338	**0.0969**	0.0338	0.0338	0.0338	0.0338
C_{tr}	Concentration at end of transport towards home		log cfu/g	-0.52	-0.49	2.54	-0.52	-0.49	-0.45	-0.52	-0.52	-0.52	-0.52

	Consumer storage												
$time_h$	Household storage time	**17**	days	4.1	4.1	4.1	4.1	4.1	4.1	**17**	4.1	4.1	4.1
T_h	Household temperature refrigerator	**12**	°C	5.68	5.68	5.68	5.68	5.68	5.68	5.68	**12**	5.68	5.68
$\mu_{max,h}$	Growth rate during home storage	**0.0366**	log/h	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	**0.0366**	0.0093	0.0093
C_{cons}	Concentration at consumption		log cfu/g	0.39	1.82	3.45	0.39	0.42	0.46	3.27	3.08	0.39	0.39
	Consumption data												
S_{size}	Serving size (mass of cold processed meat per serving)	**100**	g	31	31	31	31	31	31	31	31	**100**	31
Nr_{serv}	Number of servings (consumption days) per year per person	**275**	servings	175	175	175	175	175	175	175	175	175	**275**
	Dose-response model												
D	Ingested dose (number of cells consumed per single serving)		cfu	77	2059	88049	77	82	90	58185	37113	247	77
$P_{ill,\ hr}$	Probability of illness per contaminated serving for high-risk population			8.13×10^{-11}	2.18×10^{-09}	9.33×10^{-08}	8.13×10^{-11}	8.70×10^{-11}	9.57×10^{-11}	6.17×10^{-08}	3.93×10^{-08}	2.62×10^{-10}	8.13×10^{-11}
$R_{serv,\ hr}$	Risk per serving for high-risk population			1.70×10^{-12}	4.56×10^{-11}	1.95×10^{-09}	2.15×10^{-12}	1.82×10^{-12}	2.00×10^{-12}	1.29×10^{-09}	8.22×10^{-10}	5.48×10^{-12}	1.70×10^{-12}
$P_{ill,\ lr}$	Probability of illness per contaminated serving for low-risk population			1.82×10^{-12}	4.88×10^{-11}	2.09×10^{-09}	1.82×10^{-12}	1.95×10^{-12}	2.14×10^{-12}	1.38×10^{-09}	8.80×10^{-10}	5.86×10^{-12}	1.82×10^{-12}
$R_{serv,\ lr}$	Risk per serving for low-risk population			3.80×10^{-14}	1.02×10^{-12}	4.36×10^{-11}	4.80×10^{-14}	4.07×10^{-14}	4.47×10^{-14}	2.88×10^{-11}	1.84×10^{-11}	1.22×10^{-13}	3.80×10^{-14}
	Ratio for the high-risk population (risk per serving of extreme scenario / risk per serving of default)			1	**27**	**1147**	**1.3**	**1.1**	**1.2**	**759**	**482**	**3.2**	**1.57***

* ratio was calculated from the number of illness cases ($R_{serv,\ hr} \cdot \mathrm{Nr_{serv}} \cdot Pop_{hr}$)

3.7.5 Appendix E. Number of listeriosis cases and Years of Life Lost (YLL)

Table E1. Number of listeriosis cases and Years of Life Lost of the high-risk population (persons 65 years and older and pregnant women (neonates)), low-risk population, and total population, estimated for different household storage conditions: A) default with 5.7 °C for both high-risk and low-risk population (baseline as shown in **Table 3.2**); B) difference between storage temperature of older individuals of 6.1 °C (persons 65 years and older), and younger individuals of 5.5 °C (low-risk population and pregnant women), based on the results of the consumer survey; C) storage temperature of the upper shelf of 7.7 °C for both high-risk and low-risk population, as determined in the 24-hour temperature measurements; and D) extreme storage temperature of the upper shelf of 13.4 °C for both high-risk and low-risk population, as determined in the 24-hour temperature measurements

	A: Default		*B: Old (6.1 °C) / Young (5.5 °C)*		*C: Upper shelf (7.7 °C)*		*D: Extreme Upper shelf (13.4 °C)*	
	cases	*YLL*	*cases*	*YLL*	*cases*	*YLL*	*cases*	*YLL*
High-risk population	175		229		582		5186	
- Persons 65 yrs and older	166 (87%)	415 (59%)	218 (89%)	545 (64%)	553 (87%)	1383 (60%)	4927 (87%)	12318 (60%)
- Pregnant women (neonates)	9 (5%)	115 (16%)	11 (5%)	140 (16%)	29 (5%)	370 (16%)	259 (5%)	3302 (16%)
Low-risk population	16 (8%)	172 (25%)	15 (6%)	169 (20%)	52 (8%)	559 (24%)	465 (8%)	4999 (24%)
Total population	191	702	244	854	634	2312	5651	20619
Ratio (cases of scenario / cases of default)			**1.3**		**3.3**		**29.6**	

Chapter 4

Campylobacter in the domestic kitchen: Linking human and microbiological behaviour

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Abstract

Campylobacter is a major cause of foodborne illness worldwide, and poultry products are considered as the main source of campylobacteriosis. This study provides insight into the hygienic practices of handling raw chicken at home in the Netherlands and quantifies the impact of these practices on the incidence of campylobacteriosis in a quantitative microbiological risk assessment (QMRA), with a specific focus on the number of illness cases rather than the risk per serving. A survey was conducted among Dutch consumers (n = 1974) to assess their raw chicken handling practices. The results showed that 95 % of consumers reported always or often thoroughly cooking chicken, indicating high compliance with safe practices. However, less safe practices were also reported, such as washing chicken before preparation (36 %) or replacing dishcloths once a week or less (23 %). Demographic analyses showed that females followed safe food-handling practices better than males, and respondents from households with children or with pregnant household members adhered better to safe practices than households without these characteristics. Quantitative experiments were conducted to measure the cross-contamination and transfer rate of *Campylobacter jejuni* from raw chicken fillet to cucumber. Replacing the cutting board resulted in a 75 % decrease in the transfer rate, while replacing the knife led to a 57 % reduction, both compared to the worst-case scenario of no replacement of cutleries. The QMRA predicted that the primary factor contributing to the risk of campylobacteriosis was the initial concentration. Scenario analysis highlighted thorough cooking as the most impactful intervention at home for reducing *Campylobacter* infection, followed by hand washing after handling raw chicken meat and replacing cutting boards. Sustained efforts to lower initial contamination levels, combined with targeted communication and improved consumer practices on hygienic measures, can effectively reduce the incidence and public health impact of foodborne illnesses associated with chicken consumption.

4.1 Introduction

Campylobacter spp. are the most common cause of bacterial gastroenteritis in humans (EFSA and ECDC, 2023). Infection is generally manifested as self-limiting diarrhoea that lasts three to five days, but may require hospital care in about 5–10 % of cases. Acute infection may lead to rare late-onset complications such as reactive arthritis or the Guillain-Barré syndrome and acute neuromuscular disease (ECDC, 2024; Facciolà et al., 2017; Habib et al., 2020). Campylobacteriosis poses a significant public health burden in the European Union (EU), accounting for >137,000 reported cases per year. However, experts estimate the actual number of cases to be closer to nine million each year (EFSA and ECDC, 2023). In the Netherlands, *Campylobacter* spp. accounts for the highest disease burden related to foodborne pathogens, causing 2500 DALYs and 57,000 estimated incident cases annually (Benincà et al., 2024). Human infection usually occurs via the consumption of contaminated food, primarily via raw poultry, but *Campylobacter* can also be found in raw milk, on vegetables, or in drinking water from private wells (EFSA and ECDC, 2023). Extensive research in some countries identified raw chicken meat as a significant source of *Campylobacter* spp. infection (Havelaar et al., 2007; Mughini Gras et al., 2012; Nauta et al., 2009). Several studies examined the food-handling practices and hygiene measures of consumers regarding raw poultry and their association with campylobacteriosis (Antonise- Kamp et al., 2018; Bearth et al., 2014; Kosa et al., 2015; Kosa et al., 2019; Myintzaw et al., 2020; Shumaker et al., 2022). Food-handling practices can be affected by cultural traditions. Research by Møretrø et al. (2021) found that differences among countries in safe food- handling practices were evident, and they concluded that food safety interventions must consider the national food culture, preferences, practices and the prevalence and levels of pathogens in food. Exposure to *Campylobacter* spp. in the kitchen can happen through various pathways. The different routes add complexity to the risk assessment, as each pathway involves typical behaviour and conditions that can influence the overall risk. Cross-contamination is a significant concern, occurring when *Campylobacter* spp. are transferred from a contaminated source, like raw poultry, to a non-contaminated surface, hands or food items, such as salads or other ready-to-eat products, through either direct or indirect contact. Numerous studies examined the transfer rate of *Campylobacter* spp. from poultry to ready-to-eat products and common food contact surfaces in the kitchen (Bai et al., 2021; De Jong et al., 2008; Eriksson et al., 2023; Luber, 2009; Tang et al., 2011; Van Asselt et al., 2008; Verhoeff-Bakkenes et al., 2008). The transfer rate is defined as “the proportion (%) by which bacteria are transferred from one surface to another”, and these rates can vary in different scenarios. The wide range in transfer rates reported in literature highlights the complexity of *Campylobacter* spp. transmission’s dynamics, impacted by multiple intrinsic and extrinsic factors. Another route of exposure is through inadequate heating of chicken before consumption. As *Campylobacter* spp. are heat sensitive micro-organisms, proper heat treatment of a chicken meat

preparation eliminates the cells as an infectious agent from the portion. However, when the product is undercooked, survival of *Campylobacter* might cause illness (Brynestad et al., 2008; Uyttendaele et al., 2006; FAO and WHO, 2009). In order to quantify the effect of consumer practices on food safety, a quantitative microbiological risk assessment (QMRA) can be employed. QMRA is a modelling approach used to estimate the risk of illness when a population is exposed to a pathogen (EC, 1997). QMRAs that incorporated the consumer phase indicated that cross-contamination and undercooking in the consumer phase are important parameters to control (FAO and WHO, 2009). These consumer practices have a significant impact on the final dose at consumption. However, the scientific literature describes modelling consumer practices as complex, influenced by known and unknown factors, and with the possibility to either overestimate or underestimate its impact (Iulietto and Evers, 2023; Nauta, 2002; Pérez-Rodríguez et al., 2008). To date, limited up-to-date information is available on the food-handling practices of Dutch consumers, particularly when it comes to raw chicken preparation. This study aims to fill this gap by conducting a survey to quantitatively assess how Dutch consumers handle raw chicken. The survey findings, combined with insights from the literature and additional experiments on *Campylobacter* transfer and survival, were used to quantitatively estimate the annual incidence of campylobacteriosis associated with the consumption of raw chicken fillets. The study identifies the most risky food-handling practices, providing valuable insights for designing targeted risk communication messages aimed at addressing these high-risk practices.

4.2 Materials and methods

4.2.1 Consumer knowledge and handling of raw chicken in domestic kitchens

A questionnaire was developed to investigate consumers' practices regarding the handling of raw chicken. Questions related to food- handling practices were based on concepts that are used by the Netherlands Nutrition Centre in their educational materials concerning safe handling of raw chicken. The included questions covered three topics: (i) socio-demographic information of the respondent, (ii) information of household members who are at higher risk (YOPI: young children below 4 years, persons of 65 years and older, pregnant women, immunocompromised persons, and persons who were using immunosuppressants or antacids), and (iii) users' habits regarding handling raw chicken in the domestic kitchen (**Table 4.1**). A more detailed description of the characteristics of the respondents can be found in **Appendix A**.

Table 4.1. Questions and answer options regarding food-handling of raw chicken

Question	Answer options *
1. I wash my hands with water and soap after touching raw meat (e.g., to put it in the pan).	never (0); rarely (0.25); sometimes (0.5); often (0.75); (almost) always (1)
2. I use kitchen utensils (knife, cutting board) which has been in contact with raw meat NOT for other products.	never (0); rarely (0.25); sometimes (0.5); often (0.75); (almost) always (1)
3. I do NOT fully cook chicken (pink/translucent on the inside).	(almost) always (0); often (0.25); sometimes (0.5); rarely (0.75); never (1)
4. I wash raw chicken before preparation.	(almost) always (0); often (0.25); sometimes (0.5); rarely (0.75); never (1)
5. I store raw meat in the refrigerator covered and separated from other items.	never (0); rarely (0.25); sometimes (0.5); often (0.75); (almost) always (1)
6. I replace my dishcloth with a clean or new one.	2-3 times per month or less or when it starts to smell or stink (0); once a week (0.5); 2-6 times a week (0.75); once a day or more often (1)

* degree of safe practices between brackets, where 0 represents unsafe practice and 1 represents safe practice. These numbers were not mentioned in the questionnaire.

Data collection was performed by the panel agency Flycatcher in 2021. Selected consumers were asked by e-mail to participate in the survey. The goal was to sample 2000 consumers to obtain a representative result. Considering an expected response rate of 65 %, an initial sample of 3187 consumers was randomly selected from the participant database of the panel agency based on socio-demographic representativeness, i.e., age, gender, educational level and geographics. In case of a positive response a questionnaire was delivered online. The questionnaire introduction included detailed information about the purpose of the study (e.g., aim, estimated time required for completion, information about anonymity). Inclusion criteria were being aged between 18 and 69 years, and currently living in the Netherlands. In total 2000 consumers participated, and 1974 fully completed the questionnaire. For questions concerning safe food-handling practices, participants were asked to rate their practices on a five-point scale ranging from 'never' to '(almost) always'. These responses were then calibrated to values between 0 and 1, where 0 represented unsafe practices and 1 represented safe practices (see **Table 4.1** for details). To assess handling practices specifically related to raw chicken, responses to the six relevant questions were aggregated and averaged to generate a single score per participant. Subsequently, participants were categorized into two groups: those exhibiting safe food-handling practices (with an average score of 0.75 or higher) and those exhibiting unsafe food-handling practices (with an average score lower than 0.75). The threshold of 0.75 was chosen because it indicated that the participant scored between 0.75 and 1, reflecting a high level of adherence to safe food- handling practices. To assess variations in participants' characteristics (such as age, gender, education level,

and YOPI characteristics) and their safe food-handling practices, a *t*-test was employed with a significance level of α =0.05. All data analyses were performed in JASP (0.17.1.0). water.

4.2.2 Quantification of cross-contamination of *Campylobacter jejuni*

4.2.2.1 Preparation of Campylobacter jejuni *strain cocktail*

Three *C. jejuni* strains were used in this study: Ca 1087, Ca 1352 and Ca 1809 (provided by the Netherlands Food and Product Safety Authority (NVWA) and isolated from chicken meat). *Campylobacter* stock cultures were grown in Heart Infusion broth (HI, Bacto HI, Becton, Dickinson and Company, US, ref. 238,400) for 24 h under micro- aerobic conditions using an Anoxomat (Advanced Instruments USA; gas mixture 5 % O_2, 7.5 % CO_2, 7.5 % H_2 and 80 % N_2) at 41.5 °C, then supplemented with 30 % glycerol (Oxoid, UK) and stored at -80 °C. To obtain pre-cultures for the experiments, *C. jejuni* strains were plated from the -80 °C cryovials onto Columbia agar base (CAB, Oxoid, supplemented with 5 % (*v*/v) lysed horse blood (Oxoid, UK, ref. SR0050B)), and grown for 48 h at 41.5 °C under micro-aerobic conditions. Subsequently, single colonies were resuspended in HI and cultured for 24 h at 41.5 °C under micro-aerobic conditions to obtain stationary phase cultures. The inoculation cocktail (10 mL) was prepared by mixing 1 mL of each overnight culture of the three *C. jejuni* strains to 7 mL Peptone Physiological Salt solution (PPS). This cocktail had a concentration of approximately 10^7 to 10^8 CFU/mL. To mimic a maximum concentration present on the chicken fillet of 10^4 CFU/g, the cocktail was diluted in PPS to 10^6 CFU/mL. An overview of the preparation of *C. jejuni* strain cocktail is given in **Appendix B1**.

4.2.2.2 Transfer of Campylobacter jejuni *from chicken fillets to cut cucumber*

Fresh, chilled chicken fillets (approximately 100 g each, packaged under modified atmosphere) and fresh cucumbers (plastic-wrapped) were purchased in separate batches from a local supermarket and stored at 4 °C. Chicken fillets were selected due to the association with *C. jejuni* contamination (ECDC, 2024), and ranking as the second most consumed animal meat in the Netherlands (Van Rossum et al., 2023). Cucumbers were chosen for possible cross-contamination because of their low acidity (pH of 5.8), which supports survival of *C. jejuni* (Kärenlampi and Hänninen, 2004), the ease to obtain straight cut slices to maximize transfer, and frequent consumer use as they rank as the second most consumed raw vegetable in the Netherlands (Van Rossum et al., 2023). To prepare inoculated chicken fillet, approximately 100 g of fresh chicken fillet was weighed into stomacher bags and inoculated with 1 mL cocktail containing 10^6 CFU. The fillets were then massaged for 60 s to ensure even distribution of the cells on the chicken. These fillets were stored at 4 °C for 24 h to allow the cells to attach. Two samples of inoculated chicken fillet were prepared. One sample was used to determine the number of *Campylobacter* cells that could be recovered from uncut chicken fillet (see eq. 1).

For this purpose, 100 mL of PPS was added to one bag containing an inoculated chicken fillet, which was then massaged for 60 s. Decimal dilutions were made, and 100 µL of different dilutions were spread onto RAPID' *Campylobacter* medium plates (RCA, Bio-Rad, Raymond Poincare, France ref. 3,564,295 and 3,564,296), and incubated for 48 h micro- aerobically at 41.5 °C. The second inoculated chicken fillet was used for cross-contamination scenarios. The inoculated chicken fillet (100 g) was placed on a plastic polyethylene cutting board (24 ×14 cm, Action, Netherlands), and cut into four equal pieces and then removed from the cutting board. The cutting procedure was performed using a 20 cm stainless steel knife (Ernesto, Lidl, Netherlands) that was decontaminated with 70 % ethanol and thoroughly dried before use. Subsequently, on the same cutting board, a cucumber was sliced with a decontaminated knife into six pieces, each weighing about 10 g and with a thickness of approximately 0.5–1 cm. A plastic fork was employed to secure the chicken or the cucumber on the cutting board. The contact area between the chicken fillets and the cutting board was 112 cm^2 (15.3 ×7.3 cm), and for the cucumber 111 cm^2 (6 times 18.5 cm^2). Prior to usage, the cutting boards were washed, decontaminated with 70 % ethanol, and allowed to dry. Modifications to cucumber preparation were implemented based on three distinct scenarios:

(i) Worst-case scenario (W): No replacement of the knife, fork, and cutting board after handling raw chicken and subsequently cutting the cucumber.

(ii) Knife and fork replacement (K): Replacement of the knife and fork, with no replacement of the cutting board after handling raw chicken and subsequently cutting the cucumber.

(iii) Cutting board replacement (C): Replacement of the cutting board, with no replacement of the knife and fork after handling raw chicken and subsequently cutting the cucumber.

Following the execution of each scenario, the six cucumber pieces were transferred to a stomacher bag, weighed, mixed with 50 mL of PPS, and massaged for 60 s. A subsequent decimal dilution (10^{-1}) was carried out, and 100 µL of the solution was spread onto RCA plates. To lower the detection limit, 1 mL of the undiluted sample was spread over three RCA plates as well. Subsequently, the plates were incubated for 48 h under micro-aerobic conditions at 41.5 °C, and the resulting colonies were counted. Each scenario was repeated seven times. A visual representation of each scenario can be found in **Appendix B2**.

The transfer rates from chicken to cucumber for various scenarios were calculated based on the final contamination levels on the cucumber and the contamination on the uncut chicken fillets. Although typically only one side of the chicken fillet contacts the cutting board, the contamination of the entire uncut fillet was considered to ensure consistency in the calculation. The calculation was performed using the formula:

$$Transfer\ rate\ (\%) = \frac{CFU\ on\ 6\ cucumber\ slices}{CFU\ on\ uncut\ chicken\ fillet} * 100 \quad [1]$$

To test the differences between the transfer rates among the different preparation scenarios, a two-sample *t*-test was employed. The significance level utilized for the testing was α =0.05. The transfer rates observed in the experimental findings were compared with those reported in the literature. The inclusion criterion for the literature search was the availability of experimental data on transfer of *Campylobacter* spp. from raw chicken to ready-to-eat salad products. Articles that did not provide such information, such as those lacking initial concentrations or presenting data only graphically, were excluded from the analysis.

4.2.3 Quantitative microbiological risk assessment

A QMRA was performed with emphasis on consumer handling practice of chicken meat products before consumption. In the exposure assessment step, stages of manufacturing and distribution of the product before the retail phase were not included. Additionally, it excluded the purchase, transportation from the supermarket to home, and storage at home, assuming no growth or cross-contamination of *Campylobacter* spp. occurred during these stages (Duffy and Dykes, 2006). A stochastic model was developed of *Campylobacter* spp. from raw chicken meat. Its structure was based on information derived from the consumer survey (section 2.1), previous risk assessments and experimental work performed in this study combined with information found in literature. Six exposure routes through consumer handling of raw chicken meat were considered (**Figure 4.1**): (i) via hands to lips; (ii) via hands to RTE salad; (iii) via cutting board to RTE salad; (iv) via knife to RTE salad; (v) via undercooked cut and uncut meat, and (vi) via washing of raw chicken to RTE salad. To incorporate experimental data from this study, an additional combined route was introduced, merging two transmission steps: from raw chicken to the cutting board/knife, and from the cutting board/knife to the RTE salad. The model framework for the exposure assessment is a variant of the model as described by Ssemanda et al. (2024). Other transmission routes like spreading to the kitchen environment or spreading from the contaminated cutting board to cooked chicken were not included in the model, because no related questions were included in the questionnaire and literature showed that spreading of *Campylobacter* to the kitchen environment besides cutting board was limited (Iulietto and Evers, 2023).

4.2.3.1. Consumption data

Data about individual consumption patterns (typical serving size and number of servings) of poultry products and RTE salad of the Dutch population were retrieved from the Dutch National Food Consumption Survey 2019–2021 (Van Rossum et al., 2023). For poultry the Food Groups ‘chicken fillet, raw’ and ‘chicken without skin’ were chosen. For RTE salad, the Food Groups ‘leafy greens’ (lettuce) and ‘fruiting vegetables’ (tomatoes and cucumber) were chosen. A pert distribution was fitted

to this data, where P^5, P^{50}, and P^{95} values represent the minimum, most likely, and maximum values respectively. The likelihood of preparing raw chicken and ready-to-eat (RTE) salad together in a single meal was also determined using data from the Dutch National Food Consumption Survey 2019–2021 (Van Rossum et al., 2023). This was calculated by dividing the occasions when they are consumed together by the total occasions when chicken is eaten. Detailed information is given in **Table 4.2**.

4.2.3.2. Initial concentration

Data on the initial concentration of *Campylobacter* spp. on raw chicken fillets from retail stores were derived from the Netherlands Food and Product Safety Authority (NVWA) for the period 2010 to 2015 (NVWA, 2018b), and the period 2015 to 2022 (NVWA, 2024). The latter was used as the default in the QMRA model. The data were categorized into the following groups: < 0.04 CFU/g (not detected in 25 g); presence but ≤10 CFU/g; 10 CFU/g < x ≤ 100 CFU/g; and 100 CFU/g < x ≤ 1000 CFU/g. The prevalence of *Campylobacter* spp. is integrated within these categories, with the <0.04 CFU/g group representing the non-detected samples (65 % of cases), while the remaining 35 % reflects the presence of *Campylobacter* in higher concentration groups, thereby informing the overall prevalence and concentration distribution estimation. The upper limits of these categories were chosen and log-transformed, and a cumulative normal distribution was fitted using @Risk software (@Risk 8.2 for Excel, Palisade, Ithaca, USA) with a mean of - 2.04 log CFU/g (standard deviation (SD) 1.70 log CFU/g) for the period 2015 to 2022 (default). For the period 2010 to 2015, a mean of - 2.83 log CFU/g (SD 2.19 log CFU/g) was estimated and this was used in the scenario-analysis. Doses of less than one colony forming unit (CFU) per chicken from iterations were included (i.e., the distribution was not truncated), although such doses do not occur in reality. Nevertheless, the beta- Poisson dose response model used in this study (Eq. 3) can integrate this effect (Basset et al., 2010), and an expected dose of for example 0.1 CFU/serving means that the dose is 1 CFU in 10 % of the servings, as the beta-Poisson model gives approximately the same outcome for 0.1 * P_{ill} (1), as for P_{ill} (0.1).

4.2.3.3. Consumer handling - cross-contamination

Cross-contamination occurs when cells from raw chicken meat products are transferred to uncontaminated surfaces or food items, including hands, cutting boards, knives, or RTE salads. In the model framework (**Figure 4.1**), cross-contamination is relevant for exposure routes 1 (raw chicken – hands – lips – ingestion), 2 (raw chicken – hands – RTE salad – ingestion), 3 (raw chicken – cutting board – RTE salad – ingestion), 4 (raw chicken – knife – RTE salad – ingestion), and 6 (raw chicken – washing – RTE salad – ingestion). To estimate the occurrence of cross-contamination, the findings from the consumer survey were employed (**Table 4.1**). The probability of cross-contamination was represented by a

cumulative distribution, with scores ranging from 0 to 1, where 0 indicates undesired practices and 1 indicates desired practices. However, it is important to note that not all cells are transferred. In the model, it is assumed that only loosely attached cells are involved in cross-contamination, similar to the drip fluid model described by FAO and WHO (2009). The fraction of the number of cells that are able to cross-contaminate (i.e., fraction of loosely attached cells) is described by a uniform distribution with a minimum of 0.01 and a maximum of 0.1 (FAO and WHO, 2009). A literature search was conducted to extract quantitative data from experiments on cross-contamination from poultry to food or non-food surfaces. Our search included an extensive summary of literature in transfer rates available until March 2020, as provided by Iulietto and Evers (2023), supplemented with findings from our own literature search. The most stringent inclusion criterion for the literature search was the availability of experimental data on bacterial transfer for the steps defined in the model framework (**Figure 4.1**). If the articles did not provide such information, they were excluded. The variation within each study was characterized using either a beta distribution, a pert distribution, or a normal distribution, fitted to the results. **Table C1** of **Appendix C** provides an overview of the data compiled from the literature as used in the QMRA model. In each iteration, a sample was drawn from the relevant distribution of the transfer rate sourced from a randomly selected scientific article. To incorporate experimental data from this study, we introduced an additional combined route where transmission from raw chicken to the cutting board/knife and from the cutting board/knife to the RTE salad were merged (**Figure 4.1**). Consequently, the QMRA model was adjusted, merging steps 3 and 4 of the model into one (see **Appendix D** for details of the adjusted QMRA model). The transfer rates observed in the experimental findings were fitted with a normal distribution for three conditions (worst case, knife replacement, board replacement). The normal distribution was truncated between 0 and 0.05 to prevent negative transfer rates and extremely high transfer rates. Additionally, the distribution of transfer rates reported in the literature were compiled. **Table C2** of **Appendix C** provides an overview of the data used in the adjusted QMRA model. In each iteration, a sample was drawn from the relevant distribution of the transfer rate, randomly sourced from either the experimental data from this study or from a selected scientific article.

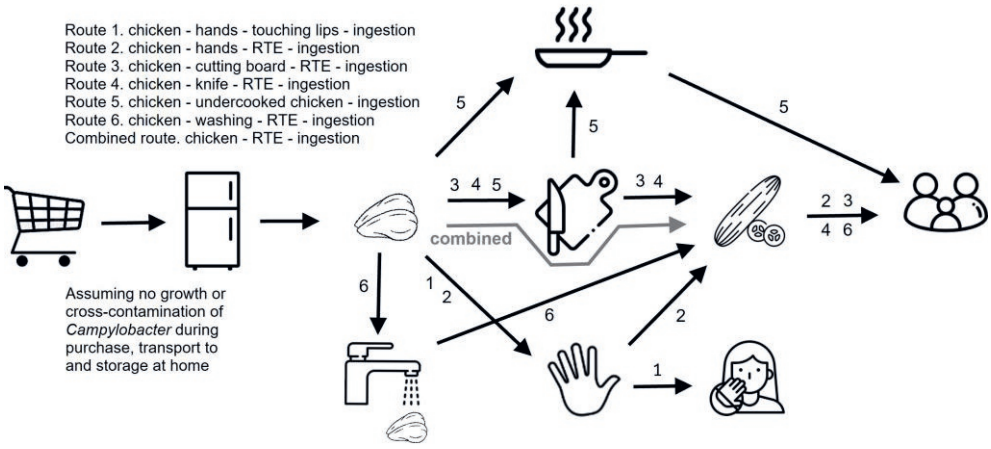


Figure 4.1. Conceptual model framework for the domestic environment, illustrating the associated risk exposure routes for the transmission and ingestion of *Campylobacter* spp.. Icons from free pick at flaticon.com.

4.2.3.4.Consumer handling - cooking

In addition to considering cross-contamination, the impact of cooking was also taken into account, as undercooked products may harbour surviving campylobacters, posing a risk of illness. The probability of undercooking was assessed through the consumer survey (question 3 in **Table 4.1**) and depicted using a cumulative distribution. It is important to note that while undercooking may happen, not all cells will necessarily survive the heating process. Only the proportion of cells in the 'protected' area will survive. This proportion was estimated to be between 10 and 20 % of the cells with a mode of 15 % (FAO and WHO, 2009). In order to estimate the log reductions that could occur in areas of the chicken that are 'protected', it was assumed that during cooking these 'protected' areas would be exposed to a temperature represented by data reported in the FDA Home cooking temperature database (Audits International and FDA, 2017). The time that these areas are exposed to this temperature was assumed to range from 0.5 to 1.5 min (FAO and WHO, 2009). A *D/z*-value model, as described by FAO and WHO (2009) and Al- Sakkaf (2021) was applied, expressed as:

$$\log(D) = \log(D_{ref}) + \left(\frac{T_{ref} - T}{z}\right) \quad [2]$$

where D_{ref} represents the *D*-value at the reference temperature T_{ref} (in °C), T (in °C) denotes the temperature of bacterial exposure in the 'protected' area, and z represents the temperature increase (in °C) required for one log reduction of the *D*-value. For integration into the QMRA model, a random sample was drawn from the various regression lines identified in the studies by FAO and WHO (2009) and Al-

Sakkaf (2021) (**Appendix C**). In the case of proper cooking, no exposure via route 5 was assumed (i.e., $Prob_{exp5}$ =0 in 88 % of the iterations). In cases of undercooking, variation in time, temperature, and *D*-values was used to determine the extent of log inactivation, with $Prob_{exp5}$ based on the consumer survey (e.g., in 7 % of the iterations, $Prob_{exp5}$ was 0.25; see **Table 4.2**).

4.2.3.5.Consumer handling – washing chicken

Washing raw chicken before preparation may lead to cross- contamination, as the juices and wash water can come into contact with other foods, surfaces, and utensils (Carmody et al., 2022; Cates et al., 2019; Chea et al., 2022; Shumaker et al., 2022). Limited quantitative information is available regarding the transfer rate of *Campylobacter* spp. during the washing of raw chicken. The findings of Chea et al. (2022) were used where the transfer rate to RTE salad was determined after washing raw chicken. The probability of contamination of RTE salad during washing of chicken was assessed using data from the studies of Chea et al. (2022) and Shumaker et al. (2022). The probability of washing chicken before preparation was assessed through the consumer survey and depicted using a cumulative distribution. The overall probability of exposure from contaminated RTE salad via the washing of raw chicken is calculated by multiplying the probability that both chicken and RTE salad are consumed in one meal by the probability that chicken is washed, and then by the probability of contamination of RTE salad during the washing process. The pathway of creating aerosols during washing and thereby contaminating surface areas, and the potential removal of some *Campylobacter* spp. during washing chicken were not included due to the lack of quantitative data on these topics.

4.2.3.6.Exposure assessment outputs

At the end of the exposure assessment, the total number of cells (dose) of *Campylobacter* spp. consumed per serving was obtained for each transmission route separately. The probability of exposure was then calculated based on the likelihood of each route to occur.

4.2.3.7.Hazard characterization

A beta-Poisson model (Eq. 3) was used as dose-response model, chosen for its effectiveness in describing the dose-response relationship across all *Campylobacter* serotypes and its frequent utilization in previous studies (FAO and WHO, 2009). The dose-response model is represented by the equation:

$$P_{inf} = 1 - (1 - r)^{D} \quad [3]$$

where, P_{inf} denotes the probability of infection given a dose, *D* represents the ingested dose per serving and *r* represents the probability of infection from consuming one single cell with a beta distribution (0.21, 59.95) for *Campylobacter* spp. (FAO and WHO, 2009). Subsequently, the conditional probability of illness

was determined using eq. 4, where $P_{ill,\ inf}$ stands for the dose-independent conditional probability of getting ill given infection and a beta distribution (30, 61) was used (FAO and WHO, 2009).

$$P_{ill} = P_{inf} \cdot P_{ill,inf} \quad [4]$$

4.2.3.8.Risk characterization

In 2023, the population at risk encompassed the entire Dutch population, in total 17,811,291 individuals, as reported by Statistics Netherlands (Statistics Netherlands CBS, 2023). The consumer survey revealed that 91 % of Dutch consumers include chicken in their diet, exposing them to *Campylobacter* spp.. Consumers were categorized into two groups: those who both eat and cook (preparation group), and are exposed through all routes, and those who only eat (consumption group), and are exposed through routes 2, 3, 4, 5, and 6. It was assumed that there is one cook per household. The Dutch household size was retrieved from Statistics Netherlands (Statistics Netherlands CBS, 2023). A pert distribution was fitted with a minimum of 1 person, a most likely of 1.5, and a maximum of 7 persons per household. Monte Carlo simulations were performed to determine the distribution of P_{ill} using @Risk simulation software (@Risk 8.2 for Excel, Palisade, Ithaca, USA), as an add-in to Microsoft Excel, with 1,000,000 iterations. For each iteration, the P_{ill} per serving was calculated for each transmission route. Subsequently, the risk per serving was calculated by multiplying P_{ill} with the probability of exposure for each transmission route. For each risk group (preparation and consumption group), the respective overall risk per serving was computed by subtracting the product of no risk (i.e., one minus risk per serving) for all the applicable transmission routes from the maximum attainable probability value (one) as shown in **Table 4.2**. The number of cases per year was estimated by multiplying the arithmetic mean risk per serving for preparation ($R_{serv\,cook}$) and consumption ($R_{serv\,eat}$) by the average number of servings of chicken meat per year per person, which was 47 ($Nr_{serv\ chicken}$). This result was then multiplied by the number of persons in the preparation group (Pop_{cook}) and the consumption group (Pop_{eat}), respectively. The total number of cases ($Nr_{cases\ total}$) was calculated by summing the number of cases in the preparation group ($Nr_{cases\ cook}$) and the consumption group ($Nr_{cases\,eat}$). This was repeated 50 times to calculate the estimated mean and standard deviation of the number of cases. The number of cases was also calculated performing a Bernoulli trial for each of the 1,000,000 iterations, taking into account the risk per serving ($R_{serv,\ cook}$ and $R_{serv,\ eat}$) for that iteration (i.e., serving), and evaluate whether this results in an illness case (Abe et al., 2023). A value of 1 indicated an illness case, whereas a value of 0 indicated no illness case. In total, the preparation group consumes 325,091,660 servings per year (calculated as average number of servings per person per year ($Nr_{serv\ chicken}$) times the number of persons in the preparation group (Pop_{cook})), and the consumption group consumes 433,455,563 servings per year (calculated as average number of servings per person per year ($Nr_{serv\ chicken}$) times the number of

persons in the consumption group (Pop_{eat})). Therefore, the number of cases per year was determined from 325 trials of 1,000,000 iterations for the preparation group and 433 trials of 1,000,000 iterations for the consumption group, making it in total 758 trials of 1,000,000 iterations. The total number of cases is then calculated by summing up all illness cases from all trials, which represent all servings consumed in the whole population. To calculate the estimated mean and the standard deviation of the number of cases per year, this was repeated 50 times, which simulates 50 years (so overall 38 billion iterations in total were performed). Detailed information can be found in **Appendix E**. This method differs from the calculation of the standard deviation as described by Van der Vossen-Wijmenga et al. (2024) where the standard deviation was determined with 100 Bernoulli trials of 1 million iterations in total. This, however, does not reflect the variation of all consumed servings per year, but the variation in a million servings. An overview of the QMRA model and the parameters' values and/or distributions is shown in **Table 4.2**. To validate the developed QMRA model, the outputs were compared with the epidemiological data for campylobacteriosis in the Netherlands (Friesema et al., 2024).

