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Food Safety

Prevention of the Biological Contamination of Food

Processing/Distribution and Consumer Usage

Coordinated by
Thierry Bénézech
Christine Faille

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Preface

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Throughout the food chain, foodstuff can be exposed to hazardous agents that lead to contamination. Foodstuffs can therefore be the vector for different types of hazards with adverse effects on foodstuff quality and consumer health. All stages, such as primary production, processing, storage, transportation, retail and consumer, are sources of contamination and the development of undesirable microorganisms.

Assessing the biological hazards and managing the risks posed by the potential presence of these unwanted microorganisms along the food chain is a never-ending challenge.

This book deals with risk management, focusing on microbiological risks. The aim is to reconsider this risk in order to prevent and/or control it. This book belongs to a collection of three books on the theme of "food security", including:

– the book coordinated by Nabila Haddad covering both chemical and microbiological hazards;

– the book coordinated by Jeanne-Marie Membré covering the microbiological risk assessment associated with the food processing/distribution chain.

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Introduction

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A good knowledge of the control strategies and means implemented along the food chain after the primary production step, aiming to mitigate the microbiological risks, is a prerequisite for any further improvement, but it is not sufficient. Indeed, in order to better prevent and therefore control these risks, it is essential to investigate both the phenomena of surface contamination and those associated with the elimination of this contamination by cleaning and disinfection operations. Thanks to these new insights, a certain number of innovations can already be proposed (new surfaces, materials and cleaning and disinfection procedures, etc.) for future development on an industrial or domestic scale. To partly cover this vast topic, 14 chapters have been defined.

The first three chapters provide a wide range of information on the risks associated with bacterial contamination of surfaces in the food industry, HACCP (Hazard Analysis Critical Control Points) approaches for the control of such contamination and the methods for detecting it:

– Chapter 1 considers the phenomenon of cross-contamination of food and its possible consequences in terms of risks to human health. Cross-contamination is defined as the direct or indirect transfer of bacteria or other microorganisms from a contaminated surface to an uncontaminated product and can occur at any stage of food production, as well as during distribution, and even in restaurants and at the consumer's home.

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– Chapter 2 concerns the implementation of HACCP to ensure the hygiene of all surfaces subject to these undesirable microbial contaminations. This approach is fully detailed in accordance with standards and regulations.

– Chapter 3 details the available commercial methods for the assessment of surface microbial contaminations in the food industry. This control consists of the detection and/or enumeration of pathogenic and non-pathogenic microorganisms sampled from the environment of food processing plants.

The next five chapters provide details on the parameters that can affect the development of these contaminations and propose solutions to limit their impact. These include the properties of materials (Chapters 4 and 5), the design of the plant as a whole (Chapter 6) and the equipment and processing lines (Chapters 7 and 8):

– Chapter 4 presents the performance of metallic materials commonly used in the food industry, especially in relation to their chemical, thermal and mechanical properties. The choice of these materials is discussed according to the direct or indirect contact with food, all in perspective with the national or international legislations in force.

– Chapter 5 focuses specifically on the complex interplay between the physicochemistry, chemistry and topography of surfaces that influence interactions between bacteria and materials. This chapter also describes the solutions to resolve these issues.

– Chapter 6 focuses on the hygienic design of food factories to provide defense against external factory hazards; defense against internal factory hazards and brand protection issues; management of the internal flows of people, ingredients, product, packaging, air and wastes to prevent cross-contamination; and maintenance of hygienic conditions via structural rigidity and material durability.

– Chapter 7, a very detailed work with a great deal of very useful information for the equipment manufacturers, food processors or inspectors/auditors, is devoted to the hygienic design of processing lines. With typical examples of poor hygienic design, the necessary technical and practical guidance is provided to identify and control food safety hazards associated with food processing equipment. Some principles of hygienic design are generic in nature, while individual equipment components (piping, pumps, valves, tanks, etc.) have their own specific requirements. The authors thus demonstrate that, although initially more expensive, hygienically designed equipment is also more sustainable and cost-effective in the long term.

– Chapter 8, also dealing with the hygienic design of equipment, aims to present the potential consequences of good and bad design on surface contamination and cleaning efficiency based on a good knowledge of the underlying mechanisms.

While Chapter 8 lays the foundation for all considerations of hygiene operations, i.e. those related to cleaning and disinfection operations, the following four chapters detail the practices currently used, new technological and methodological developments, and the new approaches currently being investigated at the laboratory level:

– Chapter 9 deals with the state of the art of hygiene operations in the food factories. This also includes smart and other emerging technologies framed in the whole food supply chain, to create a picture of the added value that the technology can bring to the sector. Moreover, the evolutions towards the Internet of Things (IoT) paradigm adoption are also presented.

– Chapter 10 goes further in describing the potential value of various innovative cleaning methods. This chapter reviews and analyzes promising mechanical and chemical strategies for biomass removal.

– Chapter 11 presents the state of the art of the disinfection in the food processing environments. The authors demonstrate that the biofilm control (killing and removal from surfaces) is currently attained by the application of combined cleaning and sanitation strategies.

– Chapter 12 deals with new approaches to improve disinfection efficacy, such as new disinfectants, new disinfectant application strategies, nanotechnology and self-disinfecting surfaces to overcome the failure of chemicals and conventional methods. Among the new approaches that have emerged is the search not only for new antimicrobial and antibiofilm molecules, which is quite conventional, but also for methods to prevent the spread of antimicrobial resistance while providing a sustainable disinfection alternative.

The last two chapters consider the supply chain and the consumer place, two elements of the whole food chain that have a significant impact on food safety:

– Chapter 13 deals with food safety problems during transport arising from physical and chemical contaminations and from the growth of spoilage and pathogenic microorganisms in perishable foodstuffs. Without proper cleaning between loads and hygienic design of the containers, the risk of cross-contamination is significantly increased.

– Chapter 14 presents the crucial role of consumers in mitigating food safety risks. Indeed, although food products are becoming safer thanks to strict regulations and developing technologies, food safety risks can only be fully controlled if consumers also follow good hygiene practices.

To conclude, this book provides an extensive review of the management of microbial risks throughout the food chain after the primary production stage, but it does not claim to be exhaustive. The interested reader will be able to deepen their knowledge thanks to the numerous references mentioned in each chapter.

1

Cross-contamination of Food by Contaminated Surfaces

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Globally, the World Health Organization (WHO) estimates that 600 million people become ill each year after eating contaminated food. It was estimated by the World Bank in 2018 that annual production losses due to foodborne illnesses were $95.2 billion with an annual cost of treating the sickness of $15 billion and $5 billion in lost trade in low- and middle-income countries. In the United States, the annual cost of illness due to the major pathogens (*Salmonella*, *Toxoplasma gondii*, *Listeria monocytogenes*, Norovirus, *Campylobacter*) is estimated to be $15.5 billion in medical expenses and lost productivity (Scharff 2012). The symptoms associated with these diseases vary depending on the pathogen. They are mainly digestive (diarrhea, vomiting), but can go to more serious and even fatal forms such as meningoencephalitis with *L. monocytogenes* or hemolytic uremic syndrome (HUS) following an infection with a Shiga toxin-producing *Escherichia coli* (STEC).

Contaminations can occur at different levels of the field to "fork" scenario. In animals, for example, they can occur while the animal is still alive, in its wild or farmed environment, and also *post-mortem*, during the preservation of the product, due to the dissemination of pathogens from the digestive contents to the consumed parts. Contamination can also occur during the processing of the product, either directly through human handling and the industrial environment, or indirectly, for example, with contaminated water. Indeed, cross-contamination is defined as the

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direct or indirect transfer of bacteria or other microorganisms from a contaminated product to a non-contaminated product (Pérez-Rodríguez et al. 2008). It can occur at any stage of food production, and also during distribution and even in restaurants and at the consumer's premises. There are three main types of cross-contamination: food-to-food, equipment-to-food and person-to-food. The most common errors that cause cross-contamination (Bennett et al. 2013) are the inadequate cleaning of processing equipment or utensils (67%) and storage in a contaminated environment (39%). Handlers' hands have also been shown to be involved in 42% of foodborne outbreaks between 1975 and 1998 in the United States (Kadariya et al. 2014).