Table 4.2. Overview of input variables for the QMRA model for *Campylobacter* spp. in the consumption phase

ID	*Input variable*	*Distribution / formula*	*Unit*	*Data source / reference*
	Family and consumption			
$Nr_{persons\ household}$	Number of persons in a household eating a chicken meal	RiskPert (1; 1.5; 7)	persons	Statistics Netherlands CBS (2023)
$Serv_{cooked\ chicken}$	Serving size cooked chicken per person	RiskPert (17.1; 71.3; 214.5)	g	Van Rossum et al. (2023)
$Weight_{cooked\ chicken\ per\ meal}$	Weight of cooked chicken prepared for the family meal	$Serv_{cooked\ chicken\ per\ meal}$ * $Nr_{persons\ household}$	g	Calculated
$Conv_{factor}$	Conversion factor from weight cooked meat to weight raw meat	$Weight_{raw\ chicken}$ / $Weight_{cooked\ chicken}$	1.25	Dutch branded food database (not published)
$Weight_{raw\ chicken\ per\ meal}$	Weight of raw chicken prepared for the family meal	$Weight_{cooked\ chicken\ per\ meal}$ * $Conv_{factor}$	g	Calculated
$Nr_{serv\ chicken}$	Number of servings (consumption days at home) of chicken fillet per year per person	RiskPert (1; 31; 156)	servings	Van Rossum et al. (2023)
$Prob_{chicken\ RTE}$	Probability that chicken and RTE are consumed together	$Nr\ times_{chicken\ and\ RTE\ consumed\ together}$ / $Nr\ times_{total\ chicken\ consumed}$	0.25	Van Rossum et al. (2023)
	Initial concentration			
$C_{0,\ log}$	Initial log concentration on raw chicken meat of *Campylobacter*	RiskNormal (-2.04; 1.70)	log CFU/g	NVWA (2024)
C_0	Initial concentration on raw chicken meat of *Campylobacter*	$10\text{^}C_{0,\ log}$	CFU/g	Calculated
N_0	Number of cells on raw chicken meat of *Campylobacter*	C_0 * $Weight_{raw\ chicken\ per\ meal}$	CFU/raw chicken	Calculated
F_{loose}	Fraction of loosely attached cells	RiskUniform (0.01; 0.1)		FAO and WHO (2009)
$N_{0\ loose}$	Number of cells on raw chicken meat that are loose and can cross-contaminate	N_0 * F_{loose}	CFU/raw chicken	Calculated
	Transport to home			
	Assuming no growth, inactivation or cross-contamination of *Campylobacter*			
	Consumer storage			
	Assuming no growth, inactivation or cross-contamination of *Campylobacter*			

	Preparation			
	Route 1) Chicken – hands – lips – human			
$N_{start\ route1}$	Number of cells as start of route 1	$N_{0\ loose}$	CFU	Calculated
$Tr_{chick\text{-}hand}$	Transfer from raw chicken to hands	Sample from distributions		Literature in Appendix C
N_{hand}	Number of cells on hands	$N_{0\ loose} * Tr_{chick\text{-}hand}$	CFU	Calculated
$Tr_{hand\text{-}lips}$	Transfer from hands to lips/mouth	Sample from distributions		Literature in Appendix C
N_{lips}	Number of cells via fingertips to lips	$N_{hand} * Tr_{hand\text{-}lips}$	CFU	Calculated
$Nr_{touch\ mouth}$	Number of times that fingertips touch the lips/mouth in 30 minutes (time for cooking)	Sample from distributions	times	Literature in Appendix C
$Dose_{human1}$	Number of cells (dose) ingested by the cook touching mouth via hands	$N_{lips} * Nr_{touch\ mouth}$	CFU	Calculated
$Prob_{hand\text{-}w}$	Probability that hands are washed after touching raw chicken	RiskCumul (0;1;{0\0.25\0.5\0.75\1}; {0.02\0.05\0.13\0.29\1})		Voedingscentrum (2021)
$Prob_{hand\text{-}nw}$	Probability that hands are not washed	1- $Prob_{hand\text{-}w}$		Calculated
$Prob_{exp1}$	Probability of exposure from contaminated fingers by touching the mouth (route 1)	$Prob_{hand\text{-}nw}$		Calculated
	Route 2) Chicken – hands – RTE – human			
$N_{start\ route2}$	Number of cells as start of route 2	$N_{hand} – (N_{lips} * Nr_{touch\ mouth})$	CFU	Calculated
$Tr_{hand\ RTE}$	Transfer from hands to RTE salad	Sample from distributions		Literature in Appendix C
$N_{RTE\ (from\ hand)}$	Number of cells on RTE (for family) via hands that can be consumed	$N_{start\ route2} * Tr_{hand\ RTE}$	CFU	Calculated
$Dose_{human2}$	Number of cells (dose) ingested per serving RTE salad (via hands)	$N_{RTE\ (from\ hand)} / Nr_{persons\ household}$	CFU	Calculated
$Prob_{exp2}$	Probability of exposure from contaminated RTE via hands (route 2)	$Prob_{chicken\ RTE} * Prob_{hand\text{-}nw}$		Calculated
	Route 3) Chicken – cutting board – RTE – human			
$N_{start\ route3}$	Number of cells as start of route 3	$N_{0\ loose} - N_{hand}$	CFU	Calculated
$Tr_{chick\ board}$	Transfer from chicken to cutting board	Sample from distributions		Literature in Appendix C
$N_{board\ (from\ chicken)}$	Number of cells on cutting board from chicken	$N_{start\ route3} * Tr_{chick\ board}$	CFU	Calculated
$Tr_{board\ RTE}$	Transfer from cutting board to RTE salad	Sample from distributions		Literature in Appendix C
$N_{RTE\ (from\ board)}$	Number of cells on RTE (for family) from cutting board	$N_{board\ (from\ chicken)} * Tr_{board\ RTE}$	CFU	Calculated
$Dose_{human3}$	Number of cells (dose) ingested per serving RTE (via board)	$N_{RTE\ (from\ board)} / Nr_{persons\ household}$	CFU	Calculated

$Prob_{board\ knife\ not\ RTE}$	Probability that board / utensils are NOT used for RTE salad after cutting chicken	RiskCumul (0;1;{0\0.25\0.5\0.75\1}; {0.06\0.10\0.17\0.32\1})		Voedingscentrum (2021)
$Prob_{board\ knife\ RTE}$	Probability that board / utensils are used for RTE salad after cutting chicken	1-$Prob_{board\ knife\ not\ RTE}$		Calculated
$Prob_{exp3}$	Probability of exposure from contaminated RTE salad via board (route 3)	$Prob_{chicken\ RTE}$ * $Prob_{board\ knife\ RTE}$		Calculated
	Route 4) Chicken – knife – RTE – human			
$N_{start\ route4}$	Number of cells as start of route 4	$N_{0\ loose}$ - N_{hand} - $N_{board\ (from\ chicken)}$	CFU	Calculated
$Tr_{chick\ knife}$	Transfer from chicken to knife	Sample from distributions		Literature in Appendix C
$N_{knife\ (from\ chicken)}$	Number of cells on knife from chicken	$N_{start\ route4}$ * $Tr_{chick\ knife}$	CFU	Calculated
$Tr_{knife\ RTE}$	Transfer from knife to RTE salad	Sample from distributions		Literature in Appendix C
$N_{RTE\ (from\ knife)}$	Number of cells on RTE (for family) from knife	$N_{knife\ (from\ chicken)}$ * $Tr_{knife\ RTE}$	CFU	Calculated
$Dose_{human4}$	Number of cells (dose) ingested per serving RTE salad (via board)	$N_{RTE\ (from\ knife)}$ / $Nr_{persons\ household}$	CFU	Calculated
$Prob_{exp4}$	Probability of exposure from contaminated RTE salad via board / utensils (route 4)	$Prob_{chicken\ RTE}$ * $Prob_{board\ knife\ RTE}$		Calculated
	Route 5) Chicken - undercooked chicken – human			
$N_{0\ left}$	Number of cells on raw chicken after touching hand, lips, cutting board and knife	N_0 - N_{hand} - $N_{board\ (from\ chicken)}$ - $N_{knife\ (from\ chicken)}$	CFU	Calculated
$N_{start\ route5}$	Number of cells on raw chicken in the pan (50% whole chicken fillet and 50% cut chicken)	(0.5 * N_0) + (0.5 * $N_{0\ left}$)	CFU	Expert opinion
$Prob_{undercooked}$	Probability of undercooked chicken	RiskCumul (0;1;{0\0.25\0.5\0.75\1}; {0.88\0.95\0.97\0.98\1})		Voedingscentrum (2021)
$Prop_{protected}$	Proportion of cells on chicken that permit chance of survival	RiskTriang (0.10, 0.15, 0.20)		FAO and WHO (2009)
$N_{protected}$	Number of cells on cooked chicken with chance of survival	$N_{start\ route5}$ * $Prop_{protected}$	CFU	Calculated
$N_{protected,\ log}$	Log number of cells on cooked chicken with chance of survival	$\log_{10}(N_{protected})$	log CFU	Calculated
$Time_{protected}$	Exposure time at exposure temp for cells in 'protected' area	RiskTriang (0.50, 1.00, 1.50)	minutes	FAO and WHO (2009)
$Temp_{protected}$	Exposure temp during cooking in 'protected' areas	RiskNormal (70.34; 11.44; Risktruncate(38;116))	°C	Audits International and FDA (2017)
$D_{protected}$	*D*-value (at this temp)	Sample from distributions	minutes	Literature in Appendix C
$N_{protected\ lr,\ log}$	Log reduction in 'protected' area	$Time_{protected}$ / $D_{protected}$	log	Calculated

$N_{undercooked,\ log}$	Total log number of cells surviving cooking (undercooked)	$N_{protected,\ log}$ - $N_{protected\ lr,\ log}$	log CFU	Calculated
$N_{undercooked}$	Number of cells surviving cooking on cooked chicken fillet (undercooked)	10^log$N_{undercooked,\ log}$	CFU	Calculated
$Dose_{human5}$	Number of cells (dose) ingested per serving of undercooked chicken	$N_{undercooked}$ / $Nr_{persons\ household}$	CFU	Calculated
$Prob_{exp5}$	Probability of exposure from undercooked chicken (route 5)	$Prob_{undercooked}$		
	Route 6) Washing chicken – RTE – human			
$N_{start\ route6}$	Number of cells as start of route 6	$N_{0\ loose}$ - N_{hand}	CFU	Calculated
$Tr_{wash\ chicken\ RTE}$	Transfer from washing chicken to RTE salad	0.018		Chea et al. (2022)
$N_{RTE\ (from\ washing\ chicken)}$	Number of cells on RTE (for family) via washing of chicken that can be consumed	$N_{start\ route6}$ * $Tr_{wash\ chicken\ RTE}$	CFU	Calculated
$Dose_{human6}$	Number of cells (dose) ingested per serving RTE (via washing chicken)	$N_{RTE\ (from\ washing\ chicken)}$ / $Nr_{persons\ household}$	CFU	Calculated
$Prob_{wash\ chicken}$	Probability that chicken is washed	RiskCumul (0;1;{0\0.25\0.5\0.75\1}; {0.52\0.64\0.72\0.77\1})		Calculated
$Prob_{wash\ chicken\ RTE}$	Probability that RTE is contaminated during washing of chicken	Sample from distributions		Literature in Appendix C
$Prob_{exp6}$	Probability of exposure from contaminated RTE via washing chicken (route 6)	$Prob_{wash\ chicken}$ * $Prob_{chicken\ RTE}$* $Prob_{wash\ chicken\ RTE}$		Calculated
	Probability of infection of 1 cell (beta Poisson model)			
α	Alpha parameter	Constant 0.21		FAO and WHO (2009)
β	Beta parameter	Constant 59.95		FAO and WHO (2009)
r	Dose-response parameter for beta Poisson model	RiskBeta (α = 0.21; β = 59.95)		FAO and WHO (2009)
	Probability of infection given a dose of cells			
$P_{inf\ human1}$	Probability of infection from contaminated fingers to mouth (route 1)	1-(1- r) ^ $Dose_{human1}$		Calculated
$P_{inf\ human2}$	Probability of infection from contaminated RTE via hands (route 2)	1-(1- r) ^ $Dose_{human2}$		Calculated
$P_{inf\ human3}$	Probability of infection from contaminated RTE via board (route 3)	1-(1- r) ^ $Dose_{human3}$		Calculated
$P_{inf\ human4}$	Probability of infection from contaminated RTE via knife (route 4)	1-(1- r) ^ $Dose_{human4}$		Calculated

$P_{inf\ human5}$	Probability of infection from undercooked chicken (route 5)	1-(1- r) ^ $Dose_{human5}$		Calculated
$P_{inf\ human6}$	Probability of infection from washing chicken (route 6)	1-(1- r) ^ $Dose_{human6}$		Calculated
	Risk of illness per serving			
$P_{ill,\ inf}$	Probability of illness given infection	RiskBeta (α = 30; β = 61).		FAO and WHO (2009)
$R_{serv\ human1}$	Risk of illness from contaminated fingers to mouth (route 1)	$P_{inf\ human1}$ * $P_{ill,\ inf}$ * $Prob_{exp1}$		Calculated
$R_{serv\ human2}$	Risk of illness from contaminated RTE via hands (route 2)	$P_{inf\ human2}$ * $P_{ill,\ inf}$ * $Prob_{exp2}$		Calculated
$R_{serv\ human3}$	Risk of illness from contaminated RTE via board (route 3)	$P_{inf\ human3}$ * $P_{ill,\ inf}$ * $Prob_{exp3}$		Calculated
$R_{serv\ human4}$	Risk of illness from contaminated RTE via knife (route 4)	$P_{inf\ human4}$ * $P_{ill,\ inf}$ * $Prob_{exp4}$		Calculated
$R_{serv\ human5}$	Risk of illness from undercooked chicken (route 5)	$P_{inf\ human5}$ * $P_{ill,\ inf}$ * $Prob_{exp5}$		Calculated
$R_{serv\ human6}$	Risk of illness from washing chicken (route 6)	$P_{inf\ human6}$ * $P_{ill,\ inf}$ * $Prob_{exp6}$		Calculated
	Overall risk of illness per serving			
$R_{serv\ cook}$	Risk of illness per random serving for a person involved in chicken preparation and eat	1-(1-$R_{serv\ human1}$)*(1-$R_{serv\ human2}$)* (1-$R_{serv\ human3}$)*(1-$R_{serv\ human4}$)* (1-$R_{serv\ human5}$)*(1-$R_{serv\ human6}$)		Calculated
$R_{serv\ eat}$	Risk of illness per random serving for a person who only eat	1-(1-$R_{serv\ human2}$)*(1-$R_{serv\ human3}$)* (1-$R_{serv\ human4}$)*(1-$R_{serv\ human5}$)* (1-$R_{serv\ human6}$)		Calculated
	Population			
$F_{eat\ chick}$	Fraction of population who eat chicken	0.91		Voedingscentrum (2021)
Pop_{tot}	Total population	17,811,291	persons	Statistics NL (2023)
Pop_{chick}	Population of people who eat chicken	$F_{eat\ chick}$ * Pop_{tot}	persons	Statistics NL (2023)
Pop_{cook}	Population of people who are preparing and eating chicken (on average 1 cook per household)	Pop_{chick} / $Nr_{persons\ household}$	persons	Per household one cook who prepares and eats chicken
Pop_{eat}	Population of people who eat but are not preparing and cooking chicken	Pop_{chick} - Pop_{cook}	persons	Calculated

	Illness occurrence			
$Nr_{cases\ avg,\ cook}$	Number of illness cases per year (average) for the cooks involved in preparation and eating	$\overline{Nr_{serv\ chicken}} * \overline{R_{serv\ cook}} * Pop_{cook}$	cases per year	Calculated with $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$ and n = 1,000,000 iterations
$Nr_{cases\ avg,\ eat}$	Number of illness cases per year (average) for who only eat and are not involved in preparation	$\overline{Nr_{serv\ chicken}} * \overline{R_{serv\ eat}} * Pop_{eat}$	cases per year	Calculated with $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$ and n = 1,000,000 iterations
$Nr_{cases\ avg,\ total}$	Number of illness cases per year (average) for the total population	$Nr_{cases\ avg,\ cook} + Nr_{cases\ avg,\ eat}$	cases per year	Calculated
$Nr_{cases\ bern,\ cook}$	Number of illness cases per year (Bernoulli) for the cooks involved in preparation and eating	Bernoulli ($R_{serv,\ cook}$), if illness = 1, if not = 0	cases per year	Sum of 325 trials with n=1,000,000 iteration each
$Nr_{cases\ bern,\ eat}$	Number of illness cases per year (Bernoulli) for who only eat and are not involved in preparation	Bernoulli ($R_{serv,\ eat}$), if illness = 1, if not = 0	cases per year	Sum of 433 trials with n=1,000,000 iteration each
$Nr_{cases\ bern,\ total}$	Number of illness cases per year (Bernoulli) for the total population	$Nr_{cases\ bern,\ cook} + Nr_{cases\ bern,\ eat}$	cases per year	Calculated

4.2.3.9. Sensitivity analysis

Three types of sensitivity analyses were conducted on the baseline model (**Table 4.2**) to identify the most crucial factors influencing the overall risk per serving ($R_{serv\ cook}$) and the number of illness cases.

(i) A tornado chart was created to illustrate the impact of the model input variabilities on the output variability (i.e., risk per serving ($R_{serv\ cook}$)), using Spearman's rank correlation coefficient.

(ii) A deterministic approach was used to determine the effect of worst-case scenarios of the model input variables on the $R_{serv\ cook}$. For this, an input variable was set at a high value (e.g., P^{95} for a normal distribution) while keeping the rest of the input variables at their mean values, and then comparing the resulting risk per serving to the risk per serving in the mean scenario (i.e., all input variables set to their mean values).

(iii) To evaluate illness cases, the underlying input values that resulted in illness cases (denoted by a value of 1 from the Bernoulli trial) were analysed. For different input variables (e.g., initial concentration), distribution charts were created. These charts depicted the distribution of the 758 million iterations with a blue line (equivalent to the number of servings per year for the total population), while the corresponding input values from these iterations resulting in illness cases were represented by orange bar charts.

4.2.3.10. Intervention scenarios

To assess the influence of input variables on the incidence of campylobacteriosis cases, 'what-if' scenario analyses were performed by adjusting the baseline model (see **Table 4.2**) as follows:

(i) - Limiting (truncating) the initial concentration to a maximum of 3 and 2 log CFU/g.

- Using the distribution of the initial concentration from the period 2010–2015, instead of the period 2015–2022 (default).

- Using the logarithm of the arithmetic mean and the lower limit of the categories of the initial concentration, instead of the upper limit, to create the distribution of the initial concentration. For example, in the category 10 CFU/g < x ≤ 100 CFU/g, the upper limit is 2 log CFU/g (default), the log of the arithmetic mean is 1.74 log CFU/g, and the log of the lower limit is 1 log CFU/g.

(ii) Simulating contamination through all routes, with one route excluded at a time. Route 1: No contact with lips during preparation; route 2: RTE salad not contaminated by hands; route 1 + 2: No contamination via hands; route 3: Always replacing the cutting board; route 4: Always replacing the knife; route

5: Ensuring chicken meat is always fully cooked; route 6: Chicken is never washed before preparation.

(iii) Simulating exclusive responsibility for contamination through a single specific route. Route 1: Contamination solely through lips; Route 2: Contamination solely of RTE through hands; Route 1 + 2: Contamination solely via hands; Route 3: Contamination solely through the cutting board; Route 4: Contamination solely through the knife; Route 5: Contamination solely through undercooked chicken meat; Route 6: Contamination solely through washing chicken before preparation.

4.3 Results

4.3.1 Consumer knowledge and handling of raw chicken in domestic kitchens

In total 1974 (=n) consumers participated and completed the questionnaire. The ratio of males to females, the age distribution, and the education levels are detailed in **Appendix A**, which also includes the exact questions asked in the consumer survey along with the frequency. **Figure 4.2** provides an overview of how consumers handle raw chicken at home.

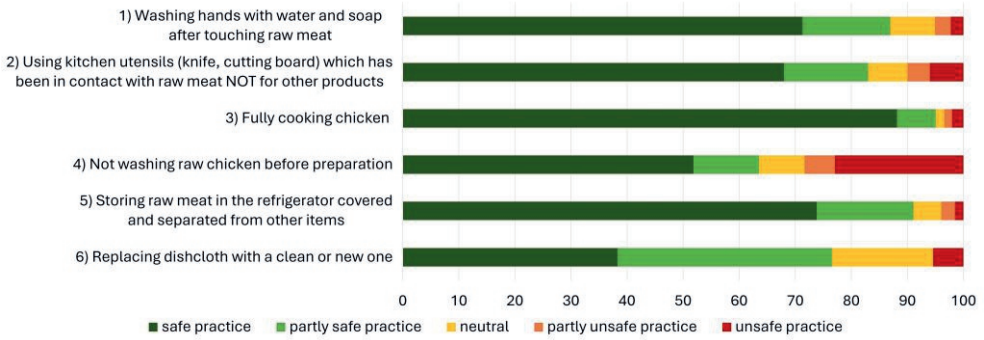


Figure 4.2. Percentage of the population reporting specific practices regarding handling raw chicken.

On average, respondents demonstrated safe food-handling practices (meaning safe practice or partly safe practice) in 80 % of the cases, based on the analysis of all six food-practice questions. Cooking chicken thoroughly demonstrated the highest compliance, i.e., always or often full cooking of chicken (95 %), followed by storing raw meat properly covered (91 %). Washing hands after touching raw meat and changing cutting boards and knives were followed at rates of 87 % and 83 %, respectively. The least followed practices were changing dishcloths daily or multiple times a week (77 %) and the discouraged practice of washing raw chicken before preparation (64 %), indicating that 23 % and 36 % of the respondents

replace dishcloths only once a week or less, and always or often wash chicken before preparation, respectively. Different demographic groups showed different practices (**Figure 4.3**).

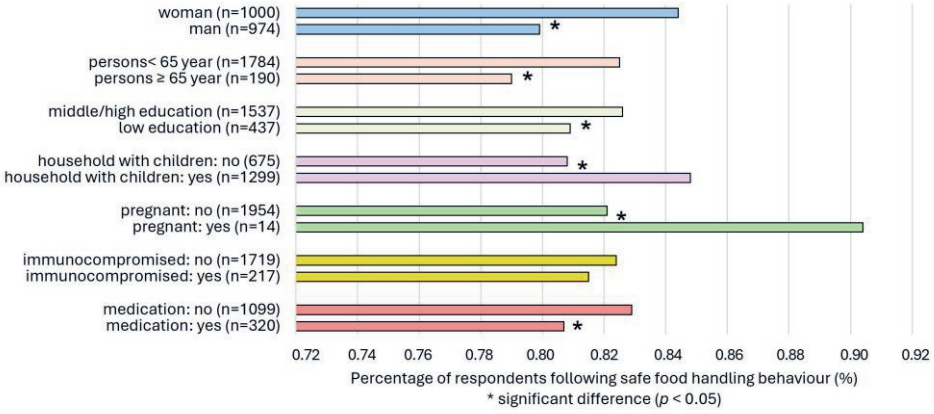


Figure 4.3. Percentage of safe food-handling practices per consumer group. Not all respondents filled in the questions regarding pregnancy, immunocompromised and medication.

Women adhered to safe food-handling practices better than men, and individuals younger than 65 years of age better than individuals of 65 years and older. Young women showed the highest compliance (0.85), significantly higher than older women (0.80), while older men showed the lowest (0.78). Households with children followed safe food-handling practices significantly better than those without children. No significant difference was observed between households with children younger than 4 years old and those with children 4 years and older. Pregnant women (n = 14) demonstrated significantly higher compliance, particularly in hand washing and replacing cutting boards and knives. Notably, persons taking medication showed lower compliance, as did the immunocompromised group, though the latter was not statistically significant. There is a correlation between these groups, as both were older than the overall participant average age (53 years versus 44 years). When compliance differences for persons taking medication and the immunocompromised group were examined within each 10-year age group, no significant differences were found, indicating that the correlation is mainly explained by age. Approximately 28 % of people reported frequently or always washing raw chicken. This practice was more common among older adults (54 %), and those with lower education levels (44 %). Therefore, the practice of washing raw chicken significantly contributed to differences in safe food-handling practices based on age and education. However, when the chicken-washing question was excluded, the difference in safe food-handling behaviour by education level was no longer significant, while the difference between individuals under 65 and those 65 or older remained significant

(p = 0.041), though the difference between the two age groups became smaller. Notably, a larger proportion of individuals aged 65 and older had lower education levels compared to younger respondents, which may explain the observed correlation.

4.3.2 Quantification of cross-contamination of *Campylobacter jejuni*

Using artificially inoculated chicken fillets (6 log CFU (SD 0.1 log CFU) per chicken fillet), different cross-contamination scenarios were employed to prepare six cucumber slices. Under the worst-case scenario (W), the average end contamination level was 4.3 log CFU (SD 0.3 log CFU) per cucumber portion of six slices. When the knife/fork was replaced (K), the resulting contamination level was 3.9 log CFU (SD 0.3 log CFU) per cucumber portion, while replacing the cutting board (C) led to a level of 3.6 log CFU (SD 0.4 log CFU) per cucumber portion. Per experiment, the transfer rate was calculated based on the CFU count per portion of 6 cucumber slices (**Figure 4.4**). The average transfer rate for knife replacement (1.0 %) and cutting board replacement (0.6 %) was significantly lower than the worst-case scenario of 2.3 %, with the transfer rate for cutting board replacement being significantly lower than that of knife replacement. Replacing the cutting board led to a 75 % decrease in bacteria transfer compared to the worst-case scenario, while replacing the knife/fork resulted in a 57 % decrease. This emphasizes the slightly larger role of the cutting board in spreading bacteria to cucumbers compared to the knife/fork. In total 6 literature studies were found which met the inclusion criteria (Van Asselt et al., 2008; Bai et al., 2021; Chen et al., 2001; Luber et al., 2006; Montville and Schaffner, 2003d; Verhoeff-Bakkenes et al., 2008), showing a wide variation between the transfer rates. Bai et al. (2021) conducted a study most similar to ours, measuring the transfer rate from inoculated chicken fillet to cucumber using a plastic cutting board and knife. They observed transfer rates of 5.3 % in the worst-case scenario, 5.8 % when replacing the plastic cutting board, and 1.5 % when replacing the knife. These findings suggest that using a clean knife resulted in a significantly lower transfer rate from chicken to cucumber compared to using a clean cutting board, which contrasts with our results. Other studies by Van Asselt et al. (2008) and Verhoeff- Bakkenes et al. (2008) also examined the overall transfer rate to ready-to-eat chicken fruit salad, finding much lower transfer rates of 0.27 % and 0.12 %, respectively. One of the factors that differed from our study is that in the studies of Van Asselt et al. (2008) and Verhoeff-Bakkenes et al. (2008) a fruit salad was made, which has a low pH, conceivably reducing the measured transfer rate due to *Campylobacter*'s lower tolerance to acidic environments. On the other hand, our experiment was designed conservatively, as the surfaces touched by the chicken were predominantly touched by the cucumber.

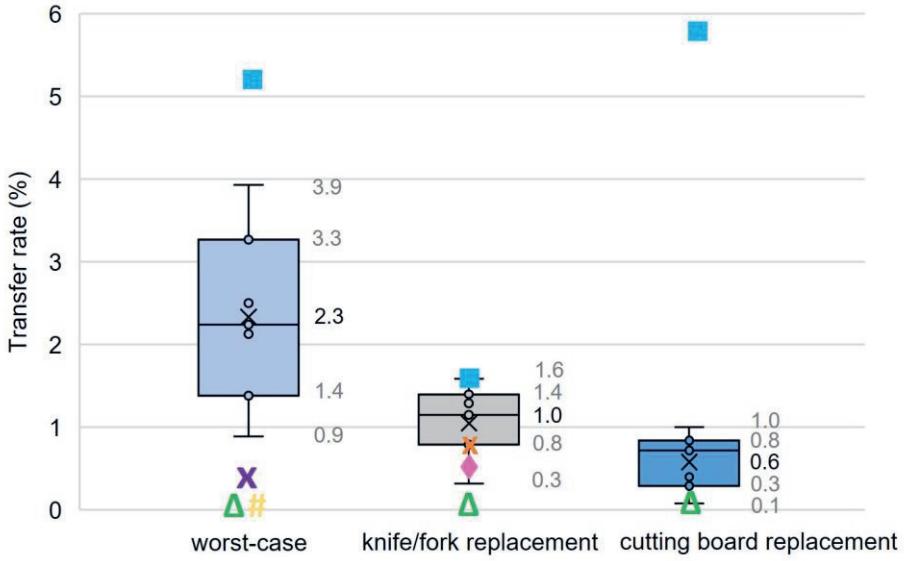


Figure 4.4. Transfer rate from chicken fillet to cucumber (%) of the worst-case scenario (i.e., using same knife/fork and cutting board for cutting raw chicken fillet and cucumber slices), only knife/fork replacement and only cutting board replacement (n = 7). The transfer rates are shown next to the boxplot, which includes the mean (X), median (—), and the 5th, 25th, 75th and 95th percentile (in grey font). The coloured symbols represent transfer rates reported by others X (Van Asselt et al., 2008), ■ (Bai et al., 2021), ◆ (Chen et al., 2001), x (Montville and Schaffner, 2003), # (Luber et al., 2006), Δ (Verhoeff-Bakkenes et al., 2008).

The study of Chen et al. (2001), Luber et al. (2006) and Montville and Schaffner (2003) focused on individual transfer steps, such as from chicken meat to the cutting board and then from the cutting board to salad. On average, they found lower transfer rates, but also here the set-up was quite different from ours.

4.3.3 Quantitative microbiological risk assessment (QMRA)

To predict the number of campylobacteriosis cases per year related to chicken consumption for the total population, one million iterations were performed in @RISK. The risk per serving was determined for both the preparation group and consumption group. From this, the number of cases was determined using two different approaches. First, the number of cases per year was estimated by multiplying the arithmetic mean risk per serving for both preparation and consumption by the average number of servings of chicken meat per year per person. This result was then multiplied by the number of individuals in each group, and the total cases were calculated by summing the cases from both groups. This procedure was repeated 50 times, predicting 41,690 cases per year for the total

population (SD 1312). Secondly, this calculation (based on the arithmetic mean) was validated by performing a Bernoulli trial for each iteration (i.e., serving) taking into account the risk per serving ($R_{serv,\ cook}$ and $R_{serv,\ eat}$), and evaluate whether this resulted in an illness case or not. The number of cases per year was determined from 325 trials of 1,000,000 iterations for the preparation group and 433 trials of 1,000,000 iterations for the consumption group, making it in total 758 trials of 1,000,000 iterations. This procedure was repeated 50 times to determine the variation in number of cases per year. This approach yielded an average result consistent with the arithmetic mean calculation, predicting 42,591 illness cases per year for the total population (SD 183). Notably, the Bernoulli method resulted in a lower standard deviation compared to the arithmetic method (i.e., SD 183 compared to 1312). The standard deviation determined using the arithmetic method aligns more closely with the standard deviation based on the confirmed cases as reported in Friesema et al. (2024) (**Appendix E**). The Bernoulli trials with 325 and 433 million iterations show that the arithmetic mean is a good estimate for the number of cases. The fact that rerunning @RISK increases the standard deviation of the number of cases shows that even these millions of iterations do not yet sufficiently describe the variation in risk per serving. To describe the extreme events, even more iterations are needed. Therefore, the standard deviation (SD) of the 50 @RISK runs is more representative than the SD of the 758 million Bernoulli trials.

Of the total illness cases, 54 % (22,335 cases) were attributed to individuals who both prepare and eat chicken (preparation group), while 46 % (19,358 cases) were linked to individuals who solely eat chicken (consumption group). Among the population, the preparation group represents 43 %, whereas the consumption group makes up 57 %. This highlights the significant role of the cook in handling raw chicken meat in domestic kitchens in contributing to the occurrence of campylobacteriosis (a factor of 1.5 higher risk). The default QMRA model used only literature data for transfer. In this study, we also experimentally determined the transfer rate where steps 3 and 4 were combined. We adjusted the QMRA model to incorporate these experimental data. The adjusted QMRA model (see **Appendix D**), which combines steps 3 and 4 and includes both literature and experimental data, predicted an average of 51,524 campylobacteriosis cases per year for the total population. This observed incidence is higher than the estimate from the default QMRA model. This discrepancy is likely due to the conservative design of the experiment; in most cases, surfaces contacted by the chicken were subsequently touched by the cucumber, a scenario more conservative than typical practice conditions. Additionally, in typical practice conditions, *Campylobacter* spp. may adhere more strongly to the chicken than in the experimental setup.

4.3.3.1. Sensitivity analysis

To assess the influence of input variability on the variability of the overall risk per serving, a sensitivity analysis was conducted, and the results are visualized in a tornado plot (**Figure 4.5**). The variability in both the dose-response parameter (r) and the initial log concentration ($C_{0,\,log}$) of *Campylobacter* spp. exhibited clearly the highest impact on the output variability (i.e., risk per serving ($R_{serv\,cook}$)). Additionally, variability in parameters such as the fraction of loosely attached cells, the serving size of cooked chicken, and practices like replacing the cutting board or knife, washing hands after preparing chicken meat, and washing chicken also contributed to the output variability, but to a much lesser extent. Not fully cooking the chicken meat was identified as a minor factor influencing the variability of the number of illness cases. Utilizing a deterministic approach with fixed input variables, changing them one by one at their maximum values, it was observed that increasing the initial concentration from - 2.04 to 0.76 log CFU/g had the most significant impact on the final output, with a risk ratio of 650 (see **Appendix F**). Additionally, lowering the exposure temperature during cooking from 70.3 °C to 51.5 °C also affected the final output strongly by a factor 38. Factors such as the dose-response parameter (r), the number of servings of chicken fillet, the serving size of cooked chicken, and neglecting hand washing after handling raw chicken influenced the final output by ratios of 5.3, 3.3, 2.5, and 2.5, respectively.

The results of the deterministic approach do not fully align with the findings of the sensitivity analysis as depicted in **Figure 4.5**. A sensitivity analysis using correlation coefficients shows the impact of input variability on the output variability. However, it may not highlight the most critical factors for the final number of cases, as these are often influenced by extreme values in the distributions of several parameters. In contrast, the deterministic approach examines input variables individually and may overlook potential correlations between them.

To further explore the factors contributing to illness cases, the distribution of several input variables was compared to the actual values associated with illness cases (**Figure 4.6**). This comparison helps to trace back which conditions led to illness cases. Orange bar charts were used to visualize the actual values that resulted in illness, while a blue line represented the distribution of the input variables. In these graphs the frequency distribution of the input variables for servings that resulted in an illness case can be compared to the general frequency distribution of the input variables. In case these distributions are fully overlapping, this means that a variable does not have an impact on the number of cases, while if the input variables for the illness cases are clearly deviating and only covering a small part of the input distribution, this means that only in a minor part of the input variables cases occur and the variable does have an important effect on the number of cases of illness.

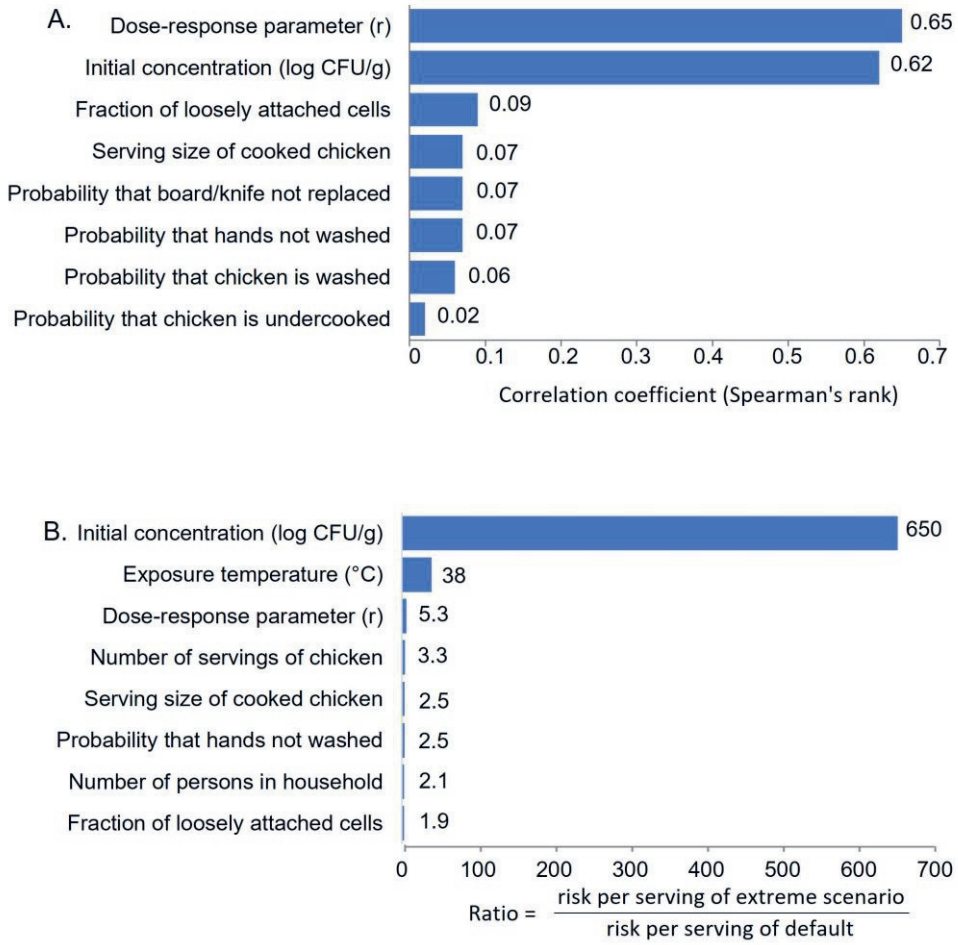


Figure 4.5. Sensitivity analysis showing: (A) the correlation coefficients (Spearman's rank) of the variability of the input variables on the variability of the risk per serving ($R_{serv\ cook}$) using the stochastic approach, and (B) the ratio of the risk per serving ($R_{serv\ cook}$) of the extreme scenario divided by the risk per serving of the mean scenario using the deterministic approach.

Model simulations indicated an average initial concentration of - 2.0 log CFU/g for the input distribution, compared to 2.1 log CFU/g for the values associated with illness (**Figure 4.6A**). This 2.1 log CFU/g value exceeded the 99th percentile of the concentration distribution, indicating that illness cases occur at the extreme right tail of the distribution. Notably, over 50 % of illness cases primarily manifest at initial concentrations exceeding 2.0 log CFU/g. A similar trend was observed for the average total ingested dose: - 2.7 log CFU for the input distribution versus 2.2 log CFU for the illness-related values (**Figure 4.6B**).