It has long been recognized that the surfaces of workshops and equipment in the food industry are involved in the contamination of food and ultimately the cause of a significant amount of food poisoning. For example, a study conducted in 1995 by the World Health Organization in Europe revealed that 25% of food poisoning was associated with cross-contamination (equipment surfaces, operators) (Tirado and Schmidt 2001). Beyond the deaths recorded, the social and economic costs can be extremely significant with a destroyed brand image for the company and also for an entire sector.

The Cleaning and Disinfection (C&D) operation is a fundamental operation in the food industry because it must control the post-contamination of food related to materials and the environment. The implementation of a C&D plan is a regulatory obligation described in the EU feed and food law ("Hygiene Package" 2006). Thus, the EC 178/2002 regulation (General *Food Law*) indicates that no foodstuff should be put on the market if it is dangerous, i.e. harmful or unfit for consumption. Moreover, in the regulation on the hygiene of foodstuffs (EC 852/2004), it is required that any hazard be identified that should be prevented, eliminated or reduced to an acceptable level. Furthermore, in the regulation EC 2073/2005 on microbiological criteria for foodstuffs, Article 5.2 stipulates that manufacturers must control bacterial contamination in their environments (premises, facilities, equipment). In addition, in France, since 2018, the EGAlim law indicates that corrective action plans must be implemented following the detection of a pathogen in the production environment, and they must be communicated to the authorities. But a number of factors including a non-effective C&D plan can lead to the persistence of bacteria in the company. This notion of persistence has been described for many years in the environment of different food industries and during food epidemics and is mainly due to the presence of bacterial biofilms on surfaces which can be difficult to eliminate if not treated quickly.

1.1. Surface contamination

Biofilms are microbial communities (bacteria, fungi, algae or protozoa) colonizing a biotic or abiotic surface, and frequently included in a matrix of extracellular exopolymers, which protects them from environmental aggressions encountered in companies. Bacterial biofilms, the most frequent in agro-industrial environments, are composed of various species, pathogenic and non-pathogenic. In addition, the presence of inaccessible areas or those difficult to access thorough cleaning in the workshops (ceiling, walls) is conducive to the development of these bacterial biofilms that can detach from their medium and spread in the industrial environment. These complex microbial communities sometimes have the ability to persist on surfaces despite C&D operations. Furthermore, the massive use of detergents and disinfectants can lead to the adaptation of bacteria to this chemical stress and to an increased resistance to subsequent stresses.

1.1.1. *Viable but non-culturable cells (VBNCs)*

Different environmental and physicochemical factors (temperature, pH, salts, natural light) can induce in bacteria the appearance of VBNC forms (Besnard et al. 2002), which cannot grow on routine agar media but still have a metabolic activity. Generally speaking, this VBNC state is considered as a strategy of the cells to ensure their survival in unfavorable conditions. When conditions become favorable again, bacteria in the VBNC state can return to a culturable state, as has been shown for *Vibrio* strains following an increase in temperature or a restored availability of nutrients (Su et al. 2013). These VBNC forms are also often found within biofilms, as in pathogenic bacteria such as *Staphylococcus aureus* (Pasquaroli et al. 2014) and *L. monocytogenes* (Gião and Keevil 2014; Brauge et al. 2020), and some bacteria retain pathogenicity in this form (Oliver 2005). Hygiene procedures can also be the cause of the appearance of VBNC forms (Brauge et al. 2020). Once in the food, the VBNC forms can revive, multiply and even regain virulence after resuscitation into culturable cells in the case of pathogens (Li et al. 2014). In addition, the nature of surfaces is an environmental factor that can impact the culturability and viability of adhered bacteria (Silva et al. 2008).