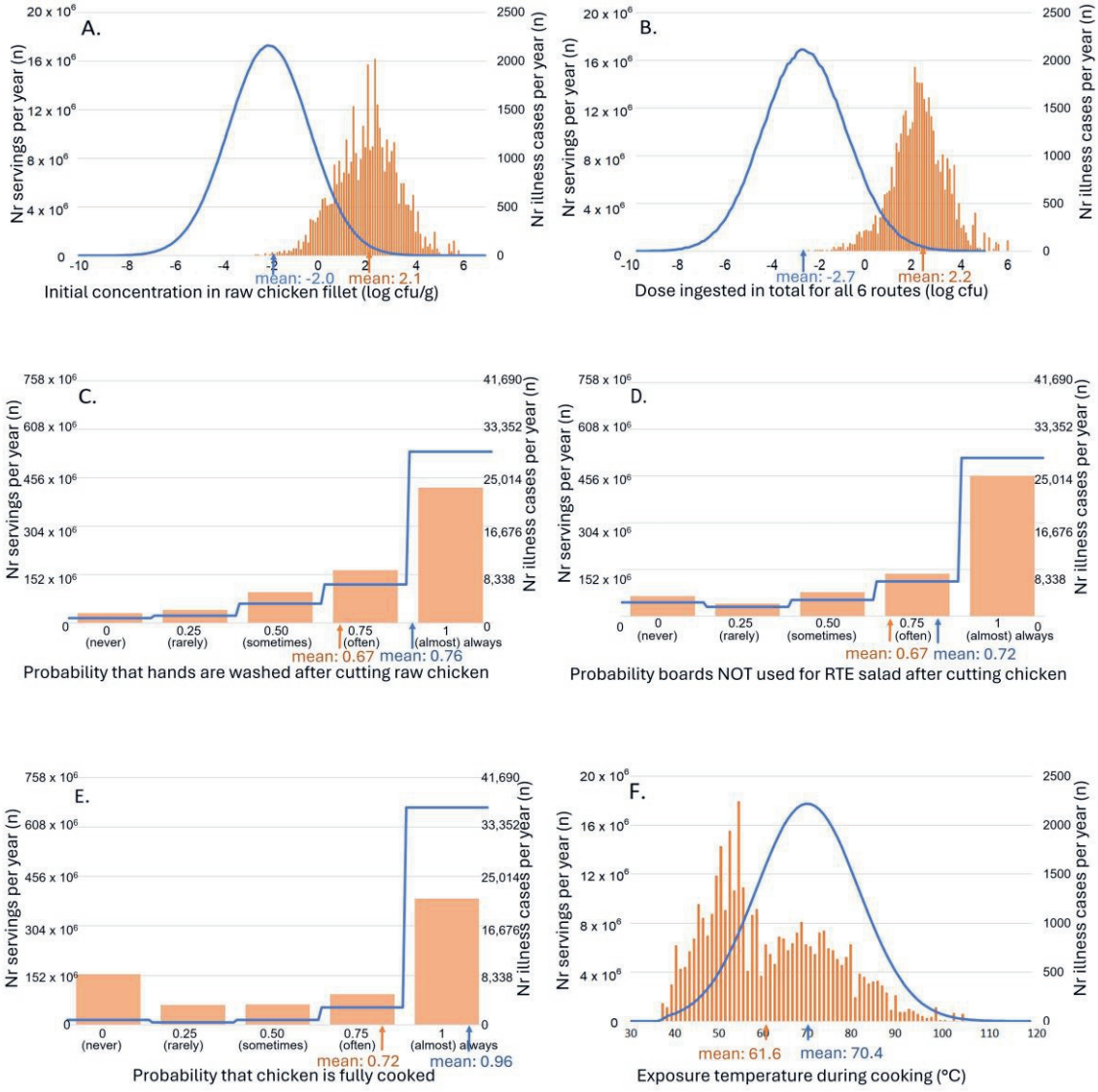


Figure 4.6. Frequency distribution of input variables of the 758 million iterations with a blue line (equivalent to the number of servings per year for the total population): initial concentration (A), total dose ingested through all routes (B), probability of washing hands after touching raw chicken (C), probability of replacing the cutting board for RTE salad after cutting raw chicken (D), probability that chicken is fully cooked (E), and exposure temperature of chicken meat during cooking (F). The orange bar charts represent the corresponding input values from only those of these 758 million iterations that resulted in illness cases. These bar charts encompass all cases from both populations: individuals involved in chicken preparation and consumption, as well as those who only consume chicken but are not involved in its preparation

To investigate consumer practices that resulted in illness, model simulations of hand washing, replacing cutting boards, and thoroughly cooking chicken were analysed (**Appendix G**). **Figure 4.6C** shows that the average hand washing rate among individuals in illness cases was lower than the mean input distribution (67 % versus 76 %). Although most consumers wash their hands after touching raw chicken, a higher proportion of those who did not wash their hands were among the illness cases. The risk of infection decreased with increased hand washing frequency. Consumers who never, rarely, or sometimes washed their hands had a 2.6, 2.3, or 2.0 times higher risk, respectively, compared to consumers who (almost) always washed their hands. The most left bar in **Figure 4.6C** (people that report to never wash their hands) is only 2 % of the total number of people/servings, but gives 4.1 % of the number of illnesses (see also **Appendix G**), showing that the orange bar is almost a factor two higher than the blue bar, showing large increase of the relative risk. A similar trend can be seen for replacing cutting boards (**Figure 4.6D**), where the average rate among individuals in illness cases was lower than the mean input distribution (67 % versus 72 %). For thoroughly cooking chicken, the difference was most outspoken (**Figure 4.6E**).

Although 88 % of all consumers indicated that they (almost) always fully cook their chicken, the proportion in illness cases in this group was 51 %. This indicates that nearly half of the illness cases are linked to consumers who do not consistently cook their chicken fully. Consumers who never or rarely fully cooked their chicken had a 17.6 or 13.8 times higher risk, respectively, compared to those who (almost) always fully cooked their chicken. Additionally **Figure 4.6F** shows that the average cooking temperature of the illness cases was lower than the average cooking temperature of the input distribution (61.6 °C versus 70.4 °C, respectively). A more detailed description of the difference between the input distribution and the values associated with illness cases can be found in **Appendix G**. The distribution figures highlight not only the significance of the initial concentration of *Campylobacter* on raw chicken, but also emphasizes how consumer practices can impact the risk of illness. Particularly properly cooking chicken meat, followed by hand washing and replacing cutting boards.

4.3.3.2. Scenarios

Scenario analyses were conducted to determine the impact of various input variables on the estimation of the risk of campylobacteriosis from preparation and consumption of chicken meat (**Figure 4.7**). The first scenario involved the reduction of the maximum initial concentration of *Campylobacter* spp. on raw chicken meat to a maximum of 3.0 and 2.0 log CFU/g. The analysis revealed a significant correlation between reducing the maximum initial concentration of *Campylobacter* spp. and the subsequent decrease in the number of estimated cases of campylobacteriosis. Specifically, a maximum initial concentration of 3.0 log CFU/g (truncation at 99.85 % of the original distribution) resulted in 25 % reduction of the cases, and further lowering it to 2.0 log CFU/g (truncation at 99.15

% of the original distribution) resulted in a reduction of >50 %. This indicates that only a very small fraction of all consumed fresh chicken products, is responsible for the majority of the illness cases. These findings underscore the critical role of initial concentration in driving the incidence of campylobacteriosis. This is supported by the analysis depicted in **Figure 4.6A**, where a notable proportion of cases were associated with initial concentrations exceeding 2 log CFU/g, with a mean concentration of 2.1 log CFU/g. Furthermore, a comparison was made between the initial concentration of *Campylobacter* spp. from the periods 2010–2015 and 2015–2022. The average initial concentration in 2010–2015 was - 2.83 log CFU/g (SD 2.19 log CFU/g), which increased to - 2.04 log CFU/g (SD 1.70 log CFU/g) in 2015–2022, but with lower spread. This shift in contamination levels corresponded with a 1.6-fold reduction in *Campylobacter* cases, having 66,836 cases in 2010–2015 and declining to 41,690 cases in 2015–2022. The higher number of cases in 2010–2015 was largely attributable to a broader distribution of contamination levels, with a greater proportion of chickens having initial contamination levels above 100 CFU/g (1.4 % in 2010–2015 compared to 0.9 % in 2015–2022). Epidemiological data from the European Centre for Disease Prevention and Control (ECDC, 2024) similarly indicate a 1.3-fold reduction in reported *Campylobacter* cases in the Netherlands over the same timeframe. Although the ECDC data encompass all sources of campylobacteriosis, and not only chicken, the observed trend aligns with the findings of this study.

In the default QMRA model, the logarithm of the upper limit of the initial concentration category was used (e.g., for the category 10 CFU/g < x ≤ 100 CFU/g, the upper limit used was 2 log CFU/g). What-if scenarios were conducted using the logarithm of the arithmetic mean and the lower limit of the categories, instead of the upper limit, to create the distribution of the initial concentration (e.g., for the category 10 CFU/g < x ≤ 100 CFU/g, the log of the arithmetic mean is 1.74 log CFU/g, and the log of the lower limit is 1 log CFU/g). Using the log of the arithmetic mean or the lower limit for the distribution, instead of the upper limit, resulted in average initial concentrations of - 2.35 log

CFU/g (SD 1.73 log CFU/g) and - 3.05 log CFU/g (SD 0.93 log CFU/g), respectively. This corresponded to 29,651 illness cases for the distribution using the log of the arithmetic mean and 231 illness cases using the log of the lower limit. All scenarios concerning initial concentration confirm that significantly reducing high contamination levels substantially impacts the number of illness cases. Moreover, using detailed data on initial concentration, such as actual numerical concentrations (and not placing them in categories), is important for creating a reliable distribution. Subsequently, various scenarios were evaluated to assess the impact of compliance with safe food-handling practices, encompassing measures such as avoiding lip contact during chicken preparation, consistent

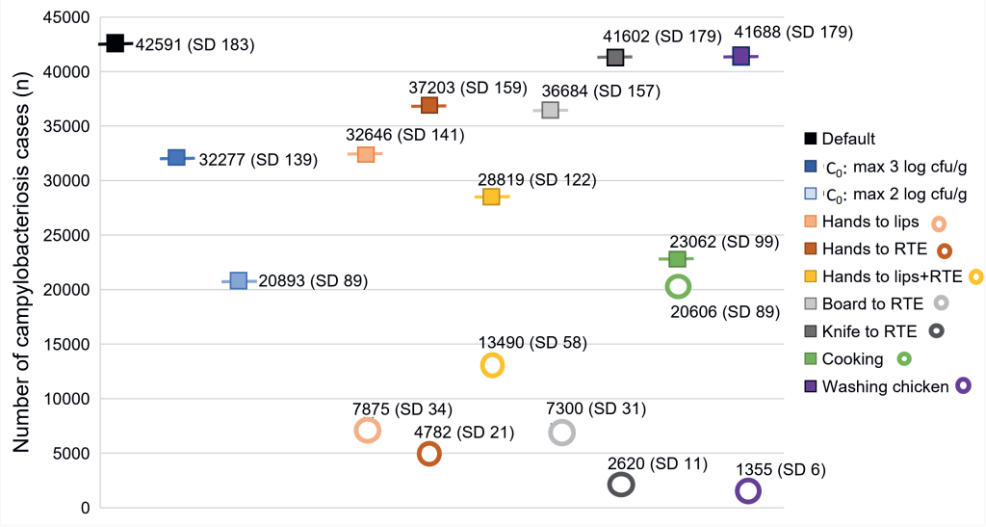


Figure 4.7. Number of campylobacteriosis cases per year (mean, SD) with different scenarios. The squares (■) show the number of illness cases when all routes are included except the one specified (which is excluded). The circles (**O**) show the number of illness cases when only the specified route is included and all other routes are excluded. SD is included here but was not published in IJFM 441, 111270.

hand washing, replacement of cutting boards and knives, thorough cooking of chicken, and refraining from washing chicken. Mitigating interventions showed that the impact of these measures varies considerably. Notably, consistent thorough cooking of chicken meat emerges as the most effective intervention, leading to a reduction of 46 % in campylobacteriosis cases. Additionally, consistent hand washing after touching raw chicken meat led to a significant reduction in illness cases by 32 %. This is illustrated in **Figure 4.7**, routes 1 and 2, as hand washing prevents contamination of the lips (route 1) and contamination of ready- to-eat food (route 2). Replacing cutting boards resulted in a 14 % reduction. Effects of practices such as replacing knives after handling raw chicken meat but before touching ready-to-eat (RTE) salad, and refrain from washing chicken were relatively limited.

These results demonstrate that, besides the importance of controlling initial concentration levels as a key strategy, consumer practices, such as thorough cooking of chicken, hand washing, and replacing cutting boards, can significantly reduce the risk of campylobacteriosis.

4.4 Discussion

Campylobacteriosis is the most reported foodborne illness in the EU, and chickens and chicken meat are identified as direct contributors to 20–30 % of human cases (ECDC, 2024). A study of Mughini Gras et al. (2022) estimated even a higher contribution of nearly 50 % in the Netherlands. The prevalence of *Campylobacter* on raw chicken directly after slaughter varies across European countries. European official control samples in accordance with Regulation (EC) No. 2073/2005 showed in Romania and Bulgaria nearly no samples above 1000 CFU/g, while Greece and Spain reported high concentrations, with respectively >64 % and 40 % of samples above 1000 CFU/g. The Netherlands falls within the middle range with a 5.9 % above 1000 CFU/g (EFSA and ECDC, 2023). Although the results of raw chicken meat in retail can be different, these official control samples taken directly after slaughter provide an indication of the initial concentration. The QMRA model highlights the significant impact of the initial concentration of *Campylobacter* on the risk of illness. Maintaining low levels of *Campylobacter* in chicken meat can substantially reduce illness cases. Particularly, preventing outliers above 100 CFU of *Campylobacter* per gram can prevent a significant number of cases. This is evident from model simulations presented in **Figure 4.6**, which show that illness cases mainly occur at high initial concentrations, with an average of 2.1 log CFU/g samples that resulted in illness cases. Scenario analysis, depicted in **Figure 4.7**, demonstrates that reducing the maximum initial concentration to 1000 CFU/g is predicted to lead to a 25 % reduction in illness cases, and further lowering it to 100 CFU/g resulted in a 50 % reduction. In 2018, the European Commission established a process hygiene criterion for *Campylobacter* in carcass broilers after chilling of 1000 CFU/g, intending to progressively increase its stringency by 2020 (from c =20 to c =15) and 2025 (from c =15 to c =10) (Zwietering et al., 2023). Although this process hygiene criterion differs from the concentration at retail (i.e., the initial concentration in this study), it is expected that stricter policies during slaughter will lead to lower initial concentrations. The model simulations from this study underscore the importance of controlling high initial concentration levels as a key strategy in reducing the incidence of campylobacteriosis.

Once at home, consumers play a crucial role in ensuring food safety. According to our questionnaire, 80 % of the respondents demonstrated safe food-handling practices for raw chicken (scoring 0.75 or higher). The highest compliance was observed for cooking chicken thoroughly and storing raw meat properly covered, followed by washing hands after handling raw meat and replacing cutting boards and knives before preparing ready-to-eat (RTE) salad. However, there was a notable gap in compliance with other safe practices such as replacing dishcloth daily and refrain from washing raw chicken. Notably, the route of infection through dishcloths is unclear, as *Campylobacter* is highly susceptible to drying and will not survive long in a dried-out dishcloth (Møretrø et al., 2021). Men complied significantly worse than women. Additionally, individuals aged 65 and older

complied worse than those under 65. These behavioural differences between young and old, and men and women likely contribute to the observed variations in campylobacteriosis cases among demographic groups. Epidemiological data indicate higher rates of campylobacteriosis among males across all ages (EFSA and ECDC, 2023). Moreover, the use of antacids like proton-pump inhibitors (PPIs) has been associated with an increased risk of campylobacteriosis (Bouwknegt et al., 2014). Increasing awareness about the risks of *Campylobacter* and preventive measures among older individuals could help reducing the number of illness cases. It should be noted that the phrasing of questions in the questionnaire is sometimes negative and sometimes affirmative, which could introduce bias. However, we expect this effect to be minimal. Furthermore, it is important to recognize the limitations of self-reported interviews. Studies indicate that self-reported practices can diverge from actual observations, highlighting the complexity of assessing food safety practices solely through interviews (Fischer et al., 2007; Jay et al., 1999; Redmond and Griffith, 2003). This suggests that reality may differ from interview reports, necessitating further observational research in domestic kitchens.

Besides insight into the extent to which Dutch consumers comply with safe food-handling practices, it is also important to understand the transmission of *Campylobacter* when the recommended guidelines are not followed. Exposure assessment is a crucial aspect of risk assessments, yet there is a lack of data regarding the transfer of *Campylobacter* from fresh chicken products to ready-to-eat items. In our experiment, cucumber was sliced on the same cutting board and with the same knife and fork used for raw chicken fillet, resulting in an average transfer rate of 2.3 %. Replacing either the cutting board or the knife/fork led to reductions in transfer rates to 0.6 % and 1.0 %, respectively. A comparison was made with existing literature; however, the diverse experimental setups, recovery methods, and calculations utilized in different studies pose challenges to directly aligning our findings. Most studies focused on individual transfer steps, such as from meat to the cutting board and then from the cutting board to salad, with only a few investigating the overall transfer rate to ready-to-eat (RTE) products. Bai et al. (2021) conducted a study most similar to ours, measuring the transfer rate from inoculated chicken fillet to cucumber using a plastic cutting board and knife. Contrary to our results, they found a higher transfer rate of 5.8 % when replacing the cutting board, which was even higher than the worst-case scenario (5.3 %) and replacing the knife (1.5 %). A controlled execution of experiments to determine the transfer rate is challenging. Furthermore, the initial load of *Campylobacter* can influence the transfer rate. Studies have shown that using a high number of *Campylobacter* for inoculation may lead to biased transfer rates, and transfer from naturally contaminated chicken can be inversely related to the initial concentration (Fravalo et al., 2009; Luber et al., 2006; Montville and Schaffner, 2003). Factors such as contact time and weight of the chicken also play a role and should be considered (Fravalo et al., 2009; Luber et al., 2006). All these variables

contribute to significant variation in the results of transfer rates, highlighting the need for further research. Despite the considerable variability in transfer rates, sensitivity analyses — such as Spearman's rank correlation and the deterministic approach — suggested that this variability had limited impact on the overall outcome of the QMRA.

Our QMRA predicted an average number of 41,690 (SD 1312) illness cases per year for the total population through the consumption of raw chicken meat. In comparison, the National Institute for Public Health and Environment estimated an average of 16,000 cases of campylobacteriosis per year through the consumption of poultry (Benínça et al., 2024). This difference could arise from the tendency of risk assessment models to lean towards worst-case scenarios, assumptions, and approximations. For example, in this study, the upper limit of the categories for initial concentration was plotted in a cumulative normal distribution. Choosing the log of the arithmetic mean significantly lowers the number of illness cases to 29,651. Using the actual concentrations for determining the distribution instead of categories can further improve the accuracy of the outcome. Additionally, the hazard characterization includes attendant uncertainty in the variability of the infectivity and pathogenicity of *Campylobacter* strains (Chen et al., 2006). Also, the composition of the ingested food and the immune status of the consumer may have a large impact on the risk of illness after the ingestion of a certain dose (Havelaar et al., 2009). Conversely, disparities between model predictions and reported incidence rates may also be attributable to underdiagnosis within microbiological surveillance systems, as observed in cases of campylobacteriosis. Considering these factors, caution is warranted when interpreting the absolute findings of QMRA models, and it is imperative to acknowledge the limitations associated with model inputs and assumptions. Nevertheless, the insights derived from QMRA models, particularly concerning relative effects, can be useful in evaluating key input variables and anticipating potential consequences of various scenarios related to the risk of campylobacteriosis. In this study, six different routes were included, which adds complexity but allows for comparison of the different routes in the domestic kitchen, thereby identifying the most relevant or critical route. Various sensitivity and scenario analyses were conducted, each offering valuable insights. Starting with the most straightforward approach, the deterministic method is an easy-to-implement approach for identifying key factors affecting the final output. However, it does not account for the full range of variability and may overlook potential correlations between input variables. In contrast, the tornado plot reveals how input variability affects output variability in risk per serving, yet this sensitivity analysis, using correlation coefficients, may not fully capture the most influential factors for the number of actual cases. On the other hand, generating distribution plots of illness cases (**Figure 4.6**) offers a clear graphical overview, enabling to trace back conditions leading to illness. Additionally, scenario analysis sheds light on how changes in input variables impact estimates of illness cases and can guide

management options. By performing these sensitivity and scenario analyses in parallel, we strengthen the conclusions drawn from a QMRA.

Our analysis identified three primary transmission routes for pathogens within the household: ensuring thorough cooking, hand washing after handling raw meat, and replacing cutting boards after use for raw meat. Numerous QMRA studies have underscored the importance of these pathways, although their relative significance may vary (Chapman et al., 2016; Eriksson et al., 2023; Iulietto and Evers, 2023; Møretrø et al., 2021; Ssemanda et al., 2024; Uyttendaele et al., 2006). Some studies suggest that the risk of cross-contamination in the kitchen outweighs that of undercooked meat (Abe et al., 2024; ANSES, 2015; Luber, 2009). For instance, Brynestad et al. (2008) found that 74 % of cases were linked to cross-contamination, while only 3 % were due to undercooked poultry products contaminated with thermotolerant *Campylobacter* spp. in Germany. Despite *Campylobacter*'s general sensitivity to heat, research indicates variability in its survival, especially under practical conditions, with some conditions showing marked resistance to elevated temperatures (Bergsma et al., 2007; De Jong et al., 2012). Additionally, Uyttendaele et al. (2006) demonstrated that inadequate heating of chicken products increases the risk of exposure to pathogens like *Campylobacter*. Our scenario analysis (**Figure 4.7**) illustrates that consistent thorough cooking of chicken is the most effective home intervention for controlling contamination. This is followed by proper hand washing and replacing the cutting board before preparing ready- to-eat foods. Interestingly, the high impact of thorough cooking contradicts the findings of Ssemanda et al. (2024), where undercooking was not the most relevant control parameter. This discrepancy is partly due to different parameters chosen in the QMRA. Ssemanda et al. (2024) used a pert distribution for temperature during cooking with a minimum of 60 °C, most likely of 64 °C, and a maximum of 65 °C (based on FAO and WHO (2002)). In contrast, our study used a normal distribution with a mean of 70.3 °C and a standard deviation of 11.4 °C (based on Audits International and FDA (2017)), resulting in a wider range of temperatures, where indeed, especially the lower range of cooking temperatures contributed to the illness cases.

In 2022, the Dutch Food Safety Authority implemented a new hygiene warning label for raw chicken meat (Warenwet, 2023). This label emphasizes the importance of following safe food-handling practices: chilling raw chicken meat, thoroughly washing hands, replacing cutting boards, and knives after contact with raw meat, and ensuring thorough cooking of the meat before consumption. These recommendations are strongly supported by the findings of this investigation. It is imperative that consumers are informed about these critical practices to reduce the risk of serious foodborne illness, with emphasis on the most vulnerable groups. Effective communication of these strategies requires the integration of social sciences (Fischer et al., 2005). Social scientists can apply their knowledge about human behaviour, combined with the understanding of human information

processing, to develop specific communication strategies. Effective communication of food safety risks by risk assessors to policymakers and the public can be challenging, and the chosen terminology can provide different risk perspectives. In **Appendix H**, some examples are provided on how risks can be expressed, based on the results of this study.

In conclusion, the combination of improved consumer practices and a lower level of initial contamination through increased stringency of the process hygiene criterion will conceivably result in a further decrease in the public health impact of this major causative agent of foodborne illness.

4.5 Data availability

The used QMRA model, along with the outcomes of one simulation with 10,000 iterations and another simulation with 1,000,000 iterations, is available at https://doi.org/10.4121/e2412c3d-f468-49bf-b736-c8c9b4d4e511.

4.6 Acknowledgement

We thank the panel agency Flycatcher Internet Research (www.flycatcher.eu) for the sampling and collecting of the data of the consumer survey. We also thank the Netherlands Food Safety Authority for providing the data on the initial concentration of *Campylobacter* spp. on raw chicken fillets from retail stores for the period 2016 to 2022. Also thanks to Akksadha Murugesan for performing the experimental work on transfer rates of *Campylobacter jejuni* from raw chicken fillets to cucumbers.

4.7 Supplementary material

4.7.1 Appendix A. Characteristics of respondents and questions asked in consumer survey

Table A1. Characteristics of respondents of consumer survey

Variable	Category	n	%
Characteristics of respondents			
Gender	male	974	49%
	female	1000	51%
Age	18-24 yrs	128	6%
	25-39 yrs	633	32%
	40-54 yrs	576	29%
	55-64 yrs	447	23%
	65-69 yrs	190	10%
Level of education [1]	low	437	22%
	medium	842	43%
	high	695	35%
Characteristics of respondents' household			
Children below 4 years in household	yes	118	6%
Older persons above 65 years	yes	199	10%
Pregnant	yes	14	1%
Immunocompromised [2]	yes	217	11%
Use of medication that lower the immune system [3]	yes	320	16%

[1] education level high (university, college, higher vocational, general secondary, and intermediate vocational education), middle (general intermediate, and lower vocational education), and low (elementary education or less).

[2] household members who have indicated to have an autoimmune disease (multiple sclerosis, rheumatism, Crohn's disease, diabetes, kidney- or liver disease, cancer treatment, organ transplantation, HIV/ADIS).

[3] household members who use medication that lower the immune system (immune suppressive, antibiotics, antacids).

4.7.2 Appendix B. Visual presentation of the preparation of the *Campylobacter jejuni* cocktail and the scenarios

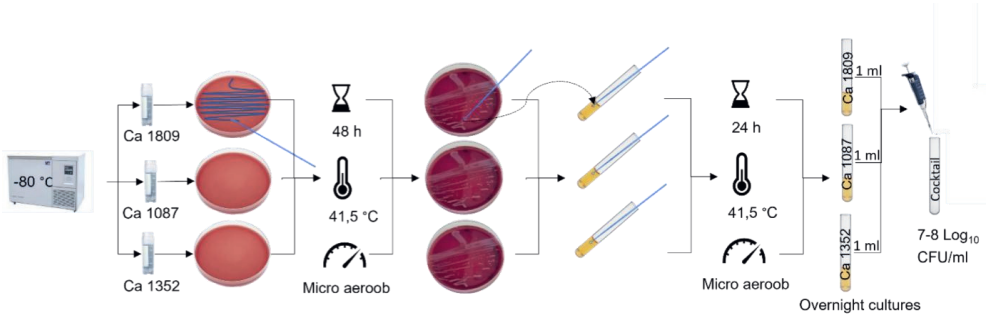


Figure B1. Preparation of the *C. jejuni* cocktail used for the experiments. From left to right: Freezer -80 °C, cryovials with a frozen culture of each *C. jejuni* strain, isolation streak of frozen culture on CAB plates, incubation, transfer of (isolated) colonies to tubes with HI broth, incubation, overnight cultures, and preparation of the cocktail with 7 mL PPS.

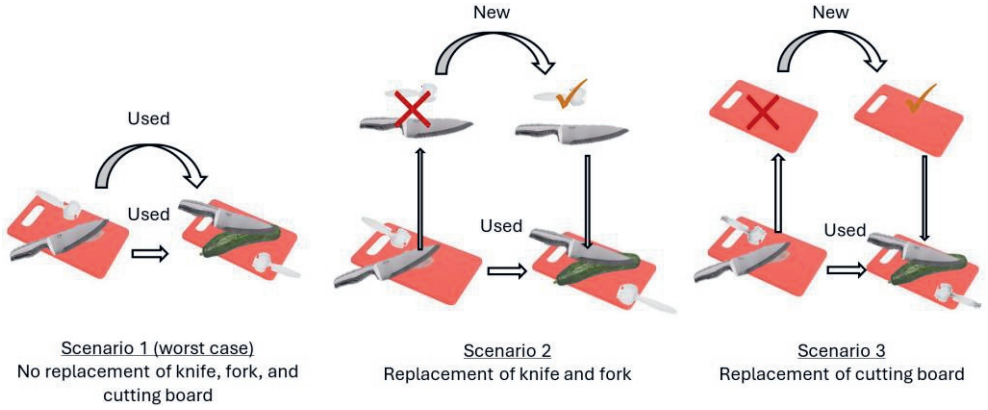


Figure B2. Visual presentation of the three different scenarios.

4.7.3 Appendix C. Overview of data from literature used for the QMRA model

Table C1. Overview of data from literature used for the default QMRA model as described in **Table 4.2**

Distribution	Parameters			Reference	
Chicken (via direct contact) to hand - route 1 and 2					**Mean transfer rate**
Beta (α, β)	90.9	667.4		Bai et al. (2021)	0.120
Beta (α, β)	0.36	9.11		Luber et al. (2006)	0.038
Beta (α, β)	0.24	8.07		Luber et al. (2006)	0.029
Beta (α, β)	1.77	41.1		Montville et al. (2001)	0.041
Beta (α, β)	0.61	6.35		Chen et al. (2001)	0.088
Beta (α, β)	0.11	2.73		Montville and Schaffner (2003)	0.039
Hand (via direct contact) to lips - route 1					**Mean transfer rate**
Pert (*min, most likely, max*)	0.339	0.363	0.41	Rusin et al. (2002) from hand [1]	0.0157
Beta (α, β)	1.1	2700		Evers et al. (2014) from hand	0.0004
Touching lips - route 1					**Nr of touching lips in 30 min**
Normal (μ, σ) - Truncate (0;12)	2	3		Kwok et al. (2015)	2.0
Normal (μ, σ) - Truncate (0;12)	4	3.57		Nicas and Best (2008)	4.0
Hand (via direct contact) to RTE salad - route 2					**Mean transfer rate**
Pert (min, most likely, max)	0.0007	0.0018	0.0038	Verhoeff-Bakkenes et al. (2008)	0.0018
Beta (α, β)	0.02	2.8		Chen et al. (2001)	0.007
Beta (α, β)	0.43	2.09		Montville et al. (2001)	0.171
Beta (α, β)	0.01	0.59		Montville and Schaffner (2003)	0.017
Beta (α, β)	0.32	1.84		Rodrigues et al. (2010)	0.148
Chicken (via direct contact) to cutting board (plastic) - route 3					**Mean transfer rate**
Beta (α, β)	2.43	219		Luber et al. (2006)	0.011
Beta (α, β)	10.2	440		Bai et al. (2021)	0.023
Beta (α, β)	0.5	5.81		Tang et al. (2011)	0.079
Beta (α, β)	1.26	8.74		Tang et al. (2011)	0.126
Beta (α, β)	0.19	3.57		Tang et al. (2011)	0.051
Beta (α, β)	0.8	7.2		Tang et al. (2011)	0.100
Beta (α, β)	1.87	9.17		Chen et al. (2001)	0.169
Beta (α, β)	1.01	7.96		Montville and Schaffner (2003)	0.113
Beta (α, β)	0.06	1.97		Jiménez et al. (2009)	0.030
Beta (α, β)	190	15000		Ravishankar et al. (2010)	0.013
Beta (α, β)	2.14[13]	1.3[14]		Goh et al. (2014)	0.141
Beta (α, β)	5.32	765		Sarjit and Dykes (2017)	0.007

Beta (α, β)	25.9	3290		Sarjit and Dykes (2017)	0.008
Cutting board (plastic) to RTE salad - route 3					**Mean transfer rate**
Beta (α, β)	0.93	8.08		Luber et al. (2006)	0.103
Pert (min, most likely, max)	0.00001	0.0011	0.0018	Verhoeff-Bakkenes et al. (2008)	0.0011
Beta (α, β)	0.35	58.3		Zhao (1998)	0.006
Beta (α, β)	3.74	43.3		Chen et al. (2001)	0.080
Beta (α, β)	0.3	4.49		Montville and Schaffner (2003)	0.063
Chicken (via direct contact) to knife - route 4					**Mean transfer rate**
Beta (α, β)	2.43	219		Luber et al. (2006)	0.011
Beta (α, β)	99.9	200000		Montville et al. (2001)	0.000
Beta (α, β)	3.84	834		Montville and Schaffner (2003)	0.005
Beta (α, β)	23.3	1400		Rodrigues et al. (2010)	0.016
Knife (via direct contact) to RTE salad - route 4					**Mean transfer rate**
Beta (α, β)	0.93	8.08		Luber et al. (2006)	0.103
Pert (min, most likely, max)	0.00001	0.0017	0.0032	Verhoeff-Bakkenes et al. (2008)	0.0017
Beta (α, β)	1.44	38.2		Zilelidou et al. (2015)	0.036
Beta (α, β)	1.3	13.2		Zilelidou et al. (2015)	0.090
Beta (α, β)	7.25	14.2		Zilelidou et al. (2015)	0.338

Determining *D*-value *Campylobacter* spp. – route 5

Strain	***z*-value (°C)**	**D_{ref} (min)**	**$Temp_{ref}$ [2] (°C)**		**Regression equation**
H-840	5.91	0.493	58.25	FAO and WHO (2009)	$\log D = ((-1/z) * Temp) + 9.549$
5-strain comp	6.35	0.677	58.25	FAO and WHO (2009)	$\log D = ((-1/z) * Temp) + 9.004$
ST-474H	11.1	0.387	58.25	Al Sakkaf (2021)	$\log D = \log D_{ref} + ((Temp_{ref} - Temp)/z)$
ST-474P	7.6	0.317	58.25	Al Sakkaf (2021)	$\log D = \log D_{ref} + ((Temp_{ref} - Temp)/z)$
ST-48H	11.3	0.378	58.25	Al Sakkaf (2021)	$\log D = \log D_{ref} + ((Temp_{ref} - Temp)/z)$
ST-48P	9.6	0.455	58.25	Al Sakkaf (2021)	$\log D = \log D_{ref} + ((Temp_{ref} - Temp)/z)$

Chicken (via washing under tap) to RTE salad – route 6		**Mean transfer rate**
-	Chea et al. (2022)	0.018

Prevalence of salad contaminated after washing chicken (%) – route 6	Prevalence
Shumaker et al. (2022)	0.060
Chea et al. (2022)	0.056

[1] Transfer rate is 0.367 from fingertip. One fingertip represents 2 cm^2 and one hand represents 140 cm^2 (Nicas and Best, 2008; Evers et al., 2014). The transfer rate from hand is calculated as (3 fingers * 2 hands)/140) * 0.367 = 0.0157.

[2] For FAO and WHO (2009) the same $Temp_{ref}$ is chosen as for Al Sakkaf (2021), so that D_{ref} can be compared more easily.

Table C2. Overview of own experimental data and data from literature used for the adjusted QMRA model as described in **Appendix D**

Distribution				Reference	
Chicken (via unwashed cutting board and knife) to RTE salad – scenario worst case					**Mean transfer rate**
Normal (μ, σ) - Truncate (0;0.05)	0.023	0.010		Own experimental data (worst case)	0.023
Not available				Van Asselt et al. (2008)	0.0027
Beta (α, β)	429	7629		Bai et al. (2021)	0.0532
Not available				Luber et al. (2006)	0.0011
Pert (min, most likely, max)	0.00001	0.0012	0.0096	Verhoeff-Bakkenes et al. (2008)	0.0024
Chicken (via unwashed cutting board) to RTE salad – scenario knife replacement					**Mean transfer rate**
Normal (μ, σ) - Truncate (0;0.05)	0.010	0.004		own experimental data (knife replacement)	0.010
Beta (α, β)	19.2	1258		Bai et al. (2021)	0.0150
Not available				Chen et al. (2001)	0.0060
Not available				Montville and Schaffner (2003)	0.0070
Pert (min, most likely, max)	0.0001	0.0008	0.0069	Verhoeff-Bakkenes et al. (2008)	0.0017
Chicken (via unwashed knife) to RTE salad – scenario cutting board replacement					**Mean transfer rate**
Normal (μ, σ) - Truncate (0;0.05)	0.006	0.003		Own experimental data (cutting board replacement)	0.006
Beta (α, β)	34	555		Bai et al. (2021)	0.0577
Pert (min, most likely, max)	0.0001	0.0010	0.0204	Verhoeff-Bakkenes et al. (2008)	0.0041

4.7.4 Appendix D. Adjusted QMRA model combining two transmission steps: from raw chicken to the cutting board/knife, and from the cutting board/knife to the RTE salad

The complete dataset of this Appendix is provided in https://doi.org/10.1016/j.ijfoodmicro.2025.111270.

4.7.5 Appendix E. Calculating the mean and standard deviation with Bernoulli trials

The complete dataset of this Appendix is provided in https://doi.org/10.1016/j.ijfoodmicro.2025.111270.

4.7.6 Appendix F. Deterministic approach to evaluate the influence of an extreme value of an individual input variable on the risk per serving while keeping the rest of the variables at the mean value

The complete dataset of this Appendix is provided in https://doi.org/10.1016/j.ijfoodmicro.2025.111270.

4.7.7 Appendix G. Proportion of total number of iterations and illness cases per probability category

Table G1. Proportion of total number of iterations and illness cases per probability category that hands are washed after touching raw chicken (**Figure 4.6C**)

Probability	0 (never)	0.25 (rarely)	0.5 (sometimes)	0.75 (often)	1.0 ((almost) always)
Proportion total nr of iterations (%)	2.0	3.0	8.0	16.0	71.0
Proportion of illness cases (%)	4.1	5.4	12.8	21.8	56.0
Number of illness cases	1709	2251	5336	9088	23346
Population in probability category	324166	486248	1296662	2593324	11507875
Risk, i.e., cases / population (-)	0.0053	0.0046	0.0041	0.0035	0.0020
Relative risk *	2.6	2.3	2.0	1.7	1.0

* Relative risk is calculated by dividing the risk of the probability (0; 0.25; 0.5; 0.75) by the risk of the reference (probability 1.0)

Table G2. Proportion of total number of iterations and illness cases per probability category that boards are not reused (without washing) for RTE salad after cutting raw chicken (**Figure 4.6D**).

Probability	0 (never)	0.25 (rarely)	0.5 (sometimes)	0.75 (often)	1.0 ((almost) always)
Proportion total nr of iterations (%)	6.0	4.0	7.0	15.0	68.0
Proportion of illness cases (%)	8.4	5.3	10.1	17.8	58.5
Number of illness cases	3502	2210	4211	7421	24389
Population in probability category	972497	648331	1134579	2243124	11021627
Risk, i.e., cases / population (-)	0.0036	0.0034	0.0037	0.0033	0.0022
Relative risk *	1.6	1.5	1.7	1.4	1.0

* Relative risk is calculated by dividing the risk of the probability (0; 0.25; 0.5; 0.75) by the risk of the reference (probability 1.0)

Table G3. Proportion of total number of iterations and illness cases per probability category that chicken is fully cooked (**Figure 4.6E**)

Probability	0 (never)	0.25 (rarely)	0.5 (sometimes)	0.75 (often)	1.0 ((almost) always)
Proportion total nr of iterations (%)	2.0	1.0	2.0	7.0	88.0
Proportion of illness cases (%)	20.4	8.0	8.2	12.4	51.0
Number of illness cases	8505	3335	3419	5170	21262
Population in probability category	324166	162083	324166	1134579	14263282
Risk, i.e., cases / population (-)	0.0262	0.0206	0.0105	0.0046	0.0015
Relative risk *	17.6	13.8	7.1	3.1	1.0

* Relative risk is calculated by dividing the risk of the probability (0; 0.25; 0.5; 0.75) by the risk of the reference (probability 1.0)

4.7.8 Appendix H. Expression of risk

Risk can be expressed in different ways, each providing different perspectives.

Table H1. Definition of different types of risk

Probability of illness (P_{ill})	Likelihood that an individual becomes ill after being exposed to a specific dose of a pathogen.
Risk per serving (R_{serv}) $(P_{ill} \times Probability_{of\ exposure})$	Probability that consuming a single serving of a particular food item will result in illness due to exposure to a specific pathogen.
Illness cases per year $(R_{serv} \times Nr_{serv} \times Population_{total})$	Total number of illness cases in a population due to exposure to a specific pathogen within one year. This can also be expressed as the number of illness cases per 100,000 people for comparison across populations.
Risk per year (R_{year}) $(R_{serv} \times Nr_{serv})$	Probability that an individual will become ill over a one-year period due to exposure to a specific pathogen.
Risk per lifetime (R_{life}) $(R_{year} \times YEAR_{lifetime})$	Probability that an individual will become ill over their lifetime due to exposure to a specific pathogen. This can be calculated by multiplying the Risk per year with the average years of a lifetime (85 years).

In **Table H2** the different risks are illustrated for 3 scenarios:

- default QMRA (as defined in **Table 4.2**).
- scenario 1: where chicken is always fully cooked by the whole population (**Appendix G**, **Table G3**).
- scenario 2: where chicken is never fully cooked by the whole population (**Appendix G**, **Table G3**).

Table H2. Expression of different types of risk for three scenarios

	Default	**Scenario 1: chicken is fully cooked**	**Scenario 2: chicken is not fully cooked**
Risk per serving (R_{serv}) $(\boldsymbol{P_{ill}} \times \boldsymbol{Probability_{of\ exposure}})$	0.00005473 (≈ 1 in 18,000)	0.00003210 (≈ 1 in 31,000)	0.000578 (≈ 1 in 1750)
Illness cases per year $(\boldsymbol{R_{serv}} \times \boldsymbol{Nr_{serv}} \times \boldsymbol{Population_{NL}})$	41,690	24,353	438,062
Risk per year (R_{year}) $(\boldsymbol{R_{serv}} \times \boldsymbol{Nr_{serv}})$	0.00257	0.00152	0.0262
Risk expressed as one in every X persons	1 / 0.00257 = ≈ 1 in 380 persons	1 / 0.00152 = ≈ 1 in 658 persons	1 / 0.0262 = ≈ 1 in 37 persons
Risk per lifetime (R_{life}) $(\boldsymbol{R_{year}} \times \boldsymbol{YEAR_{lifetime}})$	Frequency: ≈ once in 380 years ≈ 0.22 times in a lifetime (85 years)	Frequency: ≈ once in 658 years ≈ 0.13 times in a lifetime (85 years)	Frequency: ≈ once in 38 years ≈ 2.2 times in a lifetime (85 years)

In **Table H3** examples are given of possible communication, their applications for consumers, policy makers and risk assessors, and the contexts in which they are most useful.

Table H3. Examples of different types of risk and their applications for consumers, policy makers and risk assessors

Risk per serving (R_{serv})	Example: *"The risk of getting ill from Campylobacter from consuming one serving of chicken is 1 in 18,000"* Consumers: Helps communicate how "safe" a product is during a single consumption moment. A drawback is that the risk per serving is often very small, which might lead to it being underestimated. Policy makers: Less relevant as it doesn't provide insights into the overall risk level in the population. Risk assessors: Useful for evaluating the risk of specific food items, benchmarking and helps in identifying high-risk foods and prioritizing them for safety interventions.
Illness cases per year	Example: *"In the Netherlands, approximately 42,000 cases of campylobacteriosis occur each year as a result of chicken consumption."* Consumers: Not directly applicable but can be used in media communication to highlight the severity of a problem. Becomes more comprehensible when the risk is compared to other known risks. Policy makers: Helpful for prioritizing policies and assessing the impact of food safety measures. Risk assessors: Provides population-level insights and allows calculation of the burden of disease. Illness cases per 100,000 per year can be helpful for international comparison for policy makers and risk assessors.
Risk per year (R_{year})	Example: "*A consumer in the Netherlands has a 1 in 380 chance of contracting campylobacteriosis each year from consuming chicken.*" Consumers: Helps understand personal annual risk. Policy makers: Useful for evaluating the impact of interventions, such as reducing contamination levels. Risk assessors: Allows assessment of risks over time and comparison across food products or interventions.
Risk per lifetime (R_{life})	Example: "*People who consistently consume undercooked chicken are likely to experience Campylobacter infection about twice over an 85-year lifetime.*" Consumers: Helps understand the likelihood of experiencing a foodborne illness over their lifetime. By linking lifetime risk to severity, message becomes more focused and actionable. Policy makers: Can be useful for long-term strategic planning. More useful for chronic long-term effects (e.g., cancer risks from carcinogens), than acute short-term effects. Risk assessors: A way to model cumulative risk, especially for long-term exposures.

Chapter 5

From perception to behaviour: the role of communication in food safety awareness and hygiene practices over time

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Abstract

Effective public health management requires insight into public risk perception. This study synthesizes findings from two series of repeated cross-sectional surveys. The first survey (2009, 2018, 2024) compared consumer and expert risk perceptions. Consumers identified an unhealthy diet as the main food risk from 2018 onwards, whereas experts did so consistently and more strongly. Concerns about chemical risks, such as environmental contaminants, increased over time, particularly among consumers, who rated these risks higher than experts. In 2024, consumers ranked food poisoning third, after environmental contaminants, while experts ranked it second. The second survey (2015, 2021, 2024) examined whether a revised hygiene warning label on poultry packaging could improve kitchen hygiene practices. Approximately 80 % of respondents reported reading the label and considered it important and useful. The revised label, using icons rather than text, was rated as clearer and more useful by 87 % of readers. Label readers reported safer chicken-handling practices than non-readers. Higher intentions to adopt safer food-handling behaviours were most evident among those with poorer hygiene practices, older adults (65+), and lower-educated individuals under 65. These 15-year repeated surveys, combining expert-consumer comparisons with behavioural assessment, demonstrate the value of evidence-based, targeted risk communication for food safety improvement.

5.1 Introduction

Food safety is an important issue in society, yet consumer perceptions of food risks and their daily food-handling practices are complex and dynamic. Consumer perceptions of food-related risks can change significantly over time due to various factors such as increased public awareness, scientific advancements, and media coverage (Abe et al., 2020; FSA, 2022a; Nardi et al., 2020; NVWA, 2023a). For instance, incidents such as bovine spongiform encephalopathy (BSE) (Barnett and Breakwell, 2003), dioxins (Verbeke, 2001), and the horsemeat scandal in 2013, where horsemeat was sold as beef (Brooks et al., 2017), had a substantial impact on consumer risk perception. In parallel, as more information became available about the long-term health impacts of diets, consumers began to view an unhealthy diet as a major risk (Van der Vossen-Wijmenga et al., 2022). In recent years, environmental contaminants like per- and polyfluoroalkyl substances (PFAS) and microplastics have gained attention, driven by growing evidence of their presence in the food supply and potential health effects (BfR, 2020; EFSA CONTAM Panel, 2020). This shift in perception highlights the dynamic nature of consumer concerns, with social media playing an amplifying role by rapidly spreading messages and influencing public opinion (Rutsaert et al., 2014). Risk perception significantly influences how individuals respond to food risks, shaping both their behaviour and consumption choices (Campos et al., 2024; Meira et al., 2024; Nardi et al., 2020; Slovic, 1987). For example, Nardi et al. (2020) demonstrated that higher risk perception strongly decreases consumers' willingness to buy. However, beyond purchasing decisions, risk perception also determines the extent to which consumers engage in safe food-handling practices. Several studies show that a lack of specific knowledge and personal risk perception, such as optimistic bias (i.e., the belief that one is less likely to experience negative events), can contribute to risky kitchen hygiene practices, particularly during poultry handling at home (Bearth et al., 2014; Myintzaw et al., 2020; Sterniša et al., 2018). Given that improper food handling at home is an important contributor to foodborne illness (EFSA and ECDC, 2019), effective risk communication strategies are crucial. The Food and Agriculture Organization of the United Nations and the World Health Organization highlight in their handbook the role of risk perception on risk communication applied to food safety. A key principle in risk perception is that, regardless of technical risk estimates, people's perceptions of risks shape their attitudes, intentions, and behaviours. As a result, it is critically important in effective risk communication to identify and address people's perceptions as part of the risk communication process (WHO and FAO, 2016). One example of such risk communication is food labelling, which offers a direct way to communicate with consumers and may influence their perceptions and food-handling practices. Since 2001 a hygiene warning label is mandatory on the retail packages of raw poultry in the Netherlands (Warenwet, 2023). This label aims to reduce the risk of foodborne illnesses by providing safe food-handling instructions, encouraging consumers to store, handle, and prepare raw poultry safely. The hygiene warning

label was first evaluated in 2015 to examine its impact on risk perception, self-reported food-handling behaviour, and intention to change behaviour (Antonise-Kamp et al., 2018). Based on the recommendations of this study to improve the design and visibility of the label, the Dutch Ministry of Health, Welfare, and Sport decided to improve the appearance and content of the label. This revised label, which includes icons and new information regarding storing chicken at 4 degrees Celsius in the refrigerator, has been incorporated into Dutch legislation (**Figure 5.1**). Importantly, the size and placement of the label remain unchanged. Since 2023, the revised hygiene warning label is mandatory on all raw chicken meat packaging, with full compliance (100%) observed in supermarkets by 2024 according to the Dutch Food Safety Authority (NVWA, 2023b). The implementation of the revised label, however, was not accompanied by a large-scale public awareness campaign, or dedicated media coverage, coordinated point-of-sale or training initiatives.

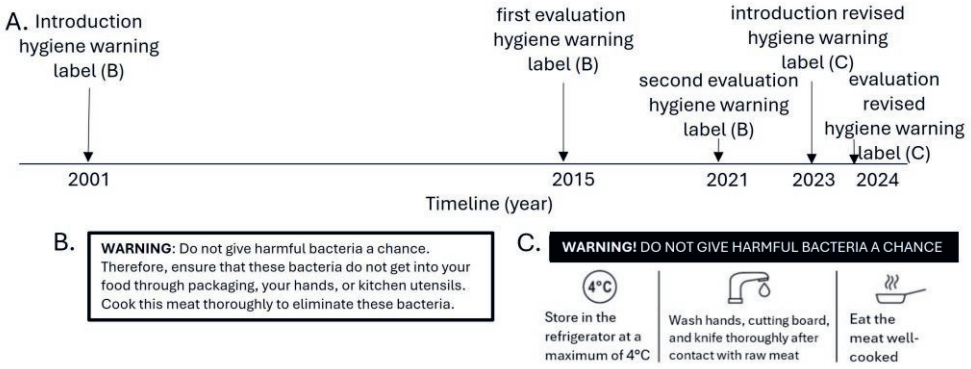


Figure 5.1. Timeline of the introduction, revision and evaluation of the hygiene warning label in the Netherlands (A). Version of the hygiene warning label from 2001 until 2022 (B) and revised version from 2023 onwards (C). The original Dutch text is given in **Appendix B**.

Long-term research on consumer behaviour and risk perception offers valuable insights into how people perceive risks and how these perceptions influence their actions (Maione, 2024; Siegrist, 2013). In this context, the present study integrates findings from two series of repeated cross-sectional surveys conducted by the Netherlands Nutrition Centre over a period of 10 to 15 years to examine food safety risk perception and communication in the Netherlands. The first study explored consumer and expert perceptions of food risks, based on surveys conducted in 2009, 2018, and 2024. The second study assesses changes over time in relation to the hygiene warning label on poultry packaging, based on surveys conducted in 2015, 2021, and 2024, with a specific focus on food safety knowledge, self-reported food-handling practices, and intention to change behaviour following the

introduction of the revised label. By conducting theory-driven, demographically representative surveys repeatedly over a long-term (15-year) period and comparing consumers' and experts' perspectives, this study provides evidence-based insight into the role of targeted risk communication strategies in supporting food safety and public health.

5.2 Materials and methods

5.2.1 Perception of food-related risks

To assess consumers' risk perception, a list of eight potential food-related risks was initially developed in 2009, based on those identified by Kampelmacher (1985) and a literature review (Frewer and Miles, 2001; Van Kreijl et al., 2006). These included chemical and microbiological risks, risks associated with new technologies, and the risk of an unhealthy diet. For each of the food-related risks, participants were asked to rate their familiarity with the defined food risk on a five-point scale (1. not familiar at all; 2. not familiar; 3. neutral; 4. familiar; 5. very familiar). Additionally, they were asked to evaluate the relevance of the risk to their health on a five-point scale (1. no risk to my health; 2. nearly no risk to my health; 3. neutral; 4. a large risk to my health; 5. a very large risk to my health; 6. no opinion). In addition to consumers, experts in the fields of nutrition, toxicology, food science, food microbiology, or food technology were asked to score the relevance of the food-related risks to people's health. A total of 2005 consumers and 62 experts completed the online survey in 2009. In 2018, this survey was repeated with the inclusion of two additional food risks: hormones/antibiotics in meat and chemicals from food packaging (e.g., plastic softeners or bisphenol A). A total of 1014 consumers and 65 experts completed the survey in 2018. Details about the studies' setup were described by Van der Vossen-Wijmenga et al. (2022). To evaluate if risk perception further changed over time, a follow-up study was conducted in 2024. A list of 11 potential food-related risks was developed based on the risks mentioned by Van der Vossen-Wijmenga et al. (2022), with the addition of two new emerging risks: PFAS and microplastics, and the exclusion of nanotechnology. The wording of the food risks in Dutch was carefully defined to avoid any positive or negative connotations, preventing respondents from being biased (**Table 5.1**). To avoid influencing participants and to capture their spontaneous responses, the 2024 questionnaire began with an open-ended question: 'What do you see as the greatest food risk to your health?'. Furthermore, in 2024, participants were instructed to select five food-related risks from the predefined list that they perceived as having the greatest impact on their health. Subsequently, they were asked to rank these five selected risks using a forced-ranking procedure, from most impactful (rank 1) to least impactful (rank 5). To determine whether risk perception influences consumer behaviour, specific questions were added in the survey of 2024 about the actions individuals take to reduce food-related risks. The survey also included questions about their

consumption of vegetables and fruits, and whether concerns about pesticide residues have influenced how they handle these foods. Mean scores and standard deviations for risk perception and familiarity with the risk were calculated for consumers and experts in 2009, 2018, and 2024. A Mann-Whitney *U* test (two-sided) was used to test for significant differences in the mean scores of risk perception between consumers and experts. A nonparametric Kruskal-Wallis test (two-sided) was used to test for significant differences between the years 2009, 2018, and 2024. The reason for choosing nonparametric tests was that the data was collected on ordinal scale (scoring 1 to 5) and was not normally distributed. Furthermore, these tests are robust when variances are not fully homogeneous (Gibbons and Chakraborti, 1991). To reduce the number of false positives (type I error), the Bonferroni correction was applied taking into account the number of tests (i.e., risks) for each of the years. In 2009, eight food risks were analysed, resulting in a corrected significance threshold of $\alpha = 0.05/8 = 0.0063$. In 2018, ten food risks were included ($\alpha = 0.05/10 = 0.0050$), and in 2024, eleven food risks were analysed ($\alpha = 0.05/11 = 0.0045$). For clarity and consistency in interpretation across years, a uniform rounded threshold of $\alpha = 0.005$ was applied when reporting statistical significance. For the 2024 survey, the correlation between familiarity with the risk and the perception of the risk was calculated using Spearman's correlation coefficient (r_s). The same method was used to calculate the correlation between age and the perception of the risk. To understand if other consumer characteristics, such as gender and education level, were associated with the perception of the risk, a nonparametric Mann-Whitney *U* test (two-sided) was used to test for significant differences in gender (male vs female), and a nonparametric Kruskal-Wallis test (two-sided) was used to test for significant differences between low, middle, and high education levels. These analyses were performed for each individual food risk, as well as for all eleven food risks combined, where an average score was calculated for each respondent across all eleven food risks. Furthermore, Mann-Whitney *U* test (two-sided) was used for significant differences in scoring the top five food-related risks. Statistical analysis was performed using JASP 0.19.1.

5.2.2 Evaluation of the impact of a hygiene warning label on the packaging of raw poultry

In 2015, the impact of the mandatory hygiene warning label on the packaging of raw poultry was studied among 514 adults (Antonise-Kamp et al., 2018). Information was gathered on participants' knowledge of safe food-handling practices for chicken, their current food-handling practices for chicken and their intention to change practices after reading the label. The Health belief model (HBM) (Strecher et al., 1997; Hanson and Benedict, 2002) provided the framework for the questionnaire, focusing on selected components.

Table 5.1. List of food risks mentioned in survey of 2009, 2018 and 2024 and the scale for rating

	Food risk	Scale*	2009	2018	2024
1.	Unhealthy diet with (too) many calories, sugar, fat, or salt	1-5	☑	☑	☑
2.	Food poisoning (e.g., by uncareful storage and preparation of food)	1-5	☑	☑	☑
3.	Pesticide residues (for example, on vegetables and fruit)	1-5	☑	☑	☑
4.	Environmental contamination in food (such as dioxins, PCBs, and heavy metals)	1-5	☑	☑	☑
5.	Chemicals that can be formed during food preparation (e.g., PAHs and acrylamide in burnt meat or overly browned fries)	1-5	☑	☑	☑
6.	Genetically Modified food (e.g., genetic engineering).	1-5	☑	☑	☑
7.	Additives (E-numbers) like colorants, flavourings, preservatives etc.	1-5	☑	☑	☑
8.	Chemicals from food packaging (such as plasticizers or bisphenol A (BPA))	1-5		☑	☑
9.	Hormones or antibiotics in meat	1-5		☑	☑
10.	PFAS in food	1-5			☑
11.	Microplastics in food	1-5			☑
12.	Nanotechnology	1-5	☑	☑	

* 1. no risk to my health; 2. nearly no risk to my health; 3. neutral; 4. a large risk to my health; 5. a very large risk to my health.

The model suggests that human social behaviour is influenced by individuals' attitudes and beliefs. Accordingly, perceived severity, perceived susceptibility, and perceived barriers were analysed as key determinants of intention to change behaviour after reading the hygiene warning label. In 2021, the study was repeated with 1,021 adults, using the exact same questions as in 2015. This repetition aimed to establish a baseline for the 'old' hygiene warning label, excluding any potential effects of time on consumer food-handling practices because of the time gap since 2015. Following the introduction and full implementation of the 'revised' hygiene warning label in 2023, the survey was conducted again in 2024 with the same set of questions and a representative panel of 1,044 adults. To assess the impact of the 'revised' hygiene warning label, results from the 2021 survey (reflecting the 'old' label) and the 2024 survey (reflecting the 'revised' label) were analysed and compared. Details about the set-up of the panels can be found in **Appendix A**. The online questionnaire consisted of six sections: (1) knowledge of safe food-handling practices for chicken and foodborne infections, (2) self-reported safe food-handling practices for chicken, (3) perceived severity of foodborne infections, (4) the likelihood of contracting a foodborne infection, (5) barriers to safe food-handling practices, (6) interpretation of the hygiene warning label and intention to

change food-handling practices for chicken after reading the hygiene warning label, and (7) demographic characteristics (see **Appendix E**). The exact wording of all questionnaire items is provided in **Appendix G**. Knowledge (section 1) was assessed using true-or-false statements. Answers were scored as 1 if correct (based on expert consensus) and 0 if incorrect, and averaged per participant. Participants with a mean score above 0.67 were classified as having adequate knowledge, while those with a score of 0.67 or lower were considered to have inadequate knowledge. The cut-off value of 0.67 (i.e., at least two-thirds of the knowledge questions answered correctly) was chosen to distinguish respondents with broadly adequate versus less adequate food safety knowledge, consistent with previous food safety survey research and expert consensus (Antonise-Kamp et al., 2018). These questions aimed to identify common misconceptions, with incorrect answers indicating areas where misunderstandings persist. Questions regarding food-handling practices (section 2), perceived severity (section 3), likelihood of foodborne infections (section 4), barriers to safe food-handling practices (section 5), and interpretation of the hygiene warning label and intention to change safe food-handling practices (section 6) were rated on a five-point scale. Behavioural responses were categorized as either safe food handling (mean score 4.0 or higher) or unsafe food handling (mean score < 4.0). Like in Antonise-Kamp et al. (2018) a threshold of 4.0 was chosen as it corresponds to the upper end of the five-point scale (e.g. 'often' or 'always'), thereby indicating consistent engagement in safe food-handling behaviour rather than neutral or occasional practices. To ensure variation in question framing, certain behaviour-related questions were formulated such that a score of 4 or 5 represented unsafe food handling. Questions that were phrased such that higher scores indicated unsafe food handling were reverse-coded prior to analysis to ensure that across all items, a score of 4 or higher consistently reflected safe food-handling behaviour. A complete overview of all behaviour items and their coding is provided in **Appendix E**. Perceived severity of foodborne infections and perceived likelihood of contracting a foodborne infection were each classified as high (mean score 4.0 or higher) or low (mean score < 4.0). Barriers to safe food-handling practices were considered present (mean score 4.0 or higher) or absent (mean score < 4.0). Finally, reading and interpretation of the hygiene warning label, as well as the intention to change food-handling practices after reading the hygiene label, were measured on a five-point scale. Intention to change food-handling practices after reading the hygiene label was summarized as intention to change (mean score above neutral, i.e., > 3.0) or no intention to change (mean score neutral or lower, i.e., 3.0 or lower). This dichotomization distinguishes respondents expressing a positive intention to change behaviour from those reporting neutral or negative intentions, in line with common practice in behavioural survey research.

Results from the questionnaires of 2015, 2021 and 2024 were analysed and compared. Descriptive statistics were used to describe socio-demographic characteristics, knowledge, safe food-handling practices, perceived severity of

food-borne infections, likelihood of contracting a foodborne infection, barriers to carry out safe food-handling practices and interpretation of the hygiene warning label and intention to change practices after reading it. Differences in evaluation of the label between respondents who had and who had not read the label before the study was tested using a Chi-square test. Chi-square analyses were also used to test factors associated with (i) knowledge of safe food-handling practice, (ii) safe food-handling practices, (iii) having read the label before the study, and (iv) intention to change behaviour after reading the label. Factors tested were age, gender, educational level, household composition, perceived health status (own and of other members of the household), having had foodborne infections in the past, food-handling practices, knowledge of food-safety practices, perceived severity of a foodborne infection, likelihood of contracting a foodborne infection, having read the label, and intention to change behaviour. Assumptions for the chi-square tests were checked by inspecting expected cell counts. When expected frequencies were below 5 in more than 20 % of cells, Fisher's exact test was used instead. Continuity correction was not applied, as sample sizes were sufficiently large. When the chi-square analysis revealed a significant association ($p < 0.05$), the odds ratio [OR] and Cramér's V were calculated to quantify the strength of the associations and measure the effect size. Statistical analyses were performed using JASP 0.19.1.

5.2.3 Procedure and data-collection

For all the aforementioned surveys, a sample of consumers in the Netherlands was primarily recruited through the panel agency Flycatcher (www.flycatcher.eu). Only in the 2009 study, the panel agency CentERdata was used. Sample sizes per survey year were based on standard practice for population-based consumer surveys and panel availability, with the aim of obtaining a demographically representative survey sample enabling subgroup analyses. Demographic representativity of the sample was checked using the 'Golden Standard', a calibration instrument that has been developed by the Expertise Centre of Marketing Insight, Research and Analytics (MOA) in collaboration with Statistics Netherlands (CBS) (MOA, 2021), which confirmed that the ratio of male/female, the age distribution, the education level, and geographical distribution of the used panel members were comparable to the information as provided by Statistics Netherlands (CBS). Panel members registered voluntarily and provided informed consent and could terminate at any time. Participants were invited by email by the panel agency and completed the anonymous, non-invasive online questionnaire voluntarily after receiving study information. As recruitment was conducted via online consumer panels, individuals with limited internet access or digital literacy may be underrepresented; however, this is unlikely to substantially affect the observed associations. Response rates were calculated as the number of completed questionnaires divided by the number of invited panel members. No post-stratification weighting was applied, as the achieved samples already closely

reflected national demographic distributions. Any remaining non-response bias is therefore expected to be limited.

Selected experts were professor or expert (generally at Ph.D. level) in the field of nutrition, toxicology, food science, food microbiology or food technology with a working experience of at least 5 years at Dutch universities or national food institutes. The majority of the above-mentioned group of experts that met the selection criteria were personally invited by email to participate in the survey. Response rates were calculated as the number of completed questionnaires divided by the number of invited experts. The expert sample comprised individuals from multiple sub-disciplines within food and health sciences; however, this recruitment approach may have resulted in some selection bias towards experts with a stronger focus on food safety-related topics, and due to the limited size of the expert group, no sub-analyses by discipline were performed.

5.3 Results

5.3.1 Procedure and data-collection

A total of 1014 (=n) consumers (response rate: 56 %) and 69 experts (response rate: 51 %) completed the survey in 2024. The ratio of male/female, the age distribution, the education level and the geographical information of the panels in 2009, 2018 and 2024 are reported in **Appendix C**.

The 2024 questionnaire began with an open-ended question. When consumers were asked to identify the greatest food-related health risk, the most frequently mentioned risks included sugar (17 %), fat (15 %), food poisoning (14 %), pesticides (10 %), and highly processed foods (5 %). Other significant food risks mentioned included additives, plastics, allergens, and alcohol. Some consumers indicated that there were no food risks at all. Experts mentioned unhealthy diet and overconsumption (55 %) most frequently, followed by food poisoning (25 %) and environmental contaminants and mycotoxins (17 %).

5.3.1.1 Consumer and expert risk perception across years

Following the open-ended questions, respondents also answered detailed closed questions. An overview of the mean scoring in risk perception of the food-related health risks by consumers and experts in 2009, 2018 and 2024 is given in **Figure 5.2**. Both consumers and experts showed an increasing trend in their perception of the risk of an unhealthy diet, but on average, consumers perceived this risk significantly lower than experts in 2009, 2018, and 2024 (**Figure 5.2A**, **5.2B**, **5.2C**). For food poisoning, no significant differences in scoring were observed between experts and consumers in any of the years. Also, the perceived risk of chemicals formed during food preparation did not differ significantly between the two groups in 2009 and 2018. For all other risks, consumers consistently rated them

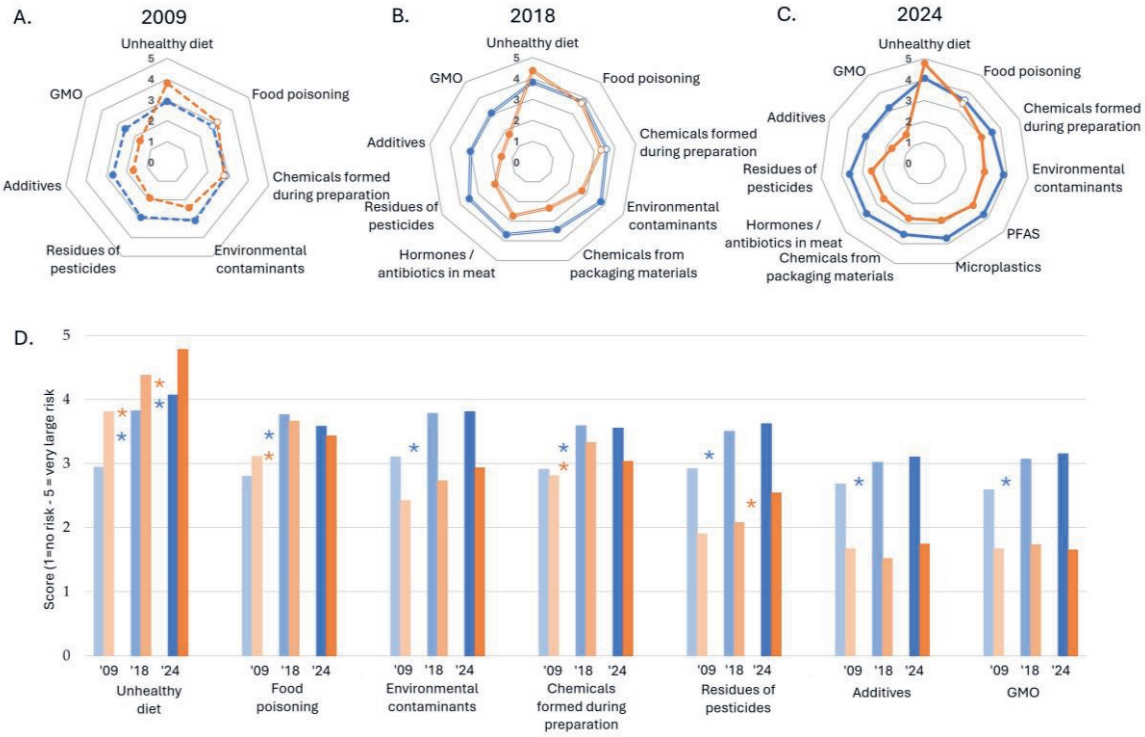


Figure 5.2. Risk perception in 2009 (panel A, dashed lines), 2018 (panel B, double striped lines), and 2024 (panel C, filled lines), and the development over time from 2009 to 2024 for each food risk that were included in all three years (D). Risk perception is expressed as mean score of the consumers (blue) and experts (orange). Significant differences ($p < 0.005$) in mean score between experts and consumers are highlighted with a filled symbol in A, B, C. Significant differences ($p < 0.005$) in mean scores between two consecutive time points (2009–2018 or 2018–2024) for consumers and experts are marked with an asterisk (*) in D.

significantly higher than experts. Especially additives and GMO were seen by experts as low (i.e., mean score smaller than two), while consumers perceived these risks as neutral to large (i.e. mean score greater than three). Details can be found in **Appendix D**.

The data reveals a significant increase in the perceived risk of an unhealthy diet between 2009 and 2024 for both consumers and experts (**Figure 5.2D**). In 2009, the average consumer risk score was 2.94, with only 37 % of consumers considering an unhealthy diet a (very) large risk to their health (score 4 or higher). This percentage increased to 66 % in 2018 and further to 76 % in 2024. Experts also reported growing concern, with 73 % rating an unhealthy diet as a (very) large risk in 2009 to 92 % in 2024. Perceptions of chemical risks, such as environmental contaminants, chemicals formed during preparation, and pesticide residues, also increased significantly among consumers between 2009 and 2018, but remained stable through 2024. Additionally, 63 % of respondents in 2024 rated newly defined

risks, such as PFAS and microplastics, as a (very) large risk to their health. Conversely, concern among both consumers and experts about microbiological risks from food poisoning increased significantly between 2009 and 2018, but slightly declined in 2024, though this decrease was not statistically significant. Since 2009, genetically modified foods and additives have consistently been perceived by consumers as the lowest food safety risks, with an even greater gap in perceived risk observed among experts.

5.3.1.2 Familiarity with food risks and association with risk perception

Besides risk perception also familiarity with the identified food risks was included in the survey. **Figure 5.3** shows the mean scoring in risk perception and risk familiarity of the food-related risks by consumers and experts in 2024. Consumers scored themselves most familiar with the risk of an unhealthy diet, food poisoning, residues of pesticides, and additives. In contrast, chemicals from packaging materials and genetically modified foods were the least recognized. A weak but significant positive correlation was observed for consumers between familiarity with the risk and perception of the risk, based on Spearman's correlation analysis and confirmed by chi-square statistics. The more familiar consumers were with the risk, the higher they perceived the risk (for all risks: $r_s = 0.333$, $p < 0.005$). This is consistent with the findings from 2009 and 2018. Notably, experts reported levels of familiarity with the risks that were, on average, quite similar to those of consumers. However, due to their specialized expertise, variation in familiarity among experts was more pronounced, as each tended to be highly knowledgeable in a specific domain. Further details can be found in **Appendix D**.

5.3.1.3 Behavioural responses and demographic patterns

More than half of the consumers (56 %) express concern about pesticide residues on fruits and vegetables. Regardless of their level of concern, approximately 74 % have not changed their eating habits. Meanwhile, 16 % reported washing their produce more thoroughly, and 10 % primarily consume organic fruits and vegetables. A smaller group modified their consumption patterns: 4 % stopped eating certain types of fruits and vegetables, while 1 % reduced their intake, mainly of soft fruits like strawberries, raspberries, and blueberries.

Women and individuals with higher education levels were found more likely to adjust their eating habits. Demographic analysis revealed a positive correlation between age and risk perception in 2024. Older consumers tended to perceive food-related risks as higher ($r_s = 0.181$, $p < 0.005$), with the average risk perception score across all food risks increasing from 3.3 among younger adults (aged 18-29 years) to 3.7 among older adults (65 years and older). This trend in age was consistent with the findings from 2009 and 2018. No significant difference was found between men and women in 2024, which contrasts with the findings from 2009 and 2018, where women significantly perceived risks to be higher than men.

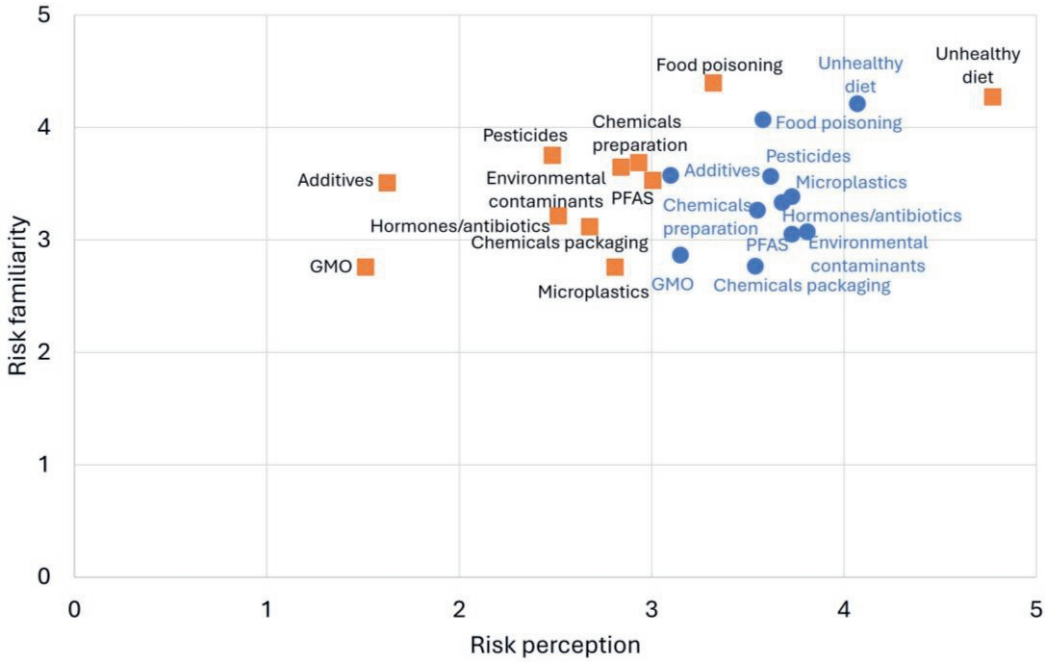


Figure 5.3. Mean score of consumers (blue) and experts (orange) risk perception and risk familiarity in 2024.

In 2024, education level was negatively correlated with risk perception. The higher the education level, the lower the perceived risk (i.e., low: 3.8; middle: 3.6; high: 3.4). This significant difference contrasts with the findings from 2009 and 2018, where no difference between education levels was observed. The differences in age, gender, and education level were less prominent in the perception of the risk of an unhealthy diet, but nevertheless, did increase over time across all demographic groups.

The ranking of food-related risks revealed that both consumers and experts identified an unhealthy diet as the top health risk. Consumers ranked environmental contaminants and microplastics second, while experts placed food poisoning in second position. In third place, consumers ranked food poisoning and pesticide residues, whereas experts identified environmental contaminants, chemicals formed during preparation, and PFAS (**Appendix D4**).

5.3.2 Evaluation of the impact of a hygiene warning label on the packaging of raw poultry

Surveys conducted in 2015, 2021, and 2024 included 514 (response rate: 52 %), 1021 (response rate: 65 %), and 1044 (response rate: 55 %) consumers, respectively. The ratio of male/female, the age distribution, the education level and

the geographical information of the panels in 2015, 2021 and 2024 are mentioned in **Appendix A** and confirmed to be representative of the general population.

5.3.2.1 Knowledge of safe food-handling practices for chicken and foodborne infections

Knowledge levels remained rather stable over time (no significant difference), with the percentage of correctly answered questions being 89 % in 2015, 92 % in 2021, and 88 % in 2024 (**Figure 5.4A**). Incorrect responses highlight areas of misunderstanding or lack of knowledge, and certain questions revealed persistent misconceptions. For example, nearly half of the respondents believed that chicken is safe to eat if it smells good, and many were unaware that most foodborne infections occur at home. To evaluate the association between knowledge and other factors, the scores from the 12 questions were categorized per individual into "adequate knowledge" (mean score above 0.67) and "inadequate knowledge" (mean score 0.67 or lower). Higher knowledge was significantly associated with better kitchen hygiene practices across all survey years (e.g., in 2024, OR 3.69 [2.49-5.29]). Interestingly, knowledge levels did not consistently influence perceptions of the severity or likelihood of foodborne infections. People with adequate knowledge also reported fewer barriers to following safe food-handling practices. For example, in 2024, 91 % of those who did not view food safety as "too time-consuming" had adequate knowledge, compared to 74 % of those who did. People with a medium or high level of education reported higher knowledge levels compared to those with a lower education level. Gender, age, living situation (alone or with others), meal preparation frequency, and health status were not significantly associated with knowledge levels. See **Appendix E** and **F** for additional details.

5.3.2.2 Safe food-handling practices for chicken

Safe food-handling practices for chicken increased significantly over time, with 70 % of respondents in 2015 and 76 % in both 2021 and 2024 scoring 4 or higher on safe food-handling practices (**Figure 5.4B**). However, compliance with using a cooler bag ('freezer bag') to transport raw chicken from the store to home and thawing frozen raw chicken inside the refrigerator remained low (20 % and 50 % in 2024, respectively). A very high level of compliance was observed for good cooking practices, with 98 % of respondents consistently ensuring that chicken is fully cooked before consumption in 2024. Respondents with better hygiene practices experienced less practical barriers like "too much fuss", "reluctance to discard chicken after expiration date" and "lack of kitchen utensils". Women consistently scored higher on safe food-handling practices than men (in 2024, 81 % vs. 69 % compliance). Age, education level, living alone or not, meal preparation frequency, and health status were not significantly correlated with kitchen hygiene practices in 2024. See **Appendix E** and **F** for further details.

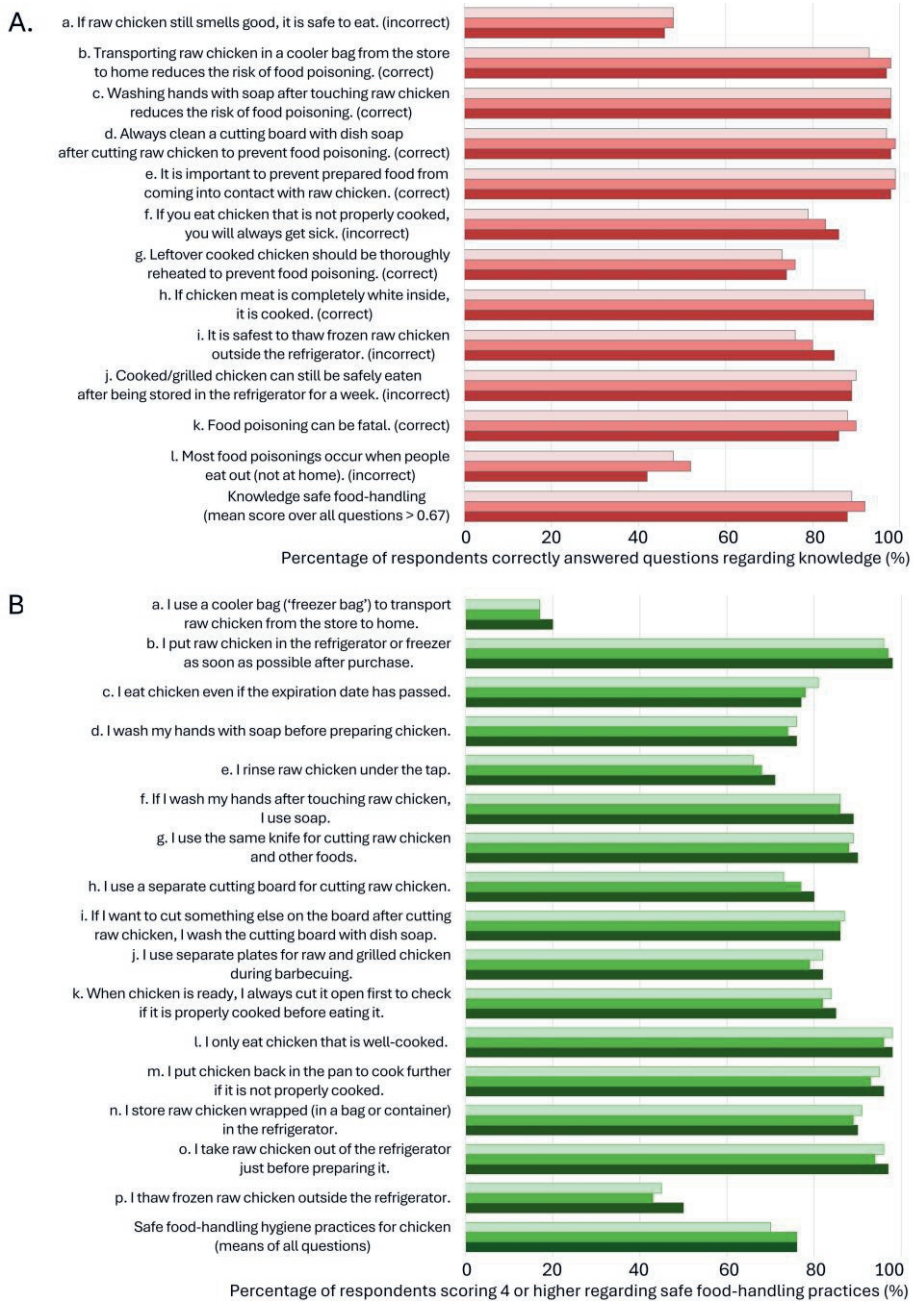


Figure 5.4. Percentage of respondents who correctly answered questions regarding knowledge of safe food-handling practices for chicken [A = knowledge] and percentage of respondents with a high score (4 = often, 5 = always) on reported safe food-handling practices for chicken [B = practices], based on the 2015 (light-coloured bars), 2021 (medium-coloured bars), and 2024 (dark-coloured bars) surveys. For knowledge-related statements, answer in brackets indicate whether the statement itself is true or false.

5.3.2.3 Perceived severity of a foodborne infection and likelihood of contracting one

In 2024, a large majority of respondents (83 %) consider foodborne infections to be serious or very serious, both for themselves and those around them. Over 90 % of consumers believe they are unlikely to contract a foodborne infection from eating chicken. Only a small percentage (6 %) acknowledge the possibility of making mistakes when buying, preparing, or storing chicken. However, if they do make such mistakes, they perceive a higher risk of infection, with 13 %, 18 %, and 21 % expressing this concern for purchasing, preparing, and storing, respectively (**Appendix E**).

5.3.2.4 Barriers to carry out safe food-handling practices

The most important barrier in following safe food-handling practices were “too much fuss”, followed by “too time-consuming” and “a lack of kitchen utensils”. E.g., in 2024, adherence to safe food-handling practices was 23 % among those who cited ”too much fuss” and 43 % among those who cited ”lack of kitchen utensils”, compared to 81 % among those who did not cite these barriers. It is worth noting that the barriers ”too much fuss” and ”too time-consuming” were correlated, with a Pearson correlation coefficient of r = 0.438. An increasing number of respondents in 2021 and 2024 expressed reluctance to discard chicken after its expiration date, with figures rising from 15 % in 2015 to 22 % in 2021 and 27 % in 2024. However, the percentage of respondents who always or often eat chicken after the expiration date remained stable throughout the years (8 % in 2015, 7 % in 2021, and 9 % in 2024).

5.3.2.5 The role of hygiene warning label

To assess the impact of the revised hygiene warning label, survey data from 2021 and 2024 were compared (**Figure 5.5**), as the transition from the 'old' to the 'revised' label occurred in 2023. Around 80 % of respondents reported having read the label, with older individuals (65 years and older) doing so more frequently than younger respondents (89 % vs. 78 %). In 2024, a significant increase was observed in the proportion of respondents who considered the label important, rising from 78 % before seeing it, to 89 % afterward. When comparing evaluations of the label between 2021 and 2024, several aspects showed notable changes. A majority of respondents (87 %) viewed the revised label as an improvement. Clarity ratings increased significantly from 86 % for the old label in 2021 to 91 % for the revised version in 2024. Perceived usefulness also rose slightly, from 88 % to 91 %. Furthermore, more respondents reported noticing new information on the revised label, increasing from 15 % in 2021 to 20 % in 2024. The most commonly identified new element was refrigerator temperature. Individuals who read the hygiene warning label prior to the study (“readers”) reported better kitchen hygiene practices than those who did not (“non-readers”). In 2024, 78 % of readers scored

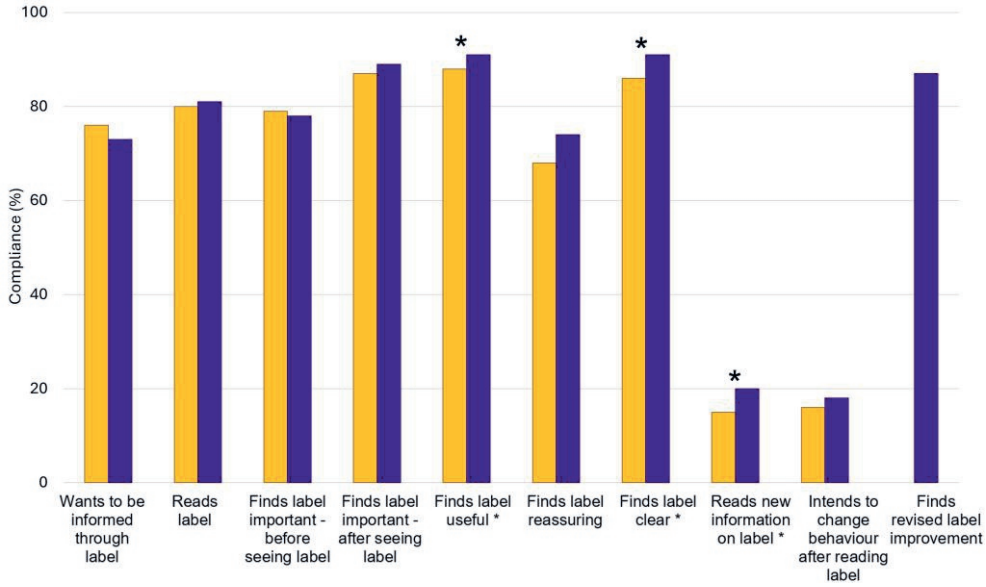


Figure 5.5. Consumers' reading, evaluation and intention to change their food-handling practices after reading the label in 2021 and 2024. Significant differences ($p < 0.05$) in mean score between 2021 (yellow bars) and 2024 (blue bars) are highlighted with an asterisk.

4 or higher on safe food-handling practices, compared to 66 % of non-readers. Overall, the proportion of respondents reporting an intention to change their behaviour after seeing the label remained relatively stable over time: 15 % in 2021 and 16 % in 2024. Chi-square analyses identified statistically significant differences in intention to change behaviour across several subgroups (see **Table 5.2**). The standardized effect sizes associated with these differences were small-to-moderate, as indicated by Cramér's V-values (**Table 5.2**). In 2024, respondents with inadequate food safety knowledge or unsafe baseline hygiene practices were more likely to report an intention to change behaviour than those with adequate knowledge or safe practices (26 % vs. 17 % and 30 % vs. 15 %, respectively). Higher percentages reporting an intention to change were also observed among respondents who perceived foodborne infections as more severe, felt personally more likely to contract a food-borne infection, had read the label before the study, or experienced practical barriers to safe food handling. Sociodemographic differences were also observed. Male participants reported a higher intention to change behaviour than female participants (22 % vs. 15 %). Similarly, older adults (65 years and older) were more likely to report an intention to change than respondents under 65 years of age (28 % vs. 15 %). Respondents with a lower educational level also showed a higher intention to change compared to those with a medium or high level of education (26 % vs. 17 %). It is worth noting that age and education were strongly inversely correlated: a larger proportion of older adults had a low education level compared to younger adults (48 % vs. 16 %).

Table 5.2. Factors significantly associated with the intention to change behaviour after reading the label in 2024, identified using chi-square analysis (odds ratio (95 % CI) with the *p*-value, Cramér's V-value)

	Intention to change behaviour (%) [#]	OR (95% CI) *p-value,* Cramér's V
Knowledge safe food-handling		
Inadequate (reference)	26	*0.58 (0.37-0.91)*
Adequate	17	*p = 0.016,* Cramér's V = *0.08*
Safe food-handling practices		
Unsafe (reference)	30	0.40 (0.29-0.56)
Safe	15	*p < 0.001,* Cramér's V = *0.17*
Severity of foodborne infections		
Non-severe (reference)	11	1.93 (1.08-3.45)
Severe	19	*p = 0.024,* Cramér's V = *0.07*
Likelihood of contracting foodborne infections		
Not likely (reference)	17	2.24 (1.42-3.53)
Likely	31	*p < 0.001,* Cramér's V = *0.11*
Read the label before the study		
No (reference)	12	1.76 (1.11-2.78)
Yes	20	*p = 0.015,* Cramér's V = *0.08*
Barriers: too much fuss		
No (reference)	16	2.37 (1.23-4.57)
Yes	32	*p = 0.008,* Cramér's V = *0.09*
Barriers: too time-consuming		
No (reference)	17	2.12 (1.17-3.84)
Yes	30	*p = 0.012,* Cramér's V = *0.08*
Barriers: lack of kitchen utensils		
No (reference)	16	2.46 (1.44-4.21)
Yes	32	*p < 0.001,* Cramér's V = *0.11*
Barriers: inadequate facilities for washing the dishes		
No (reference)	17	6.31 (2.72-14.62)
Yes	57	*p < 0.001,* Cramér's V = *0.15*
Gender		
Female (reference)	15	1.54 (1.12-2.11)
Male	22	*p = 0.007,* Cramér's V = *0.08*
Age		
Below 65 years (reference)	15	2.26 (1.62-3.15)
65 years and older	28	*p < 0.001,* Cramér's V = *0.15*
Education		
Low (reference)	26	0.52 (0.37-0.73)
Middle/High	17	*p < 0.001,* Cramér's V = *0.12*

[#] Participants with a mean score above 3 (neutral) were considered to have an intention to change behaviour. Those without an intention to change were calculated as: 100 % – percentage with intention to change behaviour.

To disentangle the effects of age and education, additional analyses were conducted using subgroups: (i) individuals under 65 years with low education, (ii) individuals 65 years and older with low education, (iii) individuals under 65 years with medium/high education, and (iv) individuals 65 years and older with

medium/high education. Respondents younger than 65 years and those with a low education level were more likely to report an intention to change behaviour than those with a medium or high education level (23 % vs. 13 %), whereas no significant educational differences were observed among respondents aged 65 years and older. Overall, age was more consistently associated with intention to change behaviour than education, as older respondents reported a higher intention to change behaviour regardless of education level. Notably, older respondents perceived foodborne infections as more severe (OR = 3.32) while considering themselves less likely to contract such infections (OR = 0.38), yet they still showed a higher intention to change behaviour. For full details on the chi-square analyses conducted in 2021 and 2024, see **Appendix F**.

5.4 Discussion

Drawing on repeated cross-sectional data collected over a 15-year period, developments in food-related risk perception and related behaviours in the Netherlands were examined. Using large, demographically representative samples and incorporating both consumer and expert perspectives, it integrates data on perceptions and self-reported behaviours, providing a broad empirical basis for interpreting temporal trends.

5.4.1 Shift in perception of unhealthy diet over time

Consumers' and experts' perceptions of food-related risks were assessed in 2009, 2018, and 2024 in the Netherlands to examine changes in awareness and risk perception over time. Both groups increasingly identified an unhealthy diet as the most significant food-related risk. This trend was also reflected in open-ended responses, where concerns about excessive sugar and fat intake were the most frequently mentioned. The growing awareness of risks associated with an unhealthy diet may reflect an improvement in consumer knowledge on this topic. However, despite the increased risk perception, the prevalence of obesity and diet-related diseases continues to rise. The Public Health Foresight Study by the Dutch National Institute for Public Health and Environment (RIVM) predicts that the percentage of overweight individuals in the Netherlands will increase from 50 % in 2022 to 64 % by 2050 (Den Broeder et al., 2024). This trend is driven by multiple factors, including the widespread availability of unhealthy foods, aggressive marketing strategies, sedentary lifestyles, socio-economic disparities, and a lack of practical knowledge about healthy eating. Tackling these challenges requires a coordinated effort to create a healthier food environment and promote informed healthy dietary choices (WHO, 2023).

5.4.2 Consumer-expert differences in perception of chemical risks

Consumers perceived chemical food-related risks consistently as more severe than experts. This outcome is consistent with previous research that showed that

involuntary exposure to (chemical) risks seems more threatening to consumers, and concerns arise about long-term effects (Hartmann et al., 2018; Kehr et al., 2013; Van der Vossen-Wijmenga et al., 2022). An example of such chemical risk is residues of pesticides. In 2024, 56 % of consumers perceived this as a (very) high risk, compared to 16 % of experts. Research indicates that subjective knowledge (i.e., an individual's perception of their own understanding of a topic) plays a significant role in shaping risk perceptions of pesticides. These perceptions are often centered on long-term health and environmental impacts, while the benefits of pesticide use, particularly for improving crop yields and ensuring food security, are less well recognized (FSA, 2022a; Nardi et al., 2020). Furthermore, consumers' perceptions of pesticide risks can influence their food purchasing choices, alongside their levels of knowledge and trust (IFIC, 2024; Meira et al., 2025; Simoglou and Roditakis, 2022). Risk perception negatively predicted the purchase intention for conventional vegetables, while trust in the product had a positive effect. Notably, a high level of trust in conventional farming practices can diminish the perceived risks (Meira et al., 2024). Our study showed that the majority of consumers who had concerns about pesticides on fruits and vegetables did not change their behaviour. Some washed their fruits and vegetables more thoroughly (16 %), some primarily ate organic (10 %), and a small portion avoided certain fruits and vegetables like strawberries and raspberries (4 %). Only a very small percentage of consumers (1 %) changed their purchasing behaviour and ate less fruit and vegetables. The consumer monitor of the Dutch Food Safety Authority (NVWA) (2008-2023) showed that consumers have the highest level of trust in fruits and vegetables from all food groups (NVWA, 2023a). While concerns about pesticide residues are prevalent, they did not significantly alter the purchasing behaviour of most consumers, who continue to trust and consume fruits and vegetables. This is reassuring, considering that fruits and vegetables provide significant health benefits, and most Dutch consumers do not meet the recommended daily intake. It is worth noting that self-reporting can introduce bias, as individuals may provide socially acceptable responses that do not accurately reflect their actual practices (Mazengia et al., 2015; Redmond and Griffith, 2003). Two newly identified chemical risks, PFAS and microplastics, raised significant concern among consumers. Approximately 63 % of consumers viewed these risks as (very) high, alongside other environmental contaminants. While experts assessed these risks as lower, about 25 % still perceive PFAS and environmental contaminants as (very) high risks, and 18 % feel the same about microplastics. Limited studies have explored public risk perception regarding PFAS and microplastics in food. A study by Tian et al. (2022) reveals growing public concern about PFAS as a major health risk, reflected in a sharp rise in social media discussions and an increasing demand for understanding its potential impacts. Another study by Fian et al. (2024) highlights high public concern about microplastics, particularly after evidence of microplastics in food and beverages. The lack of scientific consensus on their health effects, including significant knowledge gaps regarding sources, pathways, and toxicity, fuels widespread

expressions of powerlessness, and perceived inevitability concerning PFAS and microplastics.

5.4.3 Foodborne infections: risk perception, knowledge and behaviour

Foodborne infections were ranked as a high risk by both experts and consumers, though experts ranked this risk higher than consumers (**Appendix D**). Foodborne infections cause millions of illnesses and contribute to thousands of deaths each year worldwide (WHO, 2015). A variety of pathogenic bacteria, such as *Campylobacter*, *Salmonella* and pathogenic *Escherichia coli*, are found in food. It is estimated that in the Netherlands, around 200,000 incident cases are attributed to meat, and 52,000 cases to poultry each year (Benincà et al., 2024). Food preparers can reduce the risk of foodborne disease by properly handling and thoroughly cooking meat and poultry. This study reveals that knowledge of safe food-handling practices for chicken remains consistently high over the years and that self-reported adherence to these practices increased from 70 % in 2015 to 76 % in 2024. Van der Vossen-Wijmenga et al. (2024) found that, even with high reported compliance (95 % of consumers indicated they always or often fully cook chicken), thoroughly cooking chicken remained the most effective home-based intervention. Self-reported data are known to overestimate actual behaviour, as respondents may provide socially desirable answers (Mazengia et al., 2015; Redmond and Griffith, 2003). As all measures of food-handling practices, label reading, and behavioural intentions in this study were self-reported, the reported compliance rates and intentions are likely to overestimate actual behaviour. Consequently, associations between label exposure and reported behaviour should be interpreted as reflecting self-perceived behaviour and intentions rather than direct evidence of actual behaviour change. Nevertheless, questionnaires provide valuable insight into knowledge, risk perceptions, and behavioural intentions, particularly in large-scale population studies such as the present one. Comparing data from this study with other literature is challenging due to differences in questions, study design, and panel characteristics. For instance, a study by Conway et al. (2023) evaluating Irish consumers' knowledge of salmonellosis and safe food-handling practices showed a comparable overall knowledge level of 79.8 %. In contrast, a study by Myintzaw et al. (2020) on campylobacteriosis, consumers' risk perception, and knowledge associated with domestic poultry handling in Ireland found that 40.2 % of participants were average to very knowledgeable. In our study, participants were classified as knowledgeable if they answered over 67 % of the questions correctly. Raising this threshold to 80 %, reduced the proportion of knowledgeable respondents from 88 % to 67 % in 2024. Such methodological differences highlight the importance of standardized questionnaires to enable cross-country comparisons of food safety knowledge and practices. Despite these variations, a common conclusion emerges across studies: there is a clear need to strengthen consumer education.

5.4.4 Hygiene warning label as a risk communication tool

Hygiene warning labels serve as a practical communication tool, providing a relatively simple way to inform and educate consumers about safe food-handling practices. In the Netherlands, a hygiene warning label is mandatory on retail packages of raw poultry since 2001, aiming to reduce foodborne illness risks by providing clear handling instructions (Warenwet, 2023). Ideally, this introduction would help reduce the number of illness cases, but data of illness cases from the period around the label's introduction in 2001 was not available. Data on poultry-related illness cases in the Netherlands has been available since 2009, showing a decline from an estimated 59,000 cases in 2009 to 52,000 in 2022 (Benincà et al., 2024; Havelaar et al., 2012). However, it remains unclear to what extent the label has contributed to this reduction, as other factors, such as stricter industry regulations, have also been implemented with the goal of lowering illness rates. In 2015, Antonise-Kamp et al. (2018) evaluated the hygiene warning label and found that it was highly appreciated by consumers. However, the study identified opportunities for improving the visibility of the label, leading to adjustments that were implemented in 2023. Our study found that the majority of respondents viewed the revised hygiene warning label as an improvement, evaluating it as important, useful, and reassuring. In 2024, 81 % of respondents reported reading the revised label on poultry meat, a figure very similar to the 80 % observed in the 2021 survey, which reflected the 'old' version of the label. In the United States, a hygiene warning label has been mandatory on retail packages of raw or partially cooked meat and poultry products since 1994. Awareness of these labels was investigated in the first few years after their introduction (Yang et al., 2000). About half of the respondents (51 %) in the U.S. had seen the hygiene warning label, and 79 % of those had actually read the information. This is a much lower percentage compared to the findings of our study, where a higher proportion of respondents reported reading the label.

5.4.5 Target groups, barriers and intention-behaviour gap

To identify which groups respond best to hygiene warning labels, our study examined differences in reported behaviour, intentions, and barriers across population subgroups. Individuals who read the hygiene warning label prior to the study ("readers") reported better kitchen hygiene practices than those who did not ("non-readers"). In 2024, 78 % of readers scored 4 or higher on safe food-handling practices, compared to 66 % of non-readers, reflecting higher reported compliance with key practices such as separation, cooling, and thawing behaviours. The label was particularly associated with higher reported intentions to change behaviour among individuals with poorer baseline hygiene practices. Although the observed effect sizes were small, they are comparable to those reported in previous studies on warning label interventions, where behavioural effects are typically modest but robust across large populations (Purmehdi et al., 2017). Within a Health Belief Model framework, the hygiene warning label may

function as a cue to action, especially for individuals who perceive foodborne infections as serious or personally relevant, or who experience practical barriers to safe food handling. Notably, older adults reported a higher intention to change behaviour despite perceiving themselves as less susceptible to infection, suggesting that other factors than perceived susceptibility may play a more prominent role in this group. However, intention does not necessarily translate into actual behaviour change, particularly when practical barriers or established habits persist (Fulham and Mullan, 2011; Mullan and Wong, 2009). In line with this, barriers such as "too much fuss", "too time-consuming", and "lack of kitchen utensils" were negatively associated with safe food-handling practices in our study. The higher intention to change behaviour observed among older adults and lower-educated individuals under 65 years of age is encouraging, as these groups are more likely to have underlying health conditions, such as type 2 diabetes mellitus, which increase susceptibility to foodborne infections (Lund and O'Brien, 2011; Shah and Hux, 2003; Van Kreijl et al., 2006). Overall, these findings highlight the relevance of the hygiene warning label for specific target groups, while also illustrating the challenges of translating food safety knowledge into consistent behaviour.

5.4.6 Implications for warning label design, placement and communication

From an implementation and policy perspective, the design and placement of warning labels are key factors influencing their effectiveness. A significant amount of research has been conducted on warning labels for tobacco, alcohol, and food products (e.g., sugar-sweetened beverages) (Ding et al., 2024; Purmehdi et al., 2017; Zuckermann et al., 2024). For instance, a meta-analytic study by Purmehdi et al. (2017), which analysed 243 effect sizes from 66 primary studies (mainly on tobacco and alcohol), found that labels promoting safe use elicit more favourable behavioural changes (r = 0.39) than labels aimed at moderation or cessation. Highlighting the importance of the label's content and placement, the analysis further revealed that labels are more effective when preactivated through an integrated communication strategy, with the effect size increasing to r = 0.49 (Purmehdi et al., 2017). Applying these findings to the current revised hygiene warning label, relocating it from the back to the front of the packaging and incorporating it into a broader communication strategy could enhance its visibility, which may in turn, influence consumer behaviour. From a policy perspective, our results showed that hygiene warning labels can be particularly beneficial for higher-risk groups, including older adults and lower-educated younger individuals, emphasizing the need to reach these populations effectively. Communication strategies should therefore focus not only on the label's effectiveness, but also on increasing exposure among those most likely to benefit. This may be achieved by improving label visibility (e.g. prominent placement and clear visual design) and reinforcing the message through complementary channels, such as in-store communication or targeted public health campaigns.

5.4.7 Limitations and future research

Some limitations should be considered when interpreting these findings. The repeated cross-sectional design, using different respondent panels across survey waves, does not allow causal inference; observed changes over time cannot be attributed solely to the revised hygiene warning label and may reflect broader societal trends or concurrent food safety communication. In addition, reliance on self-reported behaviour and intentions may overestimate actual practices, as intention does not necessarily translate into verified behaviour. Although the samples were demographically representative, recruitment via online panels may have resulted in some underrepresentation of individuals with limited digital access. Finally, comparability across survey waves may be affected by changes in survey content and contextual factors. Moreover, analyses were conducted at an aggregate level; item-level associations between specific food safety knowledge components and specific food-handling practices were not examined and could be part of future research. Despite these limitations, the study provides valuable insight into long-term trends in food risk perception and the role of hygiene warning labels in a real-world regulatory context. Future research could strengthen causal inference by using longitudinal or experimental designs and by incorporating observational or objective measures of food-handling behaviour to better assess the real-world impact of hygiene warning labels. In addition, although risk perception and hygiene behaviour were examined in parallel, their relationship was not directly tested in this study. Future research could explicitly examine how different dimensions of risk perception relate to hygiene practices and label engagement within the same analytical framework.

5.5 Conclusions

This study highlights the growing public awareness of the risks associated with unhealthy diets, particularly excessive sugar and fat intake. While this increased awareness represents a positive development with potential benefits for public health, it also underscores the need for effective risk communication strategies that translate awareness into sustained behavioural change. While overall perceptions of the risk of food poisoning were similar, experts ranked it somewhat higher than consumers. In contrast, consumers rated chemical risks, such as environmental contaminants, PFAS, microplastics, and pesticide residues, higher than experts. The perceived lack of control and unavoidable exposure to chemical risks contrasts with the more practical actions consumers can take to reduce foodborne illness. In this context, safe food-handling practices represent a concrete and actionable area where risk communication can directly support risk reduction. This study showed that reported food-handling practices improved over time, with readers of the hygiene warning label reporting better kitchen hygiene practices than non-readers. The hygiene warning labels on poultry were widely read and well appreciated, with the revised version seen as a clear improvement.

The label appeared to be particularly relevant for individuals with poorer hygiene practices, older adults (65 years and older), and lower-educated individuals under the age of 65, and was associated with a stronger reported intention to adopt safer food-handling practices. By demonstrating both policy relevance and measurable behavioural effects, this study bridges the gap between research and practice in a real-world regulatory setting. It highlights the value of evidence-based, targeted communication tools in supporting positive and equitable improvements in food safety behaviour.

5.6 Acknowledgement

We thank Eric Boer for advising us on the statistical methods to be used.

5.7 Supplementary material

5.7.1 Appendix A. Demographic data and characteristics of respondents of survey 'Evaluation of hygiene warning label' - in 2015, 2021 and 2024

Table A1. Demographic data in percentages of 2015 panel (n = 514), 2021 panel (n = 1021) and 2024 panel (n = 1044)

	2015 Flycatcher panel (%)	2021 Flycatcher panel (%)	2024 Flycatcher panel (%)
Gender [a]			
Male	54	50	47
Female	46	50	53
Age [a]			
18-29	11	13	16
30-49	34	32	30
50-64	29	29	29
65 and older	26	26	25
Education level [a]			
Low	34	27	24
Middle	38	42	41
High	28	31	35
Geographical			
Groningen	3	4	3
Friesland	4	3	4
Drenthe	3	3	3
Overijssel	6	7	7
Flevoland	2	2	2
Gelderland	13	11	11
Utrecht	8	9	7
Noord-Holland	17	18	15
Zuid-Holland	20	20	19
Zeeland	2	3	3
Noord-Brabant	14	15	16
Limburg	9	6	10

[a] Age, gender, highest level of education and geographical information were assessed. Based on the Dutch educational system three educational levels were defined: high (university, college, higher vocational, general secondary, and intermediate vocational education), middle (general intermediate, and lower vocational education), and low (elementary education or less).

Table A2. Characteristics of respondents in percentages of 2015 panel (n = 514), 2021 panel (n = 1021) and 2024 panel (n = 1044)

		2015 (%)	2021 (%)	2024 (%)
Perceived health status	bad + moderate	5	8	8
Foodborne infections in the past	no	61	57	54
	yes	32	35	40
	unknown	7	8	6
Preparing of meals by respondent	several days per week	88	90	89
	weekly	7	7	7
	less than weekly	5	3	4
Preparing of chicken by respondent	once or more per week	56	60	62
	once or more per month	38	33	32
	once or more per year	6	7	6
Characteristics of respondents' households				
Composition of age in household *	0-5 yrs	10	9	8
	6-17 yrs	18	18	15
	18-64 yrs	62	64	65
	65 yrs and older	28	22	24
Pregnancy in household	yes	2	2	2
Food allergy in household	yes	14	15	16
Perceived health status family members	bad + moderate	4	3	4

* Totals for these four groups may exceed 100 % because households can belong to multiple groups.

5.7.2 Appendix B. Hygiene warning label in Dutch

A.

LET OP: geef schadelijke bacteriën geen kans. Zorg daarom dat deze bacteriën niet via verpakking, uw handen of keukengerei in uw eten terecht komen. Maak dit vlees door en door gaar om deze bacteriën uit te schakelen.

B.



Figure B1. Original Dutch text of the version of the hygiene warning label from 2001 until 2022 (A) and revised version from 2023 onwards (B).

5.7.3 Appendix C. Demographic data of survey 'Perception of food-related risks' - in 2009, 2018 and 2024

Table C1. Demographic data in percentages of 2009 panel (n = 2005), 2018 panel (n = 1014) and 2024 panel (n = 1014)

	2009 CentERdata panel, n (%)	2018 Flycatcher panel (%)	2024 Flycatcher panel (%)
Gender			
Male	53	49	51
Female	47	51	49
Age			
18-29	9	13	15
30-49	34	28	28
50-64	34	32	27
65 and older	23	27	30
Education level[a]			
Low	32	31	26
Middle	33	39	43
High	35	30	31
Geographical			
Groningen	4	3	3
Friesland	5	4	4
Drenthe	3	3	3
Overijssel	7	7	6
Flevoland	2	2	2
Gelderland	12	11	12
Utrecht	7	8	7
Noord-Holland	14	16	17
Zuid-Holland	20	23	21
Zeeland	3	3	3
Noord-Brabant	16	14	16
Limburg	7	6	6

[a] Based on the Dutch educational system three educational levels were defined: high (university, college, higher vocational, general secondary, and intermediate vocational education), middle (general intermediate, and lower vocational education), and low (elementary education or less).

5.7.4 Appendix D. Scoring of food risks

Table D1. Mean scoring (standard deviation) of perception of food-related health risks by consumers and experts, and difference in scoring between 2009 and 2018, and between 2018 and 2024

Food risk	Consumers				Experts			
	2009	2018	2024	Difference 2009-2018; 2018-2024	2009	2018	2024	Difference 2009-2018; 2018-2024
1. unhealthy diet	2.94 (1.20)	3.82 (1.01)	4.07 (0.98)	0.88*; 0.25*	3.81 (1.23)	4.38 (0.88)	4.78 (0.46)	0.57*; 0.40*
2. food poisoning	2.80 (1.28)	3.76 (1.14)	3.58 (1.16)	0.96*; -0.18*	3.11 (1.14)	3.66 (1.03)	3.35 (1.02)	0.55*; -0.31
3. pesticide residues	2.92 (1.01)	3.50 (1.00)	3.62 (1.03)	0.58*; 0.12	1.89 (0.87)	2.08 (1.00)	2.57 (0.97)	0.19; 0.49*
4. environmental contaminants	3.10 (1.16)	3.78 (1.01)	3.81 (1.00)	0.68*; 0.03	2.42 (0.90)	2.73 (1.01)	2.91 (0.93)	0.31; 0.18
5. chemicals formed during preparation	2.91 (1.15)	3.59 (1.00)	3.55 (1.08)	0.68*; -0.04	2.81 (1.04)	3.33 (0.95)	3.00 (0.82)	0.52*; -0.33
6. GMO	2.59 (1.05)	3.09 (1.05)	3.10 (1.16)	0.50*; 0.01	1.67 (1.09)	1.73 (1.74)	1.62 (0.75)	0.06; -0.11
7. additives	2.69 (1.01)	3.02 (1.08)	3.15 (1.12)	0.33*; 0.13	1.67 (0.91)	1.52 (0.79)	1.73 (0.68)	-0.15; 0.21
8. chemicals from packaging materials		3.44 (1.02)	3.54 (1.03)	0.10		2.33 (0.84)	2.76 (0.85)	0.43*
9. hormones / antibiotics in meat		3.68 (1.00)	3.47 (1.12)	-0.21*		2.73 (0.89)	2.58 (1.05)	-0.15
10. PFAS			3.73 (1.01)				3.07 (0.94)	
11. microplastics			3.73 (0.99)				2.86 (0.90)	

Asterisk (*) means significant difference of the mean ($p < 0.005$).

Table D2. Mean scoring (standard deviation) of familiarity with the food-related health risk and perception of the food risk, and the correlation between familiarity with the food risk and the perception of the food risk, for consumers and experts in 2024

Food risk	Consumers			Experts		
	Familiarity with risk	Perception of risk	Correlation (r_s)[a]	Familiarity with risk	Perception of risk	Correlation (r_s)[a]
1. unhealthy diet	4.21 (0.85)	4.07 (0.98)	0.274*	4.18 (0.91)	4.78 (0.46)	0.128
2. food poisoning	4.07 (0.91)	3.58 (1.16)	0.147*	4.34 (0.82)	3.35 (1.02)	0.200
3. pesticide residues	3.56 (0.94)	3.62 (1.03)	0.327*	3.71 (1.03)	2.57 (0.97)	0.010
4. environmental contaminants	3.07 (1.14)	3.81 (1.00)	0.322*	3.64 (1.12)	2.91 (0.93)	0.101
5. chemicals formed during preparation	3.26 (1.14)	3.55 (1.08)	0.238*	3.65 (1.05)	3.00 (0.82)	0.307
6. GMO	2.86 (1.14)	3.10 (1.16)	0.192*	2.74 (1.23)	1.62 (0.75)	-0.112
7. additives	3.57 (1.01)	3.15 (1.12)	0.247*	3.46 (1.11)	1.73 (0.68)	-0.141
8. chemicals from packaging materials	2.76 (1.17)	3.54 (1.03)	0.347*	3.12 (1.28)	2.76 (0.85)	0.407*
9. hormones / antibiotics in meat	3.33 (1.08)	3.47 (1.12)	0.347*	3.21 (1.13)	2.58 (1.05)	0.035
10. PFAS	3.05 (1.17)	3.73 (1.01)	0.365*	3.53 (1.18)	3.07 (0.94)	0.242
11. microplastics	3.39 (1.09)	3.73 (0.99)	0.357*	2.77 (1.09)	2.86 (0.90)	0.351
All food risks	3.38 (0.75)	3.57 (0.77)	0.333*	3.49 (0.79)	2.87 (0.58)	0.065

[a] Results of the Spearman's correlation is indicated with r_s. Asterisk (*) means a significant correlation ($p < 0.005$).

Table D3. Mean scoring (standard deviation) of perception of food-related health risks by consumers in 2024, and difference in age (younger than 65 years vs 65 years and older), gender (man vs women) and education level (low, middle, high)

Food risk	Age			Gender		Education				
	young (≤65yrs)		old (>65yrs)	women	men	low		middle		high
1. unhealthy diet	4.07		4.05	4.12	4.02	4.11		3.97		4.16
	(0.96)		(1.03)	(0.96)	(1.00)	(1.00)		(0.94)		(0.96)
2. food poisoning	3.50	*	3.75	3.52	3.63	3.90	*	3.60	*	3.29
	(1.16)		(1.15)	(1.18)	(1.15)	(1.06)		(1.20)		(1.13)
3. pesticide residues	3.53	*	3.83	3.60	3.64	3.83	*	3.58		3.51
	(1.06)		(0.95)	(1.04)	(1.02)	(1.02)		(1.09)		(0.95)
4. environmental contaminants	3.76		3.93	3.82	3.86	3.93		3.83		3.68
	(1.01)		(0.95)	(0.96)	(1.03)	(0.93)		(1.03)		(0.99)
5. chemicals formed during preparation	3.50		3.67	3.56	3.55	3.80	*	3.49		3.43
	(1.09)		(1.07)	(1.07)	(1.09)	(1.04)		(1.11)		(1.06)
6. GMO	2.97	*	3.38	3.13	3.07	3.51	*	3.16	*	2.70
	(1.19)		(1.06)	(1.15)	(1.18)	(1.14)		(1.12)		(1.11)
7. additives	3.04	*	3.39	3.18	3.12	3.48		3.23	*	2.78
	(1.17)		(0.99)	(1.11)	(1.15)	(1.03)		(1.12)		(1.12)
8. chemicals from packaging materials	3.51		3.61	3.53	3.41	3.71		3.56		3.40
	(1.04)		(0.99)	(1.07)	(1.16)	(1.02)		(1.04)		(1.01)
9. hormones / antibiotics in meat	3.36	*	3.72	3.60	3.64	3.68		3.50	*	3.26
	(1.15)		(0.99)	(1.04)	(1.02)	(1.04)		(1.12)		(1.14)
10. PFAS	3.65		3.89	3.73	3.74	3.92	*	3.69		3.61
	(1.03)		(0.96)	(0.98)	(1.01)	(0.95)		(1.04)		(1.02)
11. microplastics	3.69		3.83	3.58	3.51	3.90	*	3.72		3.62
	(1.00)		(0.96)	(1.01)	(1.04)	(0.95)		(1.02)		(0.97)
All food risks	3.51	*	3.72	3.58	3.57	3.78	*	3.57	*	3.40
	(0.77)		(0.73)	(0.75)	(0.78)	(0.77)		(0.78)		(0.71)

Asterisk (*) means significant difference of the mean ($p < 0.005$).

Table D4. Ranking of the five highest-rated food-related health risks by consumers and experts in 2024, based on a ranking question. If the difference between risks was not statistically significant (as determined by a two-sided Mann-Whitney U test with $p < 0.005$), the risks were assigned the same rank

Consumers	Experts
1. Unhealthy diet	1. Unhealthy diet
2. Environmental contaminants Microplastic	2. Food poisoning
3. Residues of pesticides Food poisoning	3. Environmental contaminants Chemicals formed during preparation PFAS

5.7.5 Appendix E. Scoring of food risks

Table E1. Percentage of respondents who correctly answered the questions regarding **knowledge** of safe food-handling practices for chicken, based on the 2015, 2021, and 2024 surveys. Brackets indicate whether the statement itself is true or false

Question **knowledge** (correct answer) *	2015	2021	2024
a. If raw chicken still smells good, it is safe to eat. (false)	48	48	46
b. Transporting raw chicken in a cooler bag from the store to home reduces the risk of food poisoning. (true)	93	98	97
c. Washing hands with soap after touching raw chicken reduces the risk of food poisoning. (true)	98	98	98
d. A cutting board that has been used to cut raw chicken should always be cleaned with dish soap before using it for anything else to prevent food poisoning. (true)	97	99	98
e. It is important to prevent prepared food from coming into contact with raw chicken. (true)	99	99	98
f. If you eat chicken that is not properly cooked, you will always get sick. (false)	79	83	86
g. Leftover cooked chicken should be thoroughly reheated to prevent food poisoning. (true)	73	76	74
h. If chicken meat is completely white inside, it is cooked. (true)	92	94	94
i. It is safest to thaw frozen raw chicken outside the refrigerator. (false)	76	80	85
j. Cooked/grilled chicken can still be safely eaten after being stored in the refrigerator for a week. (false)	90	89	89
k. Food poisoning can be fatal. (true)	88	90	86
l. Most food poisonings occur when people eat out (not at home). (false)	48	52	42
Knowledge of safe food-handling practices for chicken (mean of all questions)	**82**	**84**	**83**

* For knowledge items, responses were scored dichotomously (1 = correct, 0 = incorrect), based on the predefined correct answer (true/false). No reverse coding was applied to knowledge items.

Table E2. Percentage of respondents with a high score (4 or higher) on safe food-handling **practices** for chicken, based on the 2015, 2021, and 2024 surveys

Questions safe food-handling **practices** for chicken (score 4 or higher)	2015	2021	2024
a. I use a cooler bag ('freezer bag') to transport raw chicken from the store to home. (4=often, 5=always)	17	17	20
b. I put raw chicken in the refrigerator or freezer as soon as possible after purchase. (4=often, 5=always)	96	97	98
c. I eat chicken even if the expiration date has passed. (4=mostly not, 5=never)*	81	78	77
d. I wash my hands with soap before preparing chicken. (4=often, 5=always)	76	74	76
e. I rinse raw chicken under the tap. (4=mostly not, 5=never)*	66	68	71
f. If I wash my hands after touching raw chicken, I use soap. (4=often, 5=always)	86	86	89
g. I use the same knife for cutting raw chicken and other foods. (4=mostly not, 5=never)*	89	88	90
h. I use a separate cutting board for cutting raw chicken. (4=often, 5=always)	73	77	80
i. If I want to cut something else on the board after cutting raw chicken, I wash the cutting board with dish soap. (4=often, 5=always)	87	86	86
j. I use separate plates for raw and grilled chicken during barbecuing. (4=often, 5=always)	82	79	82
k. When chicken is ready, I always cut it open first to check if it is properly cooked before eating it. (4=often, 5=always)	84	82	85
l. I only eat chicken that is well-cooked. (4=often, 5=always)	98	96	98
m. I put chicken back in the pan to cook further if it is not properly cooked. (4=often, 5=always)	95	93	96
n. I store raw chicken wrapped (in a bag or container) in the refrigerator. (4=often, 5=always)	91	89	90
o. I take raw chicken out of the refrigerator just before preparing it. (4=often, 5=always)	96	94	97
p. I thaw frozen raw chicken outside the refrigerator. (4=mostly not, 5=never)*	45	43	50
Safe food-handling practices for chicken (mean of all questions)	**79**	**78**	**80**

* For all items, response categories were coded such that a score of 4 or higher consistently reflects safe food-handling behaviour. Items c, e, g, and p were phrased negatively and were therefore reverse-coded prior to analysis.

Table E3. Percentage of respondents with high score of perceived **severity** (score 4 or higher) of a foodborne infection from the 2015, 2021 and 2024 survey

Question perceived **severity** (score 4 or higher)	2015	2021	2024
a. How serious do you consider a foodborne infection in general? (4=serious; 5=very serious)	82	81	83
b. If I get a foodborne infection myself, I consider it 4=serious; 5=very serious.	83	83	82
c. If someone around me gets a foodborne infection, I consider it 4=serious; 5=very serious.	82	81	83
Perceived severity (mean of all questions)	**82**	**82**	**83**

Table E4. Percentage of respondents with high score of **likelihood** of contracting a foodborne infection (score 4 or higher), based on the 2015, 2021 and 2024 survey

Question **likelihood** of contracting a foodborne infection (score 4 or higher)	2015	2021	2024
a. How likely do you think it is that you will get a foodborne infection from eating chicken? (4=likely, 5=very likely)	8	9	8
b. How likely do you think it is that you will make a mistake when buying chicken? (4=likely, 5=very likely)	6	4	5
c. How likely do you think it is that you will get a foodborne infection if you make a mistake when buying chicken? (4-likely, 5=very likely)	11	13	13
d. How likely do you think it is that you will make a mistake when preparing chicken? (4=likely, 5=very likely)	6	6	6
e. How likely do you think it is that you will get a foodborne infection if you make a mistake when preparing chicken? (4=likely, 5=very likely)	13	16	18
f. How likely do you think it is that you will make a mistake when storing chicken? (4=likely, 5=very likely)	6	7	6
g. How likely do you think it is that you will get a foodborne infection if you make a mistake when storing chicken? (4=likely, 5=very likely)	13	18	21
Likelihood of contracting a foodborne infection (mean of all questions)	**9**	**10**	**11**

Table E5. Percentage of respondents reporting high **barriers** carrying out safe food-handling practices for chicken (score 4 or higher), based on the 2015, 2021 and 2024 survey

Question **barriers** to carry out safe food-handling practices (score 4 or higher)	2015	2021	2024
a. Taking measures to prevent a foodborne infection from chicken takes too much time for me. (4=agree, 5=totally agree)	7	5	5
b. I find taking measures to prevent a foodborne infection from chicken too much hassle. (4=agree, 5=totally agree)	6	4	4
c. I think it's a waste to throw away chicken if the expiration date has passed. (4=agree, 5=totally agree)	15	22	27
d. I don't have enough kitchen supplies (such as cutting boards, knives, or a cooler bag) to take all the measures to prevent a foodborne infection from chicken. (4=agree, 5=totally agree)	9	8	7
e. I don't have enough money to implement the hygiene measures. (4=agree, 5=totally agree)	3	2	2
f. I don't have enough dishwashing facilities. (4=agree, 5=totally agree)	2	1	2
g. I don't have the means to keep chicken cool. (4=agree, 5=totally agree)	1	1	2
Barriers to carry out safe food-handling practices (mean of all questions)	**6**	**6**	**7**

Table E6. Questions regarding hygiene warning label from the 2015, 2021 and 2024 survey

Question **hygiene warning label** (answer)	2015	2021	2024
a. Do you **read** the hygiene warning label on the packaging of raw chicken meat? (yes)	85	80	81
b. Wants to be **informed** about measures to take to prevent a foodborne infection from chicken through a hygiene warning label on the packaging of chicken meat. (yes)	58	76	73
c. Wants to be **informed** about measures to take to prevent a foodborne infection from chicken by government (e.g. Netherlands Nutrition Centre or National Institute for Public Health and the Environment). (yes)	14	36	44
d. **New information**: Now that you have seen this label, have you read any new information that you were not aware of before? Yes, namely that I need to ensure that bacteria on raw chicken do not get into my food.	9	8	8
e. **New information**: Now that you have seen this label, have you read any new information that you were not aware of before? Yes, namely that there are harmful bacteria in chicken meat.	7	5	4
f. **New information**: Now that you have seen this label, have you read any new information that you were not aware of before? Yes, namely that I must always keep raw chicken cold (at a maximum of 4 degrees Celsius).	7	7	11
g. **New information**: Now that you have seen this label, have you read any new information that you were not aware of before? Yes, namely that I must cook chicken thoroughly.	7	5	5
h. **Assessment**: Now that you have seen this label (again), how important do you think it is that this label is on the packaging of raw chicken meat? (4=important, 5=very important)	86	87	89
i. **Assessment**: Now that you have seen this label (again), how useful do you think it is that this label is on the packaging of raw chicken meat? (4=useful, 5=very useful)	87	88	91*
j. **Assessment**: Now that you have seen this label (again), how reassuring do you think it is that this label is on the packaging of raw chicken meat? (4=reassuring, 5=very reassuring)	71	68	74
k. **Assessment**: Now that you have seen this label (again), how good do you think it is that this label is on the packaging of raw chicken meat? (4=good, 5=very good)	86	86	89
l. **Assessment**: Now that you have seen this label (again), how clear do you think it is that this label is on the packaging of raw chicken meat? (4=clear, 5=very clear)	86	86	91*
General assessment of hygiene warning label (mean of all questions)	**83**	**83**	**87***
m. **Intention**: Now that you have seen this label, are you planning to handle the purchase of raw chicken differently in the future? (4=yes; 5=definitely)	21	15	16
n. **Intention**: Now that you have seen this label, are you planning to handle the preparation of chicken differently in the future? (4=yes; 5=definitely)	19	15	16
o. **Intention**: Now that you have seen this label, are you planning to handle the storage of raw chicken differently in the future? (4=yes; 5=definitely)	22	16	17
General assessment intention to change behaviour after reading label (mean of all questions)	**22#**	**16**	**18**

*****significant difference (p<0.05) between 2024 and 2015, and 2024 and 2021.
[#] significant difference (p<0.05) between 2015 and 2021, and 2015 and 2024.

5.7.6 Appendix F. Factors associated with knowledge of safe food-handling, safe food-handling practices for chicken, having read the label before the study and intention to change behaviour after reading the hygiene warning label

Table F1. Factors significantly associated ($p < 0.05$) with **adequate knowledge** of safe food-handling practices in 2021 and 2024, identified using chi-square analysis (odds ratio (95% CI) with the *p*-value)

	2021		2024	
	Adequate knowledge (%) [#]	OR (95% CI) *p-value*	Adequate knowledge (%) [#]	OR (95% CI) *p-value*
Safe food-handling practices				
Unsafe	85	2.59 (1.63-4.10)	77	3.69 (2.49-5.29)
Safe	94	*p < 0.001*	93	*p < 0.001*
Severity of foodborne infections				
Non-severe	93	*not significant*	82	1.84 (1.11-3.06)
Severe	92		90	*p = 0.017*
Likelihood of contracting foodborne infections				
Not likely	92	*not significant*	89	*not significant*
Likely	87		85	
Barriers: too much fuss				
No	93	0.26 (0.12-0.54)	91	0.13 (0.07-0.24)
Yes	76	*p < 0.001*	57	*p < 0.001*
Barriers: too time-consuming				
No	93	0.39 (0.18-0.88)	91	0.29 (0.15-0.54)
Yes	84	*p = 0.018*	74	*p < 0.001*
Barriers: reluctance to discard chicken after expiration date				
No	94	0.49 (0.29-0.82)	92	0.42 (0.27-0.65)
Yes	88	*p = 0.006*	83	*p < 0.001*
Barriers: lack of kitchen utensils				
No	93	0.46 (0.24-0.89)	90	0.31 (0.17-0.55)
Yes	86	*p = 0.019*	74	*p < 0.001*
Barriers: inadequate facilities for washing the dishes				
No	92	0.28 (0.07-1.02)	90	0.13 (0.06-0.33)
Yes	77	*p = 0.018*	57	*p < 0.001*
Gender				
Female	91	*not significant*	90	*not significant*
Male	92		87	
Age				
Below 65 years	92	*not significant*	88	*not significant*
65 years and older	90		90	
Education				
Low	89	1.67 (1.05-2.66)	85	1.57 (1.04-2.39)
Middle/High	93	*p = 0.030*	90	*p = 0.031*
Living alone				
No	92	*not significant*	89	*not significant*
Yes	92		90	
Preparing of meals				
Weekly or less	87	*not significant*	85	*not significant*
Several days a week or more	92		89	
Foodborne infection in the past				
No	90	2.20 (1.28-3.79)	86	1.66 (1.09-2.53)
Yes	95	*p = 0.004*	91	*p = 0.017*

Health status (own and family)				
Bad or moderate	92	*not significant*	88	*not significant*
Excellent, good or average	92		89	
Read the label before the study				
No	92	*not significant*	85	*not significant*
Yes	92		90	
Intention to change behaviour				
No	94	0.31 (0.19-0.50)	90	0.58 (0.37-0.91)
Yes	82	*p < 0.001*	84	*p = 0.016*

[#] Participants with a mean score above 0.67 were classified as having adequate knowledge. Those with inadequate knowledge were calculated as: 100 % – percentage with adequate knowledge.

Table F2. Factors significantly associated ($p < 0.05$) with **safe food-handling practices** in 2021 and 2024, identified using chi-square analysis (odds ratio (95% CI) with the *p*-value)

	2021		2024	
	Safe food-handling practices (%) [#]	OR (95% CI) *p-value*	Safe food-handling practices (%) [#]	OR (95% CI) *p-value*
Knowledge safe food-handling				
Inadequate	57	2.59 (1.63-4.10)	50	3.69 (2.49-5.29)
Adequate	78	*p < 0.001*	79	*p < 0.001*
Severity of foodborne infections				
Non-severe	59	2.54 (1.74-3.71)	58	2.55 (1.74-3.75)
Severe	78	*p < 0.001*	78	*p < 0.001*
Likelihood of contracting foodborne infections				
Not likely	76	*not significant*	76	*not significant*
Likely	75		72	
Barriers: too much fuss				
No	81	0.12 (0.06-0.23)	81	0.07 (0.03-0.14)
Yes	33	*p < 0.001*	23	*p < 0.001*
Barriers: too time-consuming				
No	81	0.19 (0.10-0.33)	81	0.19 (0.11-0.33)
Yes	44	*p < 0.001*	44	*p < 0.001*
Barriers: reluctance to discard chicken after expiration date				
No	82	0.42 (0.30-0.59)	81	0.48 (0.35-0.66)
Yes	65	*p < 0.001*	67	*p < 0.001*
Barriers: lack of kitchen utensils				
No	80	0.33 (0.21-0.52)	81	0.18 (0.11-0.30)
Yes	56	*p < 0.001*	43	*p < 0.001*
Barriers: inadequate facilities for washing the dishes				
No	78	0.18 (0.06-0.56)	78	0.18 (0.08-0.43)
Yes	38	*p < 0.001*	39	*p < 0.001*
Gender				
Female	80	0.63 (0.47-0.84)	81	0.52 (0.39-0.69))
Male	72	*p = 0.002*	69	*p < 0.001*
Age				
Below 65 years	77	*not significant*	77	*not significant*
65 years and older	73		73	
Education				
Low	76	*not significant*	73	*not significant*
Middle/High	76		77	
Living alone				
No	76	*not significant*	75	*not significant*
Yes	74		79	
Preparing of meals				
Weekly or less	69	*not significant*	76	*not significant*
Several days a week or more	77		76	
Foodborne infection in the past				
No	73	1.49 (1.08-2.04)	73	1.36 (1.01-1.84)
Yes	80	*p = 0.015*	79	*p = 0.045*
Health status (own and family)				
Bad or moderate	79	*not significant*	77	*not significant*
Excellent, good or average	76		75	

Read the label before the study				
No	67	1.79 (1.28-2.51)	66	1.78 (1.27-2.50)
Yes	78	*p < 0.001*	78	*p < 0.001*
Intention to change behaviour				
No	78	0.45 (0.32-0.65)	79	0.40 (0.29-0.56)
Yes	62	*p < 0.001*	60	*p < 0.001*

[#] Participants with a mean score 4 or higher were classified as safe food-handling practices. Those with unsafe food-handling practices were calculated as: 100 % – percentage with safe food-handling practices.

Table F3. Factors significantly associated ($p < 0.05$) with **having read the label before the study** in 2021 and 2024, identified using chi-square analysis (odds ratio (95% CI) with the *p*-value)

	2021		2024	
	Having read the label (readers) (%) [#]	OR (95% CI) *p-value*	Having read the label (readers) (%)[#]	OR (95% CI) *p-value*
Knowledge safe food-handling				
Inadequate	80	*not significant*	75	*not significant*
Adequate	80		82	
Safe food-handling practices				
Unsafe	73	1.79 (1.28-2.51)	74	1.78 (1.27-2.50)
Safe	83	*p < 0.001*	84	*p < 0.001*
Severity of foodborne infections				
Non-severe	66	2.43 (1.63-3.60)	75	1.55 (1.00-2.39)
Severe	83	*p < 0.001*	82	*p = 0.048*
Likelihood of contracting foodborne infections				
Not likely	80	*not significant*	81	*not significant*
Likely	87		81	
Barriers: too much fuss				
No	81	*not significant*	83	0.45 (0.24-0.87)
Yes	74		68	*p = 0.016*
Barriers: too time-consuming				
No	81	*not significant*	83	*not significant*
Yes	86		77	
Barriers: reluctance to discard chicken after expiration date				
No	83	0.52 (0.36-0.75)	83	*not significant*
Yes	72	*p < 0.001*	78	
Barriers: lack of kitchen utensils				
No	81	*not significant*	82	*not significant*
Yes	76		84	
Barriers: inadequate facilities for washing the dishes				
No	80	*not significant*	81	*not significant*
Yes	85		96	
Gender				
Female	76	1.66 (1.21-2.27)	79	1.42 (1.03-1.94)
Male	84	*p = 0.002*	84	*p = 0.031*
Age				
Below 65 years	77	2.83 (1.83-4.39)	78	2.33 (1.52-3.57)
65 years and older	90	*p < 0.001*	89	*p < 0.001*
Education				
Low	84	*not significant*	84	*not significant*
Middle/High	79		80	
Living alone				
No	81	*not significant*	81	*not significant*
Yes	78		81	
Preparing of meals				
Weekly or less	80	*not significant*	80	*not significant*
Several days a week or more	81		81	
Foodborne infection in the past				
No	79	*not significant*	81	*not significant*
Yes	84		83	

Health status (own and family)				
Bad or moderate	84	*not significant*	84	*not significant*
Excellent, good or average	80		81	
Intention to change behaviour				
No	79	1.84 (1.13-3.00)	80	1.76 (1.11-2.78)
Yes	87	*p = 0.013*	87	*p = 0.015*

[#] Non-readers (those who did not read the label) were calculated as 100 % – percentage of readers.

Table F4. Factors significantly associated ($p < 0.05$) with the **intention to change behaviour** after reading the label in 2021 and 2024, identified using chi-square analysis (odds ratio (95% CI) with the *p*-value)

	2021		2024	
	Intention to change behaviour (%) [#]	OR (95% CI) *p-value*	Intention to change behaviour (%) [#]	OR (95% CI) *p-value*
Knowledge safe food-handling				
Inadequate	36	0.31 (0.19-0.50)	26	*0.58 (0.37-0.91)*
Adequate	15	*p < 0.001*	17	*p = 0.016*
Safe food-handling practices				
Unsafe	26	0.45 (0.32-0.65)	30	0.40 (0.29-0.56)
Safe	13	*p < 0.001*	15	*p < 0.001*
Severity of foodborne infections				
Non-severe	9	2.19 (1.18-4.07)	11	1.93 (1.08-3.45)
Severe	18	*p = 0.011*	19	*p = 0.024*
Likelihood of contracting foodborne infections				
Not likely	15	2.45 (1.54-3.90)	17	2.24 (1.42-3.53)
Likely	30	*p < 0.001*	31	*p < 0.001*
Barriers: too much fuss				
No	15	2.85 (1.46-5.55)	16	2.37 (1.23-4.57)
Yes	33	*p = 0.001*	32	*p = 0.008*
Barriers: too time-consuming				
No	14	4.85 (2.69-8.76)	17	2.12 (1.17-3.84)
Yes	44	*p < 0.001*	30	*p = 0.012*
Barriers: reluctance to discard chicken after expiration date				
No	16	*not significant*	20	*not significant*
Yes	15		16	
Barriers: lack of kitchen utensils				
No	15	2.44 (1.48-4.04)	16	2.46 (1.44-4.21)
Yes	30	*p < 0.001*	32	*p < 0.001*
Barriers: inadequate facilities for washing the dishes				
No	16	12.1 (3.7-39.7)	17	6.31 (2.72-14.62)
Yes	69	*p < 0.001*	57	*p < 0.001*
Gender				
Female	16	*not significant*	15	1.54 (1.12-2.11)
Male	16		22	*p = 0.007*
Age				
Below 65 years	14	1.96 (1.38-2.77)	15	2.26 (1.62-3.15)
65 years and older	24	*p < 0.001*	28	*p < 0.001*
Education				
Low	27	0.39 (0.27-0.55)	26	0.52 (0.37-0.73)
Middle/High	13	*p < 0.001*	17	*p < 0.001*
Age below 65 years				
Low	17	0.49 (0.30-0.80)	23	0.52 (0.33-0.83)
Middle/High	9	*p = 0.004*	13	*p = 0.004*
Living alone				
No	16	*not significant*	18	*not significant*
Yes	19		21	
Preparing of meals				
Weekly or less	16	*not significant*	17	*not significant*
Several days a week or more	16		18	

Foodborne infection in the past				
No	18	*not significant*	19	*not significant*
Yes	15		19	
Health status (own and family)				
Bad or moderate	19	*not significant*	15	*not significant*
Excellent, good or average	16		19	
Read the label before the study				
No	11	1.84 (1.13-3.00)	12	1.76 (1.11-2.78)
Yes	18	*p = 0.013*	20	*p = 0.015*

[#] Participants with a mean score above 3 (neutral) were considered to have an intention to change. Those without an intention to change were calculated as: 100 % – percentage with intention to change behaviour.

5.7.7 Appendix G. Full questionnaire (in Dutch) as administered in the survey of the Hygiene Warning Label

The full questionnaire is provided in https://doi.org/10.1016/j.lwt.2026.119216.

Chapter 6

General discussion

6.1 Main considerations of the results of this thesis

Foodborne illnesses have been recognized for centuries as a significant public health risk, with the home kitchen playing a critical role in the transmission of pathogens (WHO, 2022). Although experts widely acknowledge that the domestic setting is a primary site for foodborne outbreaks, many consumers continue to underestimate the risks associated with food handling at home (EFSA and ECDC, 2019; Byrd-Bredbenner et al., 2013). Despite this long-standing recognition, understanding the role of consumer behaviour in food safety remains a major challenge. Household food practices are highly variable and context-dependent, shaped by routines, personal beliefs, and situational factors, which makes them difficult to study and quantify in a systematic manner (Dickinson et al., 2014; Redmond and Griffith, 2003; Young and Waddell, 2016). Nonetheless, gaining insight into consumer behaviour is essential for assessing how domestic practices influence microbial survival and growth, and thus the overall risk of foodborne illness. This thesis examined the interplay between consumer behaviour and microbiological risks to support more effective public health strategies, explicitly including risk perception and risk communication as essential factors that shape risk behaviour. Its novel contribution lies in integration: rather than addressing behaviour, risk assessment, perception, or communication in isolation, the research showed how these elements reinforce one another, yielding insights that remain hidden when viewed from a single perspective. Within this integrative framework, this thesis employed complementary approaches to reflect on risk outputs in quantitative microbiological risk assessment (QMRA), systematically using sensitivity and scenario analyses to identify key behavioural drivers of risk and the relative effectiveness of potential interventions. The explicit use of annual illness cases as an outcome metric enhances the interpretability and comparability of results across scenarios, strengthening the link between behavioural data and public health relevance.

Food-related risks are addressed from four key perspectives: risk perception, risk behaviour, risk assessment, and risk communication (see **Figure 6.1**). **Chapters 2 and 5** focused on risk perception, comparing how consumers and experts evaluate food-related risks and how these perceptions shape decision-making and behaviour. Risk behaviour was examined in **Chapters 3** and **4** through surveys and kitchen-simulated experiments investigating food storage, cooling practices, and the handling of food. These empirical data were not only used to characterise everyday food-handling routines, but were explicitly translated into quantitative microbiological risk, enabling a quantitative evaluation of how everyday food-handling practices influence microbiological risk levels. In **Chapters 3** and **4**, two quantitative microbiological risk assessments (QMRAs) were developed: one assessing the risk of *Listeria monocytogenes* in cooked ham, and another for *Campylobacter* spp. in raw chicken. These QMRA models quantified the health risks, defined as the number of illness cases, associated with specific consumer

practices, and identified critical points for intervention. Both studies demonstrated how sensitivity and scenario analyses helped to reveal the most influential determinants of risk and the relative effectiveness of potential interventions in terms of estimated illness cases. Finally, **Chapter 5** addressed risk communication by evaluating the impact of a revised hygiene warning label on poultry packaging. This intervention study assessed how changes in on-pack communication influenced consumer food-handling behaviour and highlighted how persistent consumer misconceptions can limit the effectiveness of risk communication strategies. The findings illustrated the limitations of approaches that consider either technical hazards and their associated risks or consumer behaviour in isolation, and demonstrated the added value of integrating these perspectives. In the final discussion, these insights are placed in a broader context by relating them to current policy frameworks, communication efforts, and priorities for future research.

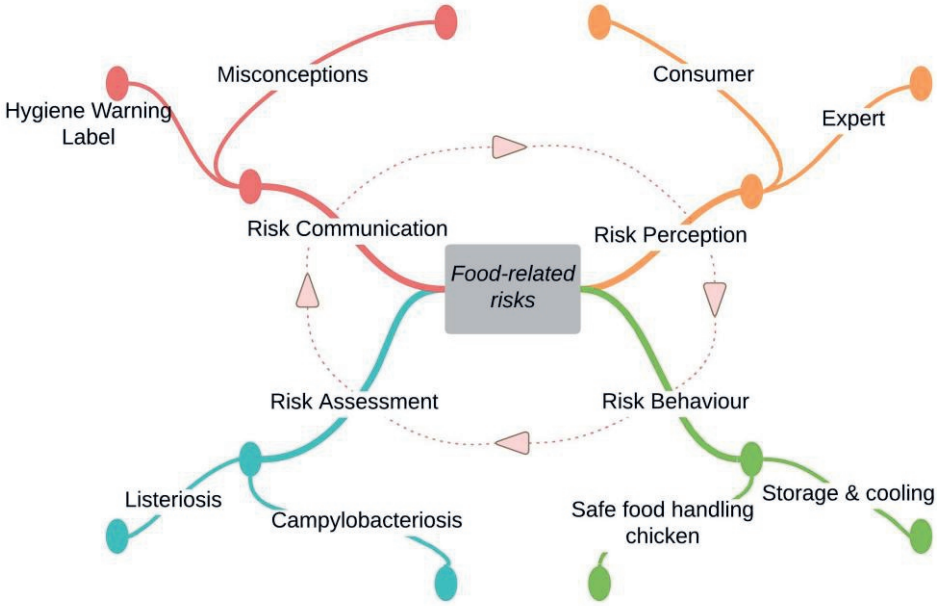


Figure 6.1. Conceptual overview of the four key perspectives on food-related risks addressed in this thesis.

6.2 Risk perception

Risk perception plays an important role in food safety analysis, as it influences both consumer behaviour and the reception of health communication. This thesis examined how perceptions of food-related risks changed among consumers and experts, drawing on surveys conducted in 2009, 2018, and 2024 (**Chapters 2** and

5). Risk perception is not static; it evolves in response to changes in society, technology, information, and emerging food safety concerns such as PFAS (per- and polyfluoroalkyl substances) and microplastics. Therefore, it is important to continue monitoring how these perceptions develop over time. These Dutch surveys complement the EFSA Eurobarometer by providing more detailed national insight into how food-related risk perceptions relate to expert views, domestic food-handling practices, and communication needs (EFSA, 2026).

6.2.1 Trends in perception of food-related risks (2009-2024)

Across all years, experts and consumers increasingly identified unhealthy diets as the most important food-related health risk. This aligns with disease burden estimates from the National Institute for Public Health and the Environment (RIVM). In 2018, unhealthy diets were responsible for approximately 400,000 disability-adjusted life years (DALYs) in the Netherlands, compared to 4,000 DALYs from foodborne infections and between 300 and 1,000 DALYs from chemical contaminants (RIVM, 2018; Van Kreijl et al., 2006). The health impact of unhealthy diets thus far exceeds that of other food-related risks. While experts have long recognized this, consumers historically perceived unhealthy diets as less clearly distinct from other risks (**Figure 6.2**). Between 2009 and 2024, however, public perception shifted, with unhealthy diets also regarded as the top concern in 2024. This is encouraging, as it reflects a growing understanding of the health consequences of dietary habits. Notably, this rise in awareness occurred across all demographic groups, independent of age, gender, or educational level. This trend is encouraging, given the substantial burden of diet-related diseases in the Netherlands, including cardiovascular disease, diabetes, and various cancers (Ocké et al., 2017). Currently, half of the Dutch population is overweight, with even higher rates among people with lower socio-economic status. Projections from the Dutch Public Health Foresight Study indicate this figure will rise from 50 % in 2022 to 64 % by 2050 (Den Broeder et al., 2025). Consumption data further demonstrate a persistent pattern of excessive intake of salt, sugar, calories, and unhealthy fats above recommended levels (Schuurman et al., 2020). Historically, public underestimation of these risks may have limited the effectiveness of health communication. However, food choices remain shaped by a complex mix of factors: widespread availability of unhealthy foods, aggressive marketing, sedentary lifestyles, socio-economic inequality, and limited practical knowledge. Addressing these challenges requires a coordinated approach that improves the food environment and supports informed choices (WHO, 2023). While awareness alone is not enough, it is a valuable crucial first step towards healthier diets and better public health.

The extent to which experts and consumers evaluated each food-related health risk as large or very large in 2024 is shown in **Figure 6.2**, with circle size reflecting the share of respondents.

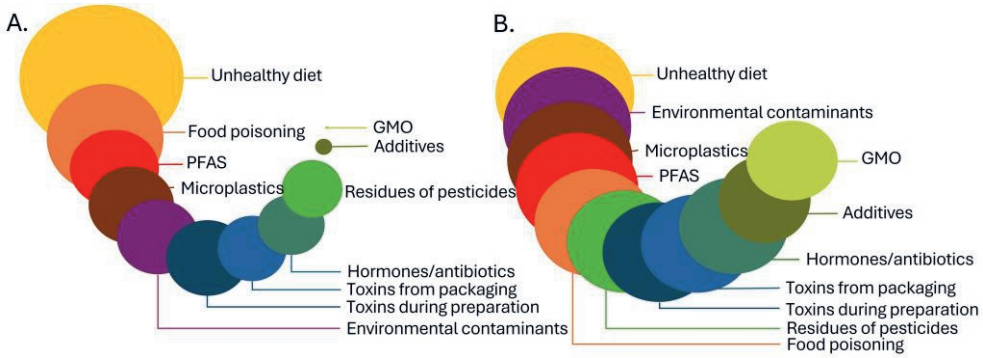


Figure 6.2. Overview of how strongly experts [A] and consumers [B] evaluated each food-related risk in 2024, with circle size indicating the relative number of respondents selecting "large" or "very large" risk.

Across the surveys, consumers rated chemical food risks much higher than experts. This aligns with earlier findings that people perceive involuntary exposures, such as chemical contaminants, as particularly threatening, especially because they are involuntary, invisible, and perceived as beyond personal control (Hartmann et al., 2018; Kehr et al., 2013). Such perceptions can shape consumer behaviour by reinforcing misperceptions about the relative magnitude and controllability of food-related health risks, which may lead consumers to overestimate involuntary risks, while underestimating risks that are more directly linked to everyday food-handling practices (IFIC, 2024; Simoglou and Roditakis, 2022; Meira et al., 2024). Two relatively new chemical risks, microplastics and PFAS, elicited strong concern among consumers. Around 63 % rated these as high or very high risks, along with other environmental contaminants. In contrast, experts judged these risks lower, though still notable: microplastics were evaluated by experts as high risks by 19 % of experts, and PFAS by 23 %. Considerable uncertainty remains regarding the potential health effects of these chemicals. Estimating their impact in terms of DALYs is methodologically challenging, as the chronic nature of the effects and long exposure periods make it difficult to establish clear causal links to individual chemical exposures. In 2024, RIVM proposed a standard, stepwise method to calculate DALYs for food-related chemical exposures (Chen et al., 2024). This study focused on method development and did not yet provide empirical results. While promising, the approach still requires practical testing and validation to develop robust, science-based estimates of the health burden from all food-related risks. In this context, it should be noted that mycotoxins were not included in the present analyses, despite their known relevance for food safety and public health (Ocké et al., 2017). Mycotoxins are naturally occurring contaminants in staple foods such as cereals, nuts, and fruits, and their health impact may increase in the future due to climate change and changing agricultural practices (EFSA, 2020). Incorporating

mycotoxins into future risk perception studies and DALY-based assessments would therefore be a valuable next step, enabling a more comprehensive comparison of chemical, microbiological, and dietary risks.

6.2.2 Behavioural responses and implications for risk communication

In 2024, 56 % of consumers considered pesticide residues a high or very high risk, compared with 16 % of experts. Because concerns about pesticides might discourage consumption of fruits and vegetables, the 2024 survey assessed whether perceived pesticide risk affects intake. Despite high levels of concern, only 1 % of respondents reported reducing their total fruit and vegetable consumption. Instead, most behavioural responses were precautionary or substitutive: 16 % reported washing produce more thoroughly, 10 % preferred organic products, and 4 % avoided specific fruits perceived to have higher residues. These findings aligned with previous studies showing that high pesticide concern rarely reduces overall produce consumption (Nardi et al., 2020; Katt and Meixner, 2020; Meira et al., 2024). In particular, individuals who predominantly consume organic products report higher perceived risks associated with conventional pesticide use (Koch et al., 2017). Maintaining adequate fruit and vegetable intake is crucial, as inadequate consumption contributes substantially to the disease burden in the Netherlands, accounting for 82,202 DALYs for low fruit intake and 63,023 DALYs for low vegetable intake in 2018 (RIVM, 2018). While risk perception may influence the type of produce selected, its impact on total intake appears limited, possibly due to the strong positive health image of plant-based foods and the general trust in the food system. Consumers rated chemical risks (environmental contaminants, microplastics and PFAS) higher than food poisoning, whereas experts placed food poisoning as the second most important risk (**Figure 6.2**). This suggests that consumers often underestimate their personal risk of foodborne illness, reflecting an optimistic bias whereby individuals perceive such risks as more likely to affect others than themselves. Such underestimation may also reduce the perceived relevance of hygiene advice, making it harder for risk communication to motivate safe food-handling behaviours. Multiple studies show that consumers frequently judge chemical risks as more concerning than biological hazards, despite the opposite being true in terms of actual health impact (DALYs) (Kher et al., 2013; Slovic, 1987; Van Kreijl et al., 2006). Furthermore, experts consider the risks of additives and GMOs to be minimal or negligible, as clearly shown in **Figure 6.2**, whereas consumers tend to perceive these risks as being of a more comparable magnitude. Despite limited scientific understanding, public concern about chemical contaminants continues to grow, potentially reflecting a broader societal pattern in which fears may become less aligned with objective risk levels, as illustrated by Batelaan's observation that a growing share of the population experiences persistent, non-realistic anxieties despite recognising their irrational nature (Batelaan, 2024). While our study examined how perceptions changed between 2009 and 2024, it did not explore the underlying

drivers of these shifts. Previous research indicated that people's concerns often extend beyond personal health to include environmental and animal welfare issues (Miles and Frewer, 2001). In recent years, such concerns have become increasingly visible in public discourse. Tian et al. (2022) reported rising social media discussions and increasing demand for clearer information about PFAS, and Fian et al. (2024) highlighted public concern about microplastics, particularly following reports of their presence in food and beverages. The combination of knowledge gaps, uncertainty, and lack of consensus on health impacts may contribute to feelings of powerlessness and inevitability among the public. These broader concerns should be taken into account in future risk communication strategies.

Implications for policy, risk communication, and research:

- ❖ Policy considerations: Prioritising unhealthy diets as the largest food-related health burden requires policies to move beyond hazard-focused discussions towards improving the overall food environment. At the same time, emerging risks such as PFAS and microplastics should remain on the agenda, ensuring that regulation can respond to both established and evolving risks.
- ❖ Communication efforts: Emphasize that everyday eating and cooking practices at home are crucial for food safety and health. At the same time, communication should address public concerns about chemical risks transparently and proactively, helping to bridge the gap between what people worry about and what poses the greatest health impact.
- ❖ Priorities for future research: Further methodological development is needed to quantify the health burden of chemical contaminants, including practical validation of DALY-based approaches. Robust DALY methods are essential for scientifically sound risk ranking, enabling chemical risks to be compared more accurately with microbiological and dietary risks.

6.3 Risk behaviour

Consumer risk behaviour in food safety is shaped by a dynamic interplay of risk perception, consumers' knowledge, risk communication, and the practical constraints consumers face in everyday food handling. This thesis examined these dynamics through three large surveys investigating refrigerator use (**Chapter 3**), the handling of raw chicken (**Chapter 4**), and responses to a hygiene-warning label (**Chapter 5**). Together, these studies provided important insights into domestic food-safety practices in the Netherlands.

6.3.1 Patterns in consumer food-safety behaviour

Across the studies, several consistent patterns emerged. Although most consumers recognized the importance of proper refrigeration, measured actual refrigerator temperatures revealed substantial deviations: one-third operated at 7 °C or higher, with a mean temperature of 5.7 °C (SD = 2.2 °C). The outliers, particularly among older adults, showed temperatures reaching up to 17 °C, with 70 % of participants exceeding the recommended 4 °C threshold (Voedingscentrum, 2025). Few consumers used a thermometer, limiting their ability to identify unsafe storage conditions. Chicken-handling practices were generally safe, especially with regard to thorough cooking, yet some less safe routines persisted, such as washing chicken or infrequent replacement of dishcloths. Together, these findings highlighted both strengths and vulnerabilities in everyday food-handling behaviour and point to a recurring disconnect between knowledge and practice. This intention–behaviour gap suggests that routines, convenience, and household habits often outweigh risk awareness, which is consistent with literature showing that food-safety practices are shaped not only by knowledge, but also by habits, attitudes, and misperceptions of microbiological risks (Begum et al., 2025; Byrd-Bredbenner et al., 2013; Evans and Redmond, 2014). A systematic review by Young and Waddell (2016) further indicates that food-handling behaviours are largely unconscious and routine, helping to explain why increased knowledge alone is unlikely to result in sustained behavioural change. Instead, social pressures (e.g., the responsibility associated with preparing food for children) and credible sources (e.g., healthcare professionals) may offer more effective leverage points for influencing food-safety behaviour. Regional, cultural, economic, and socio-demographic factors also contribute to differences in knowledge and behaviour across households. Similarly, Møretrø et al. (2021) reported cross-country variations in safe food-handling practices, concluding that communication and interventions must consider national food culture, consumer preferences, habitual practices, and local customs. However, increasing cultural diversity within countries suggests that food-handling practices may also differ substantially between communities living within the same national context. These observations underscore the importance of understanding consumer habits within a national context; the studies in this thesis therefore provide targeted insights for the Netherlands, informing both effective interventions and locally informed inputs for risk assessments. The results also revealed several encouraging behavioural tendencies. Consumers familiar with the recommended refrigerator temperature of 4 °C recorded lower temperatures, especially younger adults. The revised hygiene warning label, featuring icons instead of text, was rated as clearer and more useful by 87 % of the readers. Moreover, label readers reported safer chicken-handling practices, with the strongest behavioural intentions observed among higher-risk groups (older adults, lower-educated individuals, and those with poorer hygiene practices).

6.3.2 Implications for understanding and improving behaviour

The Health Belief Model (HBM) provides a useful lens for interpreting the behavioural patterns observed in this thesis, without implying that it offers a complete or deterministic explanation of behaviour (Strecher et al., 1997). The HBM has been applied in previous studies on safe food-handling, including research on the effectiveness of hygiene warning labels (Antonise-Kamp et al., 2018; Hanson and Benedict, 2002). Several key components, including perceived barriers, susceptibility, severity, self-efficacy, and cues to action, were clearly reflected in consumers' practices. Perceived barriers such as time pressure, "too much fuss", or a lack of utensils frequently hindered safe behaviour, particularly during raw chicken handling. Perceived susceptibility was low and is often reduced by 'optimistic bias' (i.e., the belief that one is less likely to experience negative events). As discussed in **Chapter 5**, more than 90 % of consumers believed they were unlikely to contract an infection from chicken. Many also relied on misleading cues, such as smell or appearance, as indicators of safety despite microbiological hazards being invisible and many foodborne infections being caused by food handling practices at home. Self-efficacy (i.e., confidence of one's ability to take correct action) also played a role. In 2024, a substantial proportion of consumers expressed uncertainty or reluctance in applying recommended food-safety practices; for example, 27 % reported hesitating to discard chicken past the expiration date, despite knowing the guideline. This indicates limited confidence in making safe choices when practical or emotional trade-offs are involved, reflecting a combination of low self-efficacy and perceived barriers. Cues to action, by contrast, appeared to have a modest, but positive effect. The revised hygiene-warning label functioned as a behavioural prompt: around 80 % of respondents reported reading it, and readers reported somewhat safer hygiene practices than non-readers, suggesting that such labels may support gradual improvements. The effect was most apparent among groups typically associated with higher risk, such as older adults and lower-educated consumers, who reported a greater intention to change behaviour after reading the label. These findings point to the potential of well-designed communication to contribute to incremental risk reduction and to narrowing behavioural inequalities.

It is important to note that the behavioural findings in this thesis rely mainly on self-reported data, which may overestimate compliance due to social desirability bias (Mazengia et al., 2015; Redmond and Griffith, 2003). Observational studies provide a more accurate view of real-world behaviour, while questionnaires remain valuable for assessing knowledge, perceptions, and intentions. Therefore, although the results indicate trends and differences between consumer groups, caution is warranted when generalizing self-reported compliance to actual practice. Objective measures, such as logged refrigerator temperatures, offer crucial complementary evidence. To further enhance the quality and applicability of consumer-behaviour data, harmonized surveys that simultaneously capture both food consumption and safety practices of the same participants would be

highly beneficial. Such surveys would enable the assessment of behavioural interdependencies, improve cross-country comparability by identifying cultural and regional differences, and provide robust, representative input for QMRA models. By integrating consumption patterns with actual food-handling practices, harmonized surveys can support more accurate exposure assessments and risk predictions, thereby strengthening the scientific basis for targeted interventions and international risk-management strategies (Redondo et al., 2025a, 2025b).

Implications for policy, risk communication, and research:

- ❖ Policy considerations: Integrate food-safety behaviour structurally into national food and health monitoring systems, such as the Dutch food consumption survey, to support evidence-based risk management.
- ❖ Communication efforts: Highlight that microbiological risks are invisible and embedded in everyday food-handling routines, using clear, actionable messages that counter optimistic bias and enhance personal relevance.
- ❖ Priorities for future research: Develop and implement harmonised approaches that combine objective measures (e.g., temperature logging) with self-reported data on consumption and food-safety practices, thereby strengthening QMRA.

6.4 Risk assessment

(part of this discussion section has been published in Van der Vossen-Wijmenga et al., 2025)

Risk assessment is a structured, four-step process that identifies and characterises hazards and estimates the probability of adverse health effects. In this thesis, two quantitative microbiological risk assessments (QMRAs) were developed that had strong focus on consumer behaviour in the domestic kitchen: one for *L. monocytogenes* in cooked ham (**Chapter 3**) and one for *Campylobacter* spp. in raw chicken (**Chapter 4**). Both assessments evaluated the impact of food-handling behaviours on illness risk. By quantifying these effects, QMRA provides an evidence-based foundation for targeted interventions throughout the food chain.

6.4.1 Key findings

The QMRA results demonstrated that the effectiveness of food safety interventions depended strongly on both the pathogen and the pathogen–food combination. For *L. monocytogenes*, household storage conditions, particularly time and temperature, were identified as the main drivers of listeriosis risk. Most predicted cases were associated with storing ready-to-eat cooked meat for more than seven days and/or at temperatures of 7 °C or higher. This reflects the ability of *L. monocytogenes* to grow at refrigeration temperatures, in contrast to most other foodborne pathogens. Consequently, household-level measures such as limiting storage duration, maintaining refrigeration at 4 °C, and clearer date marking offer

substantial potential for risk reduction, particularly for older adults and other vulnerable groups. Control of initial contamination at the production stage nevertheless remains important. For *Campylobacter*, thorough cooking of chicken is a key measure to reduce consumer exposure to *Campylobacter*. Data from the self-reported consumer behaviour study showed that most consumers report a high level of compliance with good cooking practices. Given this relatively high adherence, the QMRA demonstrated that further reductions in illness risk are most effectively achieved by lowering contamination levels earlier in the food production chain. This does not diminish the continued importance of thorough cooking and hygienic food handling in the kitchen, as deviations from these practices can rapidly increase exposure and illness risk. Moreover, self-reported behaviour may overestimate actual practices due to an intention–behaviour gap. Together, these findings underline the need for pathogen- and product-specific risk management and communication strategies: storage-focused messaging for products susceptible to *L. monocytogenes*, and communication emphasising adequate cooking temperatures and cross-contamination prevention for products susceptible to *Campylobacter*. QMRA-based evidence can further support effective communication by clarifying key risk drivers, countering misconceptions such as reliance on visual freshness cues, and helping to prioritise actionable messages for consumers within a comprehensive food safety approach. Food safety is a shared responsibility of food chain actors, authorities, and consumers. The research presented in this thesis helps identify where interventions are likely to have the greatest impact, thereby supporting authorities in balancing investments in upstream food chain measures and consumer-oriented interventions.

6.4.2 Methodological innovations

This thesis advanced QMRA by introducing several methodological innovations that strengthen the link between consumer behaviour, microbial dynamics, and exposure modelling.

1. Enhancing QMRA accuracy with local and detailed data

   Using detailed, locally collected data provides more realistic and actionable QMRA outcomes than relying on generic or categorical assumptions. Two examples illustrate this:

   - **Integration of behavioural data**: Both QMRAs incorporated extensive behavioural datasets from Dutch consumers rather than generic assumptions. Refrigerator temperatures and storage durations were measured directly among 534 consumers, revealing risky patterns - particularly among older adults - which were used to model *L. monocytogenes* growth. For *Campylobacter*, detailed behavioural scores from 1,974 consumers were mapped onto six exposure routes, providing a realistic representation of domestic handling variability.

- **Use of numerical concentration data:** In the *Campylobacter* study, real data on initial *Campylobacter* concentrations from the Netherlands were used from the period of 2015 to 2023 (NVWA, 2024), which allowed the QMRA to better reflect the Dutch contamination situation. Analyses showed that the chosen category limits (lower, medium or upper limit) strongly influenced predicted illness cases. Using actual numerical concentration data rather than categorical inputs produces more accurate contamination distributions, reduces structural uncertainty, and further improves alignment with real-world Dutch exposure conditions.

2. Refinement of microbial growth modelling

   Modelling approaches to estimate growth parameters (lag phase (λ), specific growth rate (μ), and maximum population density (N_{max})) were reviewed (Van der Vossen-Wijmenga et al., 2025). Their influence on risk varies with temperature, storage duration and product characteristics.

   - **Lag phase** (λ) is the time needed for microorganisms before starting exponential growth, which is relevant when microorganisms are stressed due to environmental changes. Including λ in QMRA can strongly reduce estimated illness cases, but current λ distributions may overestimate its impact, because they often rely on non–cold-adapted cultures and often do not account for environmental shifts. Although some modelling approaches exist, limited data on the effects of consecutive environmental changes and knowledge of the physiological state of the contaminants hinder accurate integration of λ in QMRA.

   - **Specific growth rate** (μ) is often modelled using the Ratkowsky relation, which assumes a linear relationship between $\sqrt{\mu}$ and temperature. Analyses showed that deviations from linearity at low temperatures could impair μ_{ref} estimation. Near the lower growth limit, small discrepancies between observed and predicted μ can disproportionately increase estimated μ_{ref} values, which in turn propagate to higher predicted growth rates, microbial concentrations, and QMRA outcomes. Variability associated with $\sqrt{\mu}$ can be incorporated in two ways: (i) by adding normally distributed variability to $\sqrt{\mu}$, assuming homoscedastic errors, or by (ii) modelling μ_{ref} as lognormally distributed, which introduces heteroscedastic variability that increases with temperature. Both methods affected QMRA outcomes differently, depending on storage conditions and proximity to growth limits.

   - **Maximum population density** (N_{max}) plays a key role in QMRAs involving *L. monocytogenes*. Overestimating N_{max} can inflate risk estimates, especially when spoilage microbiota suppresses pathogen growth. While some models apply corrective factors to avoid unrealistic outcomes, variability

in background microbiota remains a challenge for accurate implementation.

3. Hazard characterization and dose-response modelling

   Dose–response modelling strongly influences QMRA outcomes, and incorporating variability in key parameters such as the dose-response parameter *r*, rather than using fixed values, can substantially increase predicted illness cases, underscoring the need for careful parameter selection. Because available epidemiological and outbreak data for certain pathogens (e.g., *L. monocytogenes*) are limited, relying on a single dose–response model may reduce robustness. A recent probabilistic approach that combines multiple dose–response models and represents uncertainty across their estimates can provide a more realistic range of risk predictions and helps assess the impact of model choice on QMRA conclusions (Stathas et al., 2024).

4. Use of experimental data combined with literature to strengthen exposure modelling

   In the *Campylobacter* study, cross-contamination transfer rates from raw chicken to cucumber were experimentally quantified. Because transfer experiments differ greatly in setup and are influenced by factors such as initial contamination and contact time, these rates were combined with selected literature distributions (following Iulietto and Evers, 2023). In the QMRA, random samples from both sources - our own experiments and the literature - were drawn in each iteration, allowing transfer-related uncertainty to be explicitly quantified and providing a more robust parameter basis.

5. Accurately estimating the annual number of cases and its variance

   In contrast with many risk assessments, the QMRA was extended from the risk per serving and its variability to the actual public health impact by determining the number of illness cases, further extending the approach of Abe et al. (2023). Two approaches for estimating annual illness cases were compared. In the arithmetic-mean approach, the average risk per serving obtained from a 1,000,000-iteration @RISK simulation was multiplied by the total annual number of servings. This entire procedure was repeated 50 times, each time generating a new risk-per-serving distribution, resulting in a distribution of yearly case estimates that reflects between-simulation variability. In the Bernoulli-based approach, a 1,000,000-iteration risk-per-serving distribution was generated, with each iteration represented a serving. Each serving was treated as an independent Bernoulli trial, resulting in illness or no illness based on the sampled risk per serving. Several risk-per-serving distributions were generated to cover all annual servings. Although this process can be repeated to represent the consumption over the years, it always relies on a risk distribution of 1,000,000 iterations, thereby limiting the variability between

yearly outcomes. While both approaches produced comparable mean annual numbers of illness cases, the arithmetic-mean method resulted in a higher and more realistic standard deviation. By repeatedly generating new risk-per-serving distributions, this approach better captures uncertainty in the underlying risk estimates and increases the probability that rare high-risk outcomes are reflected in the annual case distribution. In contrast, the Bernoulli approach primarily captures within-year stochastic variability and tends to underestimate between-year variability, even when very large numbers of servings are simulated. Ideally, all yearly servings would be simulated within a single run and this process repeated across years to fully represent both sources of variability. However, due to the 1,000,000-iteration limit in @RISK, such an approach was not feasible here. More flexible implementations in R or Python could overcome this limitation. Further work is needed to confirm that the arithmetic-mean approach does not introduce unintended biases.

6.4.3 Sensitivity and scenario analyses

An important goal of a QMRA is to identify parameters affecting the number of illnesses to prioritise risk mitigation strategies. Sensitivity analysis is a valuable tool for identifying the key factors driving risk, as well as the sources of uncertainty in the risk estimate (Zwietering and Van Gerwen, 2000).

1. Deterministic analysis

   For quick screening or to get primary insight, a deterministic approach can be used. This is a simple method that assesses how extreme input values of variables affect the output (e.g., risk per serving). By comparing risks with one variable at a very high or low value (e.g., 95th percentile) and all other variables at their mean, the relative risk reflects the impact of the variability of each variable.

2. Regression / rank correlation

   Tornado charts based on Spearman's rank correlations are commonly used in QMRAs because they identify how variability in individual inputs is associated with the variability in the output (i.e., risk per serving). However, this approach considers inputs independently and does not capture interactions or threshold effects. In addition, it quantifies effects on the risk per serving, which may differ from effects on the number of illness cases (see also Abe et al., 2023). The number of illness cases is mainly determined by the tail of the dose distribution. Certain factors are more influential in this tail and therefore more relevant for the number of cases, while other factors mainly affect other parts of the risk per serving and are less relevant for the tail and the resulting number of cases. In the *L. monocytogenes* study, for example, the influence of the maximum population size (N_{max}) did not appear in the rank correlations, even

though scenario analyses showed that truncation of N_{max} substantially changed the predicted number of illness cases.

Global variance-based sensitivity analysis (GSA) methods, such as Sobol's approach or ANOVA-style variance decomposition, use the actual input values and quantify both main effects and interactions. These methods are suited for nonlinear QMRA models where parameter interactions play an important role. Samiotis (2025) evaluated the QMRA used in the *L. monocytogenes* study, demonstrating that Sobol's sensitivity analysis more robustly identified storage time, temperature, and N_{max} as key drivers. Further work is needed to confirm this approach, for example by applying global variance-based sensitivity analysis to QMRAs for other pathogens, such as *Campylobacter* spp.

3. Traceability visualisation

   This technique visualises how specific input values contribute to illness cases, improving model transparency. Abe et al. (2023) demonstrated this with a barcode-style display linking illness outcomes directly to input distributions. Plotting illness cases against input values highlights which ranges of factors such as initial contamination, storage time, or refrigerator temperature most strongly determine risk and where interventions may be most effective.

4. Scenario analysis / 'What-if' analysis

   Scenario analysis assesses the impact of alternative scenarios (in which variables are, for example, truncated) on the number of illness cases. It tests structural assumptions and policy-relevant alternatives and clarifies how interventions affect illness cases.

Graphical examples of these sensitivity and scenario analyses are provided in **Figures 3.4 – 3.6** in **Chapter 3** and **Figures 4.5 – 4.7** in **Chapter 4**. The advantages and disadvantages of the different sensitivity and scenario analyses are summarized in **Table 6.1**. While each approach provides useful insights, scenario analysis is particularly powerful because it directly links model structure and policy-relevant interventions to predicted illness cases, thereby offering clear guidance for risk management. However, scenario analysis also depends strongly on how scenarios are defined, which is often subjective and can meaningfully influence results. Developing more systematic and scientifically grounded approaches for scenario selection is therefore an important area for future research. Overall, combining the above-mentioned analyses strengthens QMRA conclusions and supports evidence-based decision-making.

Table 6.1. Comparison of sensitivity and scenario approaches in QMRA

Method	When to use	Advantages	Disadvantages
Deterministic	Quick screening; models with fixed input values; gaining primary insight	Very simple to implement; low computational cost; easy to explain to stakeholders	Ignores interactions between inputs; no variance; choice of extreme value can be subjective
Rank correlation	Monte Carlo samples already available; monotonic relationships expected	Computationally efficient; easy to interpret; identifies influential parameters under monotonicity	Assumes a consistent directional relationship: may miss interactions; Based on risk, less suitable for illness cases
Global variance-based	When quantitative attribution of uncertainty is needed, including interactions	Provides full decomposition of variance; captures non-linear and interaction effects	Computationally higher costs; requires careful sampling strategy; Based on risk, less suitable for illness cases
Traceability visualisation	Exploring how input values relate to illness outcomes; assessing model transparency or structure	Intuitive view of how input ranges affect illness; reveals hidden patterns; identifies intervention points, and is visually accessible.	Does not quantify variance; may be misinterpreted as causal; depends on sampling density and visual interpretation
Scenario analysis / "What-if"	Exploring structural assumptions; testing policy or management alternatives	Useful for decision-making; intuitive and easy to communicate; highlights practical implications of uncertainty	Does not quantify contribution of variability; choice of scenarios can be subjective

6.4.4 Choosing appropriate risk metrics

Selecting risk metrics that are both scientifically meaningful and accessible to end-users is crucial. International organisations such as the World Health Organization (WHO), the Food and Agriculture Organization of the United Nations (FAO), and the European Food Safety Authority (EFSA) emphasise that QMRA results must be translated into clear, actionable public health insights and presented in a transparent, accessible manner (WHO and FAO, 2016; EFSA, 2021). This includes providing context, such as comparisons with other risks, to support informed

decision-making and improve the effectiveness of risk communication. Risk can be expressed in multiple forms (e.g., probability of illness per serving, annual risk, lifetime risk, or population-level burden). For policymakers, annual illness cases are generally the most intuitive. This measure is easier to interpret than probabilities per serving and aligns closely with how public health targets and regulatory performance are evaluated. The severity of different illnesses can largely vary, and diseases can have also various end-points. DALYs (Disability-Adjusted Life Years) can integrate all the different outcomes and then provide broader public-health context and facilitate comparison across risks. A next approach could be cost-effectiveness indicators, helping most feasible interventions. Clear visualisations, such as graphs, charts, and side-by-side risk comparisons, help make complex quantitative information more accessible to both expert and non-expert audiences. In summary, while multiple risk metrics exist, combining annual illness cases with DALYs and transparent visual communication provides the most robust and user-friendly basis for risk management decisions and stakeholder communication. In **Table 6.2** some examples are provided on how risks can be expressed and their applications for consumers, policy makers and risk assessors, based on the *Campylobacter* study (**Chapter 4**). It illustrates that different risk metrics may be relevant to different stakeholders, as well as to different decisions within a single stakeholder group.

6.4.5 Uncertainties, limitations and reflections on the use of models

Despite the strengths of the models developed in this thesis, several uncertainties and limitations remain that may affect the interpretation of the results. Dose–response models, especially for *L. monocytogenes*, are sensitive to assumptions regarding population susceptibility and strain virulence, and current data availability limits the refinement of these parameters. This may lead to either over- or underestimation of absolute risk levels. Behavioural data, although extensive, largely rely on self-reported practices and may not fully reflect real household routines. Social desirability bias may have resulted in an overestimation of safe practices, potentially leading to an underestimation of actual risk. Complementary observational studies could improve accuracy, but these pose practical or ethical challenges and are difficult to conduct at scale without introducing bias. In the *Campylobacter* QMRA, transfer rates varied substantially across literature sources, and experimental conditions may not fully capture the variability of domestic kitchen environments or the actual status and location of *Campylobacter* on food contact surfaces. This variability introduces structural uncertainty into cross-contamination estimates and may affect the relative contribution of different transmission routes. Furthermore, the exclusion of certain transmission pathways, such as environmental contamination, may contribute to an underestimation of the total risk. Explicit acknowledgement and documentation of these assumptions are essential, as they represent important sources of uncertainty in the final estimates.

Table 6.2. Examples of different types of risk metrics and their applications for consumers, policy makers and risk assessors, based on the *Campylobacter* study (**Chapter 4**)

Risk per serving	Example: *"The risk of getting ill from Campylobacter from consuming one serving of chicken is 1 in 18,000"* Consumers: Shows the safety of a product for a single consumption, though very small per-serving risks may be considered trivial. Policy makers: Less relevant, as it does not reflect population-level risk. Risk assessors: Useful for evaluating specific foods, benchmarking, and identifying high-risk items for targeted interventions.
Illness cases per year	Example: *"In the Netherlands, approximately 42,000 cases of campylobacteriosis occur each year as a result of chicken consumption."* Consumers: Useful in media to illustrate risk, especially when compared to familiar risks. Policy makers: Helps prioritise policies, evaluate food safety measures, and support benchmarking. Risk assessors: Provides population-level insights and estimates disease burden. Cases per 100,000/year can be helpful for international comparison.
Risk per year	Example: "*A consumer in the Netherlands has a 1 in 380 chance of contracting campylobacteriosis each year from consuming chicken."* Consumers: Helps understand personal annual risk. Policy makers: Useful for evaluating the impact of interventions, such as reducing contamination levels. Risk assessors: Allows assessment of risks over time and comparison across food products or interventions.
Risk per lifetime	Example: "*People who consistently consume undercooked chicken are likely to experience Campylobacter infection about twice over an 85-year lifetime."* Consumers: Shows lifetime likelihood of foodborne illness, linking risk to severity for actionable messages. Policy makers: Supports long-term strategic planning, especially for chronic effects. Risk assessors: A way to model cumulative risk, especially for long-term exposures.

Redondo et al. (2025a) provide a clear example of good practice by systematically documenting uncertainties and their influence on model outcomes, demonstrating how structured transparency enhances interpretability and supports more informed decision-making.

Beyond technical aspects, it is important to reflect on the broader role of mathematical models. Models do not simply reproduce reality; they are constructed through choices about which variables to include, which assumptions to adopt, and how to treat uncertainty. These decisions are shaped by data availability, disciplinary conventions, and sometimes implicit value judgements. For instance, including certain parameters, such as lag phase (λ) or maximum population density (N_{max}), strongly influence the outcome. Similarly, choosing between homoscedastic or heteroscedastic variability can meaningfully shift outcomes, underscoring the need for transparency and critical engagement with modelling choices (as also discussed in **Section 6.4.2**).

Model outputs also shape the realities in which they are used. In this thesis, the QMRAs tended to generate higher illness estimates than those observed in epidemiological data (like more often found in QMRAs), which may reflect conservative assumptions, uncertainties in input parameters, underestimated immune effects or underreporting in surveillance systems. This illustrates that the purpose of QMRA is not to predict exact illness counts, but to assess the relative influence of key inputs, explore scenario outcomes and identify effective interventions. This distinction is crucial for policymaking. Risk assessments can guide decision-making by identifying priorities and knowledge gaps, but their results must always be interpreted within context. As Jacobs and Meester (2023) emphasise, model-based policy can falter not because a model is "wrong," but because its conditional assumptions and uncertainties are insufficiently acknowledged in decision-making. Their analysis of COVID-19 modelling illustrates how scenario-based projections, which are intended to explore possible futures under specific assumptions, can be mistakenly interpreted as precise forecasts. This misinterpretation can mask the substantial uncertainties inherent in the models and lead to overly rigid interventions that leave little room for adaptation as new evidence emerges. Models thus serve as structured reasoning tools rather than definitive representations of reality. Hence, effective use of QMRA requires explicit recognition of substantial uncertainties, transparency about assumptions, ongoing critical evaluation, and flexibility as new evidence emerges. When approached in this way, models can meaningfully contribute to robust, evidence-informed decision-making in food safety.

Implications for policy, risk communication, and research:

- ❖ Policy considerations: Use QMRA evidence to target interventions where they are most effective, e.g., upstream controls for *Campylobacter* in raw chicken and consumer-focused measures for *L. monocytogenes* in ready-to-eat foods, especially for vulnerable populations.
- ❖ Communication efforts: Translate QMRA outcomes into clear, policy-relevant risk metrics (e.g., annual illness cases and DALYs), supported by transparent and accessible visualisations, to facilitate correct interpretation and informed decision-making by policymakers and other stakeholders.
- ❖ Priorities for future research: Further improve QMRA robustness by enhancing the quality of key input data and systematically integrating advanced sensitivity and scenario analysis methods to better characterise uncertainty and support risk-based decisions.

6.5 Risk communication

Risk communication is a core component of food safety risk analysis and involves the exchange of information and opinions among risk assessors, managers, consumers, and other stakeholders (WHO and FAO, 2016; EFSA, 2021). Its aim is to provide clear, trustworthy, and actionable information that supports transparent decision-making and strengthens public confidence. Effective communication must therefore account not only for scientific evidence but also for public perceptions, values, and practical concerns.

6.5.1 Public perception and the role of information environments

Public perception plays a defining role in shaping food safety understanding and behaviour (see **Chapter 2** and **5**). In recent years, Dutch authorities, WHO, and media have intensified communication on the importance of a healthy diet, contributing to the growing perception that dietary imbalance is the most important food-related risk. At the same time, consumers often judge chemical hazards, such as microplastics or PFAS, as more harmful than microbiological ones, despite pathogens like *Campylobacter* and *Salmonella* causing far higher disease burden (Havelaar et al., 2015; Van Kreijl et al., 2006). Media, and especially social media, strongly influence these perceptions. Clear, transparent explanations from trusted experts can help reduce exaggerated risk perceptions; however, persistent scepticism toward technologies such as irradiation and genetically modified (GM) foods continues to influence how people assess their safety (Mazuki et al., 2025; Zhang et al., 2022). EFSA's 2024 roadmap further highlights misinformation as a major challenge, calling for proactive monitoring, rapid correction of false claims, and audience-specific materials (EFSA, 2024). These insights underline that risk communication cannot rely solely on

disseminating facts: messages must be relatable, tailored, and supported by trusted voices to build understanding and trust (Onyeaka, 2025).

6.5.2 Risk acceptance and regulatory asymmetry

The way food safety risks are perceived is not only a communication issue, but is also embedded in regulatory frameworks that define which risks are considered acceptable. The concept of Appropriate Level of Protection (ALOP) describes the amount of risk a regulator considers acceptable (EC, 2005; WTO, 1995). In practice, this level is often operationalised through specific regulatory targets or limits, which may differ between microbiological and chemical hazards. Microbiological criteria are process-based and feasibility-driven, without an explicit quantitative public-health target such as a maximum number of illness cases or DALY threshold (CAC, 2007b; EC, 2005). In the absence of an explicit public-health target, the existing regulatory framework (e.g., a process hygiene criterion for *Campylobacter* spp. on broiler carcasses) may be regarded as reflecting an implicitly defined ALOP, unless a specific new target is defined (EFSA, 2007; Gkogka, 2019; Zwietering et al., 2023). Chemical hazards are assessed using health-based guidance values such as the Acceptable Daily Intake (ADI), Tolerable Daily Intake (TDI) and Acute Reference Dose (ARfD) (EFSA, 2012). In risk management, exposure to chemical contaminants is generally minimised according to the ALARA principle (As Low As Reasonably Achievable) (EC, 2023). For certain hazards, particularly genotoxic carcinogens for which no safe threshold can be established, the Margin of Exposure (MOE) approach is applied, comparing estimated human exposure with doses causing adverse effects in toxicological studies. An MOE of 10,000 or higher - indicating exposure at least ten thousand times lower than effect levels - is typically considered of low concern for public health. In practice, exceedance of such benchmarks may render food “unsafe”, reflecting a framework characterised by very low tolerance for residual risk. Consequently, chemical hazards are subject to highly restrictive regulatory control, even though their current contribution to the overall burden of food-related disease is relatively limited. This asymmetry is illustrated in **Figure 6.3**, which conceptually positions chemical food risks, microbiological food risks, and unhealthy diet according to the level of personal influence involved in risk management (x-axis) and the level of regulation applied (y-axis). Circle size reflects the current contribution of each risk domain to population-level disease burden, expressed in disability-adjusted life years (DALYs) (Van Kreijl et al., 2006). It should be noted that the observed disease burden of both chemical and microbiological food risks partly reflects the effects of existing regulatory control. However, **Figure 6.3** is not intended to assess regulatory effectiveness, but to illustrate how regulatory intensity relates to perceived controllability and the allocation of responsibility, rather than to disease burden alone. The figure highlights that unhealthy diet accounts for a substantial share of the disease burden, yet is predominantly addressed through low-restriction, information-based

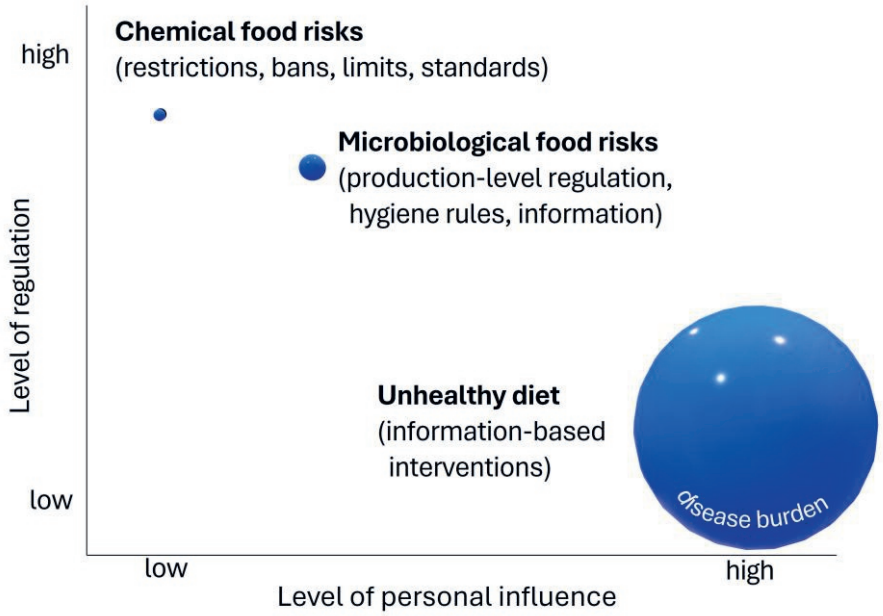


Figure 6.3. Conceptual positioning of food-related risk domains by level of personal influence (x-axis) and level of regulation (y-axis). Circle size reflects the current population-level disease burden (DALYs; data from Van Kreijl et al., 2006).

interventions that place primary responsibility on individual choice. In contrast, chemical food risks are managed through highly restrictive regulation, with minimal reliance on individual behaviour. Microbiological food risks occupy an intermediate position: while risks are regulated at the production and processing level, residual risks remain and are partly managed through consumer behaviour, supported by hygiene requirements and information measures. Taken together, these patterns suggest that regulatory intensity is shaped less by the magnitude of disease burden than by perceptions of risk controllability and responsibility. Invisible and technical risks that are perceived as beyond individual control, such as chemical contaminants, tend to elicit low tolerance for risk and high regulatory stringency, even when their public health impact is relatively small (Slovic, 1987; Frewer et al., 2007). By contrast, risks associated with everyday behaviours, including diet-related risks and foodborne infections, tend to be more socially tolerated, despite their much larger contribution to disease burden. Importantly, the level of personal influence is often perceived to be higher than it actually is, particularly for dietary behaviour, where choices are strongly shaped by the food environment (Dixon et al., 2021). From a disease-burden perspective, one might intuitively expect risks with higher DALYs to be addressed through more restrictive interventions. **Figure 6.3** illustrates that this is not the dominant organising principle of food safety and nutrition policy. Instead, regulatory responses tend to

rely heavily on communication-based interventions where responsibility is framed at the individual level. This reliance reflects assumptions about rational choice and individual control, rather than the actual distribution of determinants across individuals and their environments. Recognising this asymmetry invites reflection on whether current regulatory approaches are adequately aligned with public health impact, and whether greater emphasis on structural and environmental interventions may be warranted in domains where disease burden is high. Structured decision-support approaches, such as Multi-Criteria Decision Analysis (MCDA), may help make these trade-offs more transparent by considering health impact alongside feasibility, costs, consumer acceptance, behavioural implications, and societal values.

6.5.3 Effectiveness of communication tools and interventions

Risk communication is not limited to raising awareness; it must also support concrete, safe practices. Hygiene warning labels are a practical tool to help bridge this gap by providing actionable information to the consumer at the point of decision-making. Since 2001, raw poultry in the Netherlands has carried a mandatory hygiene warning label, which was revised in 2023 to improve clarity and usability (Warenwet, 2023). The evaluation presented in **Chapter 5** demonstrated high visibility and acceptance of the revised label: 81 % of respondents reported reading it, and most considered it important, useful, and reassuring. A key contribution of this study is the demonstrated association between label exposure and self-reported behaviour, thereby strengthening the link between research evidence and real-world regulatory practice. Consumers who reported reading the hygiene warning label also reported safer food-handling practices, with the strongest motivational effects observed among individuals with initially poorer hygiene behaviours. Moreover, older adults and lower-educated consumers under 65 showed the greatest intention to improve their practices, suggesting that well-designed labels can help reach groups that may be more vulnerable to food safety risks. Evidence from other public health domains, including alcohol and tobacco control, further supports the potential of warning labels, particularly when they are prominently displayed and embedded within broader communication strategies (Ding et al., 2024; Purmehdi et al., 2017; Zuckermann et al., 2024). Applied to food hygiene labelling, this implies that front-of-pack placement and alignment with wider public messaging may enhance their effectiveness. The effect sizes observed in this study were small to moderate, which is consistent with findings from behavioural communication interventions more generally. Systematic reviews show that communication-based approaches tend to yield modest effects at the individual level. While such interventions can successfully increase knowledge and awareness, changes in actual behaviour are often small and can be inconsistent (Young et al., 2016; Charlesworth et al., 2023; ANSES, 2015). Habitual behaviour and perceived risk play a central role in shaping food-handling practices, making sustained behaviour change through information alone

inherently challenging (Charlesworth et al., 2022). These patterns can be partly explained by individual self-regulation: interventions that require people to remember and act on information at a later time, such as mass media campaigns, often have limited influence on routine behaviour (Adams et al., 2016). In this context, hygiene warning labels differ from many other communication tools by delivering information directly at the point of action, thereby reducing cognitive effort and reliance on memory. When implemented at scale and maintained over time, even modest behavioural effects can translate into meaningful public health benefits (ECDC, 2013; Kaiser et al., 2025). The contribution of hygiene warning labels to safe food-handling behaviour is therefore best understood as context-dependent and shaped by design quality and integration with other measures. As part of a broader communication strategy, well-designed warning labels can offer a practical and cost-effective contribution to food safety policy, particularly when implemented in combination with complementary communication and behavioural interventions.

Implications for policy, risk communication, and research:

- ❖ Policy considerations: Use consumer-facing tools (e.g., hygiene warning labels) as part of a broader food safety strategy, recognising shared responsibility between the supply chain and the consumer. Where feasible, prioritise upstream measures that reduce reliance on individual behaviour, and support remaining consumer actions at the point of use.
- ❖ Communication efforts: Focus on simple, actionable guidance delivered in context (e.g., clear on-pack cues), since mass media campaigns alone often rely on high levels of recall and motivation. Address misperceptions about relative risks and tailor messages to groups with lower baseline hygiene practices using trusted and consistent sources.
- ❖ Priorities for future research: Strengthen evidence on the long-term, real-world effects of labels and campaigns on observed behaviour, and on how combined approaches (labels plus wider messaging and upstream controls) work in practice, including their feasibility and acceptability.

6.6 Concluding remarks and future perspectives

This thesis demonstrated that the domestic kitchen environment is a critical setting for foodborne illness and that consumer behaviour, shaped by risk perception, communication and practical constraints, plays a central role in determining risk. By integrating behavioural data, risk perception studies and quantitative microbiological risk assessments (QMRA), this thesis demonstrated how QMRA can be used to link everyday consumer routines to real-world health outcomes, providing a more holistic understanding of foodborne risk. Looking ahead, strengthening evidence-based food safety policy will require progress on several fronts: improving behavioural data through harmonized surveys and objective measurements; further advancing QMRA methodology, including more comprehensive sensitivity analyses, improving dose–response modelling, and systematic scenario development; and strengthening risk communication to a changing information environment by addressing common risk misperceptions through clear communication of relative risks, complemented by practical guidance and well-designed cues to action such as warning labels, particularly for vulnerable groups. Effective risk communication, grounded in sound science and responsive to public perceptions, is essential to connect these perspectives. Increasing variability in susceptibility due to an ageing population living independently, and increasing diversity in receptivity and behaviour further reinforce the need to integrate microbial and behavioural factors into QMRA and consumer risk communication. Together, these integrated approaches provide the evidence base needed to support lasting improvements in public health through both technical and communication interventions.

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Appendix

Abstract

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A

Abstract

Access to sufficient, safe, and nutritious food is essential for sustaining life and promoting health. Ensuring food safety across the entire chain, from farm to fork, remains a major challenge. This thesis examined the role of consumers in microbiological food safety through an interdisciplinary approach that integrated consumer behavioural insights with Quantitative Microbiological Risk Assessment (QMRA), thereby bridging science and practice in the prevention of foodborne illness. Consumer surveys conducted from 2009 to 2024 revealed shifting perceptions of food-related risks. Consumers identified an unhealthy diet as the main food risk from 2018 onwards, whereas experts did so consistently and more strongly. Concerns about chemical risks, such as environmental contaminants, increased over time, particularly among consumers, who rated these risks higher than experts. Empirical studies on domestic food handling and storage identified critical food safety risk factors in the home environment. By incorporating these behavioural data into QMRA, the most influential determinants of risk for two key foodborne illnesses, listeriosis and campylobacteriosis, were identified and quantified. Complementary probabilistic modelling and sensitivity and scenario analyses enhanced the robustness of the assessments, and expressing outcomes in annual illness cases increased relevance for policy and risk management. While upstream reduction of initial contamination remains essential, consumer-level practices can substantially lower the number of illness cases. For listeriosis, limiting storage to less than 7 days or below 7 °C reduced predicted illness cases by more than 80 %, a finding particularly relevant for the elderly. For campylobacteriosis, thorough cooking of chicken emerged as the most effective home-based intervention, even despite high levels of self-reported compliance, with additional risk reduction achieved by preventing cross-contamination. To support these behaviours, the mandatory icon-based hygiene warning label on poultry packaging showed potential to encourage safer food-handling practices, particularly among higher-risk groups, and was perceived as more useful than the previous text-only version. Overall, this thesis demonstrated how an integrated, data-driven approach that connects risk perception, behaviour, and quantitative risk assessment can strengthen evidence-based risk communication and support more targeted food safety interventions, thereby contributing to improved food safety and public health.

Summary

Safe food is a fundamental prerequisite for good health. In the Netherlands, as in many other countries, food safety is often perceived as primarily the responsibility of government and the food industry. However, many foodborne infections occur in the home, during storage, preparation, and consumption of food. These are not rare events: in the Netherlands, nearly one person becomes ill from contaminated food every minute. Yet on an individual level, such illness occurs only a few times in a lifetime. This difference in perspective influences how consumers perceive and prioritize food safety. This thesis focuses on the role of consumers in microbiological food safety. Quantitative microbiological risk assessment (QMRA) was used to translate consumer behaviour into quantitative estimates of bacterial intake through food and the associated risk of illness. The research is characterized by its interdisciplinary approach, integrating insights from consumer behaviour, microbiology, and risk communication instead of studying these disciplines separately. The findings demonstrate that microbiological food safety is both a technical and behavioural issue, with consumer behaviour playing a decisive role in risk assessment outcomes. Consumers make daily decisions about food storage duration, refrigerator temperature, cooking practices, and kitchen hygiene. Although these choices may seem minor, they can significantly affect the growth, survival, and transmission of pathogenic bacteria. At the same time, consumers often perceive risks differently from experts. While experts focus primarily on probability and severity of illness, consumers are more influenced by feelings, trust, fear, and visible characteristics of food. The thesis examines food safety from four perspectives: risk perception (**Chapters 2** and **5**), consumer behaviour in the home (**Chapters 3** and **4**), QMRA (**Chapters 3** and **4**), and risk communication (**Chapter 5**). Combining these perspectives provides an integrated understanding of how risks arise, how they are perceived, and how they can be effectively reduced.

Risk perception: what do people consider dangerous?

Consumer research in the Netherlands shows that perceptions of food-related risks have shifted over time. In 2009, unhealthy diets were not considered the most significant food-related health risk by consumers. Today, this perception has changed, and unhealthy diets is now ranked highest, aligning with expert assessments and burden-of-disease data. However, discrepancies remain between consumers and experts regarding other risks. Consumers express relatively high concern about chemical substances in food, such as microplastics, PFAS, and pesticides, whereas experts generally assess these risks as comparatively low. Conversely, consumers tend to underestimate their personal risk of foodborne infections. These differences in perception directly influence consumer behaviour and the effectiveness of risk communication.

Risk behaviour: what happens in the kitchen?

The research shows that knowledge about food safety does not automatically translate into safe behaviour. For example, although many consumers know that food should be refrigerated, measurements revealed that about one-third of Dutch households had refrigerator temperatures of 7 °C or higher, exceeding the recommended 4 °C and promoting bacterial growth. When handling raw chicken, unsafe practices persist, such as washing chicken under the tap or reusing kitchen cloths for multiple days. These behaviours are influenced by habits, convenience, time pressure, and optimistic risk perceptions. Some consumers rely on smell and appearance to assess food safety, even though pathogenic bacteria are invisible. Older consumers were more likely to engage in risky behaviours, including maintaining higher refrigerator temperatures (in some cases up to 17 °C), despite being more vulnerable to severe outcomes of foodborne infections. This increases health risks within this group.

Risk assessment: what is the actual health risk?

A key innovation of this dissertation is the integration of consumer behaviour into QMRA models. Detailed risk models were developed for two major pathogens: *Listeria monocytogenes* in ready-to-eat meat products and *Campylobacter* in raw chicken. These models combine data on contamination levels, bacterial growth and transfer, consumer behaviour, and dose-response relationships to estimate the number of illness cases at the population level, explicitly accounting for variation between consumers and situations. Results, based on millions of simulations, show that the impact of consumer behaviour differs by pathogen. For *L. monocytogenes*, storage time and refrigerator temperature are critical because the bacterium can grow at low temperatures. Limiting storage to no more than seven days and/or maintaining temperatures below 7 °C could reduce listeriosis cases by more than 80 %, particularly benefiting vulnerable groups such as the elderly and pregnant women. For *Campylobacter*, thorough cooking of chicken is the most important control measure at home, although over 90 % of consumers report doing this consistently. Preventing cross-contamination, such as using separate cutting boards for raw chicken and other foods, can further reduce risk. Reducing contamination earlier in the food chain also remains essential. Sensitivity and scenario analyses were important to identify which factors most strongly influence health risk. Expressing risk in terms of annual illness cases proved more useful for policy evaluation than measures such as “risk per meal,” which are less suitable for scenario comparisons. However, for personal risk perception, metrics such as risk per meal, per year, or per lifetime may be more meaningful.

Risk communication: how can consumers be reached?

Effective risk communication is essential but complex. Its impact depends not only on message content but also on presentation and timing. Trustworthy and recognizable sources enhance message uptake. Communication is particularly effective when it connects directly to everyday actions. An example is the hygiene warning label on raw chicken packaging. The revised label introduced in 2023, which includes pictograms and is mandatory in the Netherlands, was better understood and more frequently read than the previous text-based label. It was especially effective among older consumers, lower-educated individuals, and individuals who initially reported less hygienic practice. This is beneficial, as these groups are particularly vulnerable. These findings highlight the importance of simple, clear, and visually supported communication that aligns with consumers' daily routines.

Conclusion

This dissertation demonstrates that food safety is determined by the interaction between human behaviour and microbiological processes. By combining behavioural science with quantitative risk modeling, it becomes possible not only to identify which consumer choices affect the risk of foodborne infections, but also to quantify their impact. The results provide concrete directions for targeted policy measures, more effective risk communication, and future research. This integrated approach contributes to evidence-based, behaviourally informed food safety policy aimed at reducing foodborne infections and improving public health.

Samenvatting

Veilig voedsel is een basisvoorwaarde voor een goede gezondheid. In Nederland, net als in veel andere landen, wordt voedselveiligheid vaak gezien als iets dat vooral wordt geregeld door de overheid en de voedselindustrie. Toch vinden veel voedselinfecties plaats in de thuissituatie, tijdens het bewaren, bereiden en consumeren van voedsel. Daarbij gaat het niet om uitzonderingen: in Nederland wordt bijna elke minuut iemand ziek door besmet voedsel. Voor mensen persoonlijk gebeurt dit echter maar een paar keer in hun leven. Dit verschil in perspectief beïnvloedt hoe consumenten voedselveiligheid ervaren en prioriteren. Dit proefschrift richt zich op de rol van de consument in de microbiologische voedselveiligheid. Daarbij werd kwantitatieve microbiologische risicobeoordeling (QMRA) ingezet om consumentengedrag te vertalen naar concrete schattingen van de hoeveelheid bacteriën die mensen via voedsel binnenkrijgen en het risico op ziekte. Het onderzoek onderscheidt zich door het samenbrengen van kennis uit verschillende vakgebieden, waarbij inzichten uit consumentengedrag, microbiologie en communicatie in samenhang in plaats van afzonderlijk werden bekeken. Het proefschrift laat zien dat microbiologische voedselveiligheid zowel een technisch als een gedragsmatig vraagstuk is, waarbij consumentengedrag een bepalende invloed heeft op uitkomsten van microbiologische risicobeoordelingen. Consumenten maken dagelijks keuzes over voedsel: hoe lang producten worden bewaard, op welke temperatuur de koelkast staat, hoe het eten bereid wordt en hoe hygiënisch er wordt gewerkt in de keuken. Deze keuzes lijken onbeduidend, maar kunnen grote gevolgen hebben voor de groei, overleving en overdracht van ziekteverwekkende bacteriën. Tegelijkertijd blijken consumenten risico's vaak anders in te schatten dan experts. Waar deskundigen vooral kijken naar de kans op ziekte en de ernst van de gevolgen, laten consumenten zich meer leiden door gevoel, angst, vertrouwen en uiterlijke kenmerken. Het onderzoek in dit proefschrift benadert voedselveiligheid vanuit vier verschillende invalshoeken: risicoperceptie (**Hoofdstuk 2 en 5**), consumentengedrag in de thuissituatie (**Hoofdstuk 3 en 4**), kwantitatieve microbiologische risicobeoordeling (QMRA; Hoofdstuk 3 en 4) en risicocommunicatie (**Hoofdstuk 5**). Door deze invalshoeken te combineren ontstaat een integraal beeld van hoe risico's ontstaan, hoe ze worden ervaren en hoe ze effectief kunnen worden beperkt.

Risicoperceptie: wat vinden mensen gevaarlijk?

Consumentenonderzoek in Nederland laat zien dat de perceptie (het beeld dat mensen hebben) van voedselgerelateerde risico's in de afgelopen jaren is veranderd. Daarbij gaat het onder meer om risico's zoals voedselinfecties, ongezonde voeding en de aanwezigheid van chemische stoffen in voedsel, waaronder bestrijdingsmiddelen, microplastics en PFAS. In 2009 werd ongezonde voeding door consumenten nog niet gezien als het grootste voedselgerelateerde gezondheidsrisico. Inmiddels is dit beeld duidelijk verschoven en staat ongezonde

voeding ook bij consumenten bovenaan, in lijn met de inschatting die experts al jarenlang maken. Dit sluit aan bij cijfers over ziektelast, waaruit blijkt dat ongezonde voeding een veel grotere bijdrage levert aan gezondheidsproblemen dan voedselinfecties of chemische verontreinigingen. Tegelijkertijd blijft er een duidelijke kloof bestaan tussen consumenten en experts in de beoordeling van andere voedselgerelateerde risico's. Consumenten maken zich relatief veel zorgen over chemische stoffen in voedsel, zoals microplastics, PFAS of bestrijdingsmiddelen, terwijl experts deze risico's voor de gezondheid doorgaans veel lager inschatten. Omgekeerd onderschatten consumenten vaak hun eigen risico op voedselinfecties. Deze verschillen in risicoperceptie zijn relevant, omdat zij direct van invloed zijn op consumentengedrag en op de effectiviteit van risicocommunicatie.

Risicogedrag: wat doen mensen in de keuken?

Het proefschrift laat zien dat kennis over voedselveiligheid niet automatisch leidt tot veilig gedrag. Veel consumenten weten bijvoorbeeld dat voedsel gekoeld moet worden bewaard, maar in de praktijk bleek een aanzienlijk deel van de koelkasten warmer te staan dan de aanbevolen temperatuur van 4 °C. Metingen toonden aan dat ongeveer een derde van de huishoudens een koelkasttemperatuur had van 7 °C of hoger, wat de groei van bepaalde bacteriën sterk kan bevorderen. Ook bij het omgaan met rauwe kip spelen gewoonten en routines een grote rol. Hoewel de meeste mensen aangaven kip goed te doorbakken, bleken minder veilige praktijken nog steeds voor te komen, zoals het wassen van rauwe kip onder de kraan of het meerdere dagen achter elkaar gebruiken van dezelfde keukendoekjes. Deze gedragingen worden beïnvloed door tijdsdruk, gemak, gewoontegedrag en een optimistische inschatting van risico's. Daarnaast vertrouwen sommige mensen bij kip op geur en uiterlijk, terwijl ziekmakende bacteriën onzichtbaar zijn. Beide onderzoeken laten zien dat vooral oudere consumenten vaker risicovol gedrag vertoonden, zoals een hogere koelkasttemperatuur (met uitschieters tot wel 17 °C), terwijl zij tegelijkertijd tot de kwetsbaardere groepen behoren als het gaat om voedselinfecties. Dit vergroot het gezondheidsrisico voor deze groep.

Risicobeoordeling: wat is het werkelijke gezondheidsrisico?

Een belangrijk vernieuwend element van dit proefschrift is de koppeling van consumentengedrag aan kwantitatieve microbiologische risicoanalyse (QMRA). Voor twee belangrijke ziekteverwekkers, namelijk *Listeria monocytogenes* in vleeswaren zoals ham en *Campylobacter* in rauwe kip, zijn gedetailleerde risicomodellen ontwikkeld. Deze modellen combineren gegevens over besmettingsniveaus, bacteriegroei en overdracht, consumentengedrag en dosis-responsrelaties om het aantal ziektegevallen in de bevolking te schatten, waarbij verschillen tussen consumenten en situaties expliciet zijn meegenomen. De resultaten, gebaseerd op miljoenen doorrekeningen, laten zien dat het effect van consumentengedrag sterk verschilt per bacterie. Bij *Listeria monocytogenes*

spelen bewaartijd en koelkasttemperatuur een cruciale rol, omdat deze bacterie kan groeien bij lage temperaturen. De berekeningen lieten zien dat het aantal listeriosegevallen met meer dan 80 % kon worden verminderd door producten niet langer dan 7 dagen te bewaren of onder 7 °C te koelen. Dit is vooral van belang voor ouderen, zwangeren en andere kwetsbare groepen. Voor *Campylobacter* is het goed doorbakken van kip de belangrijkste maatregel in de thuissituatie, ook al geeft meer dan 90 % van de consumenten aan dit (bijna) altijd te doen. Het risico kan verder worden verlaagd door kruisbesmetting te voorkomen, bijvoorbeeld door rauwe kip en andere producten niet op dezelfde snijplank te bereiden. Daarnaast blijft het belangrijk om besmetting van kip al eerder in de voedselketen te verminderen. Een belangrijke bevinding was dat het combineren van verschillende gevoeligheidsanalyses en scenarioanalyses nodig bleek om te bepalen welke factoren en maatregelen het meeste effect hebben op het gezondheidsrisico. Deze analyses lieten zien welke aspecten, zoals bewaartijd, temperatuur of besmettingsniveau, het risico het sterkst beïnvloeden en wat er gebeurt in herkenbare 'wat-als'-situaties. Door risico's uit te drukken in het aantal ziektegevallen per jaar wordt duidelijk waar maatregelen de meeste gezondheidswinst opleveren en waar inzet het meest effectief is. De maat 'kans per maaltijd' is daarvoor minder geschikt, omdat deze minder goed aansluit bij beleidsvragen en het vergelijken van scenario's bemoeilijkt. Voor een persoonlijke inschatting van risico's zijn maten zoals kans per maaltijd, per jaar of per leven juist passender.

Risicocommunicatie: hoe bereik je mensen?

Goede risicocommunicatie is van groot belang om kennis over voedselveiligheid om te zetten in veilig gedrag, maar blijkt in de praktijk complex. Het effect van communicatie hangt niet alleen af van wat er wordt gecommuniceerd, maar ook van hoe dit is vormgegeven en wanneer consumenten ermee in aanraking komen. Betrouwbare en herkenbare afzenders vergroten daarbij de kans dat de boodschap wordt opgepakt. Uit dit proefschrift blijkt dat communicatie vooral effectief is wanneer zij aansluit bij concrete handelingen in het dagelijks leven. Een voorbeeld hiervan is het hygiëne waarschuwingsetiket op rauwe kip, dat consumenten direct bereikt op het moment van aankoop en bereiding. Het onderzoek toonde aan dat het herziene hygiëne waarschuwingsetiket met pictogrammen, dat sinds 2023 verplicht is op alle verpakkingen van rauwe kip, beter werd begrepen en vaker werd gelezen dan het eerdere tekstuele etiket. Vooral bij mensen die minder hygiënisch werken, een lagere basiskennis over keukenhygiëne hebben of ouder zijn, leidde dit tot een sterker voornemen om hun gedrag te verbeteren. Dit is gunstig, omdat deze groepen extra kwetsbaar zijn. Deze resultaten onderstrepen het belang van eenvoudige, duidelijke en visuele communicatie die aansluit bij het dagelijkse handelen van consumenten. Middelen zoals een waarschuwingsetiket kunnen daarbij een waardevolle rol spelen, vooral wanneer het zichtbaar op de voorkant

van de verpakking wordt geplaatst en wordt ingezet als onderdeel van bredere communicatie.

Conclusie

Dit proefschrift laat zien dat voedselveiligheid in belangrijke mate wordt bepaald door het samenspel tussen menselijk gedrag en microbiologische processen. Door gedragswetenschap te combineren met kwantitatieve risicomodellering wordt niet alleen zichtbaar welke keuzes invloed hebben op het risico op voedselinfecties, maar ook hoe groot dat effect is. De resultaten bieden concrete aanknopingspunten voor gerichte beleidsmaatregelen, effectievere risicocommunicatie en toekomstig onderzoek. Daarmee draagt deze geïntegreerde aanpak bij aan beter onderbouwd en meer op gedrag afgestemd voedselveiligheidsbeleid, met als doel voedselinfecties te verminderen en de volksgezondheid te verbeteren.

Dankwoord

'*Iedere reis begint met de eerste stap*.' Die zin schiet me te binnen als ik terugkijk op mijn promotietraject. Een reis die begon vanuit mijn interesse in voeding en mijn wens om daar dieper in te duiken. In mijn werk bij het Voedingscentrum was ik al volop met het onderwerp bezig, maar het academische perspectief bleef trekken. En zo volgde mijn eerste telefoontje met Marcel. Nog wat onwennig, zonder precies te weten wat de mogelijkheden waren, maar wel met veel nieuwsgierigheid. Samen met Heidy schreven wij het eerste projectvoorstel en daarmee was het avontuur echt begonnen. En nu staan we hier, aan het einde van die reis. Dat ik dit punt heb bereikt, had nooit gekund zonder jullie vertrouwen, enthousiasme, betrokkenheid en kennis. Ik heb enorm genoten van de maandelijkse overleggen; ook tussendoor was er altijd tijd om mee te denken en vragen te beantwoorden. Die openheid en het enthousiasme maakten het traject niet alleen leerzaam, maar ook heel leuk. Heel veel dank voor jullie begeleiding. Zonder jullie was dit zeker niet gelukt.

Hoe je het ook wendt of keert, zo'n reis kost veel tijd. Heel veel tijd, die ik voor een groot deel in mijn eigen uren heb gemaakt. Maar gelukkig stond ik daarin niet alleen. Thuis was er altijd steun en begrip. Sander, Thijs en Nynke, dank jullie wel. Zonder jullie was deze reis simpelweg niet te maken geweest. En vanaf nu weer wat minder avonden achter de laptop. Wel zo gezellig!

Maar deze reis had ik ook niet kunnen maken zonder de steun van het Voedingscentrum. Al vanaf het begin werd mijn eerste stap aangemoedigd en ondersteund. Het toenmalige MT – Gerda, Jovanka, Jelle en Margret – en later ook het huidige MT met Petra en Judith gaven mij de ruimte en het vertrouwen om dit traject aan te gaan. Daarnaast waren er financiële mogelijkheden om externe congressen te bezoeken, wat voor mij enorm waardevol was. Heel veel dank daarvoor. Ook dank aan Corné, die met zijn eigen promotietraject bij het Voedingscentrum liet zien dat dit daadwerkelijk mogelijk is en daarmee het pad alvast een beetje effende.

Dit onderzoek heb ik uiteraard niet alleen uitgevoerd. Veel dank aan Isabel van Winkoop en Aniek Heijthuijzen voor alle metingen aan koelkasten bij mensen thuis. Ook dank aan Hiske Poot, Mounira Tarnich, Ilse van 't Leven en Akksadha Murugesan voor hun inzet in het laboratorium. Het was geen eenvoudige opgave om de lastige bacterie *Campylobacter* goed mee te laten werken in het laboratorium. Dit had dan ook niet gekund zonder de deskundige begeleiding van Wilma Hazeleger. Je enorme kennis en ervaring op dit gebied waren daarbij ontzettend waardevol. Dankjewel daarvoor. Ook het samen begeleiden van studenten was leuk; het blijft motiverend om jonge mensen te helpen weer een stap verder te komen. Des te leuker is het om hen later in je werk weer tegen te komen en te zien waar ze terecht zijn gekomen.

A

Ook veel dank aan James Ssemanda, die mij wegwijs maakte in @Risk en mij hielp om de mogelijkheden van het programma steeds beter te benutten. Cristina Serra-Castelló, dank voor je waardevolle hulp bij het schrijven van onze publicatie. Het was heel fijn om daarbij gebruik te kunnen maken van jouw kennis en ervaring en samen tot een mooi eindresultaat te komen.

Daarnaast is er veel consumentenonderzoek uitgevoerd. Dank aan Flycatcher voor de begeleiding en ondersteuning hierbij, en aan collega's zoals Wouter en Liesbeth, met wie we de inhoud van deze onderzoeken verder hebben vormgegeven. Met veel plezier heb ik samengewerkt met mijn collega's Tara en Pascalle, met wie ik het onderzoek naar voedselrisico's verder uitdiepte. Deze samenwerking resulteerde bovendien in een prachtig artikel in NRC, 'Niet alles wat je met metingen in voeding vindt, is een risico'. Ook dank aan Ingeborg en Mariëtte, die zo enthousiast met mij hebben meegedacht over een mooie cover. En Lidy, Sophie en Daniëlle, dank voor de fijne momenten waarop we tijdens ons overleg even konden sparren. Die momenten hielpen mij om mijn gedachten weer wat beter op een rij te zetten.

Statistiek is en blijft een essentieel onderdeel van onderzoek en ook daarin heb ik veel moeten bijleren. In het bijzonder denk ik terug aan de cursus *Toegepaste statistiek* met Susanne Westenbrink. Zij werkte aan een promotietraject dat zij helaas niet zelf kon afronden. Tijdens mijn eigen promotietraject heb ik regelmatig aan haar en haar onderzoek gedacht. Ook dank aan Eric Boer, die mij verder heeft geholpen met de statistiek wanneer het echt lastig werd.

Dank ook aan mijn zussen, Rudie en Richtje, die mij tijdens mijn verdediging bijstaan. Het is jammer dat mijn vader (ús heit) dit niet meer kan meemaken en dat mijn moeder (ús mem) zich hier nu niet meer voldoende bewust van is. Juist daarom is het zo waardevol om zussen te hebben die altijd naast je staan.

En tot slot wil ik nog even stilstaan bij de wetenschap. Na mijn afstuderen koos ik bewust voor de praktijk en het bedrijfsleven, en niet voor een promotietraject. Toch werd ik in die periode wel onderdeel van een promotietraject - niet als onderzoeker, maar als patiënt. Ruim een jaar na mijn afstuderen kreeg ik de diagnose non-hodgkinlymfoon (lymfeklierkanker). In het UMC Groningen nam ik deel aan een medische trial, waarbij ik naast chemotherapie ook een stamceltransplantatie onderging. Een heel zwaar traject, voor mij en voor mijn naasten. Maar gelukkig met een goede afloop. Enkele jaren later promoveerde mijn behandelend arts, dr. Van Imhoff, mede op deze behandeling (Van Imhoff, 2007). Ik kan dus met recht zeggen dat ik heel veel te danken heb aan de wetenschap. En ik ben dan ook enorm dankbaar en trots dat ik nu, vele jaren later en op mijn eigen manier, zelf ook een bijdrage aan de wetenschap heb mogen leveren.

Ta beslút, lykas wy yn Fryslân sizze: tige tank.

About the author



Wieke van der Vossen-Wijmenga was born on March 6, 1974, and grew up in the village of Garyp in Fryslân, the Netherlands. Growing up in a rural area with close connections to food production contributed to her early interest in food. After completing secondary school, she moved to Wageningen to study Food Technology, specializing in food microbiology and toxicology.

She began her professional career in the animal feed sector, contributing to the development of HACCP systems following major food safety incidents in the 1990s. She subsequently worked in the pharmaceutical industry, assessing changes in production processes, before returning to the food sector as Head of Quality and Laboratory at McCain Foods. In this role, she gained experience in large-scale food production, team leadership, and the organizational and societal impact of food safety incidents. She also worked for several years as a lead assessor in the food industry.

Since 2010, Wieke has worked at the Netherlands Nutrition Centre (Voedingscentrum), focusing on food safety knowledge development and public communication. In this role, she acts as a spokesperson on food safety, translating scientific insights into clear and balanced messages for the media and the general public. In addition, she is the project manager of the LEDA Branded Food Database (Levensmiddelendatabank), which she helped develop into the national standard for food product information in the Netherlands, supporting consumer tools, scientific research, and public policy.

In 2021, she started as an external PhD candidate at Wageningen University. The results of her PhD research are presented in this thesis. Wieke lives in the Netherlands with her partner and two children.

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List of publications

This thesis:

Van der Vossen-Wijmenga -Wijmenga, W. P., Zwietering, M. H., Boer, E. P. J., Velema, E., Den Besten, H. M. W. (2022). Perception of food-related risks: Difference between consumers and experts and changes over time. *Food Control, 141*, 109142. https://doi.org/10.1016/j.foodcont.2022.109142

Van der Vossen-Wijmenga, W. P., Den Besten, H. M. W., Zwietering, M. H. (2024). Temperature status of domestic refrigerators and its effect on the risk of listeriosis from ready-to-eat (RTE) cooked meat products. *Int J Food Microbiol, 413*, 110516. https://doi.org/10.1016/j.ijfoodmicro.2023.110516

Van der Vossen-Wijmenga, W. P., Zwietering, M. H., Hazeleger, W. C., Den Besten, H. M. W. (2025). *Campylobacter* in the domestic kitchen: Linking human and microbiological behaviour. *Int J Food Microbiol*. *441*, 111270. https://doi.org/10.1016/j.ijfoodmicro.2025.111270

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Others:

Dapkevicius, M. L. N. E., Nout, M. J. R., Rombouts, F. M., Houben, J. H., Wymenga, W. (2000). Biogenic amine formation and degradation by potential fish silage starter microorganisms. *Int J Food Microbiol*. 57, pp. 107-114. https://doi.org/10.1016/S0168-1605(00)00238-5

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Westenbrink, S., Van der Vossen-Wijmenga, W., Toxopeus, I., Milder, I., Ocké, M. (2021). LEDA, the branded food database in the Netherlands: Data challenges and opportunities. *J Food Compas Anal, 102*, 104044. https://doi.org/10.1016/j.jfca.2021.104044

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Van der Vossen-Wijmenga, W. P., Serra-Castelló, C., Den Besten, H. M. W., Zwietering, M. H. (2025). Analysing quantitative microbiological risk assessments: from modelling approaches to informed decision-making and risk communication. *Curr Opin Food Sci, 64*, 101326. https://doi.org/10.1016/j.cofs.2025.101326

Van Meer, F., Van Asselt. E., Hoenderdaal. W., Van der Vossen-Wijmenga, W., Groenen, M., Mu, W. (in press)). Effects of socioeconomic position on food safety practices and dietary habits. *British Food Journal*.

Overview of completed training activities

A: Discipline specific activities	
- Risk Ranking (Swedish Food Agency)	2022
- Safe Consume (Safeconsume)	2022
- Consumer Food Safety Education Conference (SFSEC)	2023
- VMT Food Safety Event (VMT) **	2021, 2022
- Food microbiology pathogens (KNVM) **	2023
- Zoonoses symposium (RIVM)	2023
- Risks Future Food (KNVM) **	2024
- European symposium on food safety (IAFP) * and **	2024, 2025
- IAFP Annual meeting * and **	2024
- VMT Food Law Event (VMT) **	2025
- Food safety in changing food systems (WFSR) **	2025

B: General courses	
- Advanced statistics (WUR)	2021
- Media training (Bobderondepartners)	2021
- Course JASP (online)	2021
- Projectmanagement (Netherlands Nutrition Centre)	2021
- Training @Risk software (WUR internal)	2022
- (social) media training (Katarina Hartgers)	2022
- Course excel (Computrain)	2022

D: Assisting in teaching and supervision activities	
- Preventive Health Issues in Daily Life (CHL23306)	2022-2025
- Supervision of MSc- and BSc-thesis students (7)	2021-2024

C: Other activities	
- Preparation of research proposal (FHM WUR)	2021-2023
- PhD and student presentations (FHM WUR) **	2021, 2025
- Radio, press articles, popular science on PhD topic	2022-2025
- Review scientific articles (Int J Food Microbiol, Microb Risk Anal)	2022-2025

* Poster presentation; ** Oral presentation

Authorship statement

PhD candidate's name:	Wieke P van der Vossen-Wijmenga
First promotor:	Marcel H Zwietering
Title of PhD thesis:	Risk on the menu. An integrated recipe for safer food at home

Chapter 1 General introduction. The overall research theme and its embedding within the field of Food Microbiology were discussed with my promotors. I developed the integrated framework combining risk perception, risk behaviour, risk assessment and risk communication. I structured the thesis outline, conducted the literature review, and wrote the full first draft of this chapter. The chapter was revised after comments from my promotors.

Chapter 2 Perception of food-related risks. Difference between consumers and experts and changes over time. The study design was developed in collaboration with colleagues at the Netherlands Nutrition Centre. I contributed to refining the questions, designing the survey, and coordinating with the panel agency. I performed the statistical analyses with help from one of the authors and together with my promotors we interpreted the results. I wrote the first draft of the manuscript and revised it after comments from my co-authors.

Chapter 3 Temperature status of domestic refrigerators and its effect on the risk of listeriosis from ready-to-eat (RTE) cooked meat products. I contributed to defining the research question and designed the overall study in collaboration with my promotors. I coordinated the data collection, including the consumer survey and the 24-hour temperature measurements, which were carried out with the assistance of BSc students under my supervision. I developed and implemented the QMRA model, performed the scenario and sensitivity analyses, and interpreted the results. I wrote the first draft of the manuscript and revised it after comments from my co-authors.

Chapter 4 *Campylobacter* in the domestic kitchen: Linking human and microbiological behaviour. The research question and study approach were developed in discussion with my promotors. I contributed to the study design linking behavioural data with microbiological risk assessment. I coordinated the consumer survey data collection. Experimental data was performed with the assistance of MSc students, whom I supervised. I designed and performed the quantitative modelling and analysed the results. I wrote the first draft of the manuscript and revised it after comments from my co-authors.

Chapter 5 From perception to behaviour. the role of communication in food safety awareness and hygiene practices over time. The research idea was developed in collaboration with my promotors and colleagues at the Netherlands Nutrition Centre. The research idea was developed in collaboration with my promotors and colleagues at the Netherlands Nutrition Centre. I contributed to the design of the communication intervention and evaluation study. I coordinated with the panel agencies to organize data collection and ensure the quality and continuity of the measurements. I analysed the data and interpreted the results in the context of risk perception and behavioural theory. I wrote the first draft of the manuscript and revised it after comments from my co-authors.

Chapter 6 General discussion. I developed the conceptual integration of the four perspectives addressed in this thesis (risk perception, risk behaviour, risk assessment and risk communication). I wrote the first draft of this chapter independently and revised it after feedback from my promotors. The final version was approved by both promotors.

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Between risk and safety lie
the choices we make every day.