1.1.2. *Persistence of strains in agroindustrial environments*

The notion of persistence of strains in industrial environments has often been reported in the literature as it could be the cause of recontamination of food (Nakari et al. 2014). Indeed, bacteria, such as *L. monocytogenes*, *Pseudomonas* sp. and

Staphylococcus sp., are able to resist and survive the selection pressures found in production facilities (biocide, temperatures, pH.). Other authors (Demaître et al. 2021) have examined the presence and genetic diversity of *L. monocytogenes* in three pork cutting plants in Belgium (868 samples). They suggested occasional introduction and repeated contamination and also the establishment of some persistent clones adapted to meat in all cutting plants. It was also shown that *Vibrio* strains are able to form biofilms on different equipment in the fish industry during the process and that these biofilms were still detected after C&D procedures (Bonnin-Jusserand et al. 2019). Another study (Palma et al. 2020) correlated the persistence in the industrial environment with the intrinsic properties of certain types of *L. monocytogenes*, such as their ability to form biofilms, their high tolerance to environmental stresses (osmotic shock, desiccation, low temperature) linked to adaptive proteomic responses as well as their resistance to disinfectants and heavy metals. Furthermore, food processing environments are known to be a hypothetical reservoir of genetic elements that can be mobilized and transferred between microbial communities offering ecological advantages to the recipient bacteria. For example, quaternary ammonium compounds are often used as biocide in the food industry, and it has recently been shown that isolates of *L. monocytogenes* could show increased resistance to this biocide through the expression of genes encoding efflux pumps located on transposable genetic elements (transposon, plasmid) (*emrE, qacH, brcABC*) or on the chromosome (*lde, mdrL)*, and that they were associated with genes for resistance to heavy metals (arsenic and cadmium). Recent work has shown that interactions and symbiosis of microorganisms, in addition to inherent genetic and external environmental factors, contribute to the persistence of *L. monocytogenes* in food production environments (Zwirzitz et al. 2021).

1.1.3. *Monitoring the effectiveness of C&D procedures*

The control of the effectiveness of C&D procedures is a major issue for companies in the framework of the sanitary control plan. However, if these procedures are generally well defined, it is different for the implementation and follow-up of self-monitoring. In SMEs, the control of the effectiveness of C&D operations is often limited to a few surface microbiological analyses. One of the main limitations encountered to evaluate the effectiveness of C&D procedures and to quantify residual contaminants is the difficulty in removing the flora present strongly adherent to surfaces or integrated in biofilms. The traditional methods most commonly used today consist of making an “impression” of the surface to be analyzed by contact with agar or using different techniques (cotton, polyester, rayon swabs, sponges, wipes) to remove adherent soil and residual cells. The effectiveness of the methods used to remove the dirt is very variable depending on the tool, and

also on the type of surface (material, roughness, etc.), the nature and structure of the biofilm (especially for mixed biofilms often encountered on industrial sites) and also the operator. In this case, some of the substances produced by the resident bacteria within the biofilms (secreted polymers = EPS) could act on the "attachment" of the pathogens and the structuring of the mixed biofilm (interaction with the EPS of the pathogens), thus affecting the ease of removal.

Many devices are marketed to assess the hygienic character of surfaces. These devices are based on the detection and quantification of organic and microbial residues, the latter requiring or not a bacterial growth. To limit the variability between operators, it is essential to set up a relevant sampling scheme and to use templates to identify the surface to be sampled.

1.2. Examples of cross-contamination related CFI (collective foodborne illnesses)

The involvement of cross-contamination in food-borne epidemics has been suspected or even demonstrated many times, in different food chains and for different pathogens.

A particularly telling example of cross-contamination involved a milk powder production unit of the company "Snow Brand Milk Products" in Osaka, Japan in 2000, which caused the worst gastroenteritis epidemic ever recorded in Japan (more than 14,000 people affected). Analysis of the milk revealed the presence of a heat-resistant toxin produced by *S. aureus* (Asao et al. 2003). Snow Brand initially claimed that the equipment that caused the cross-contamination, a valve in the secondary production line, was rarely used. In fact, it later turned out that it was used almost every day but was not cleaned regularly. While valve maintenance was previously performed on a weekly basis, the valves had not been properly maintained for a month prior to the occurrence of the accident. The company also claimed that the contaminated area was "the size of a small coin", but later examination revealed that it was much larger (see: http://brandfailures.blogspot.com/2006/12/brand-pr-failures-snow-brand-milk.html). As a result of the accident, the company's sales plummeted, and it was forced to close five and then eight of its plants, including the site involved in the poisoning.

Other pathogens are known to cause sometimes major gastroenteritis outbreaks related to cross-contamination. Recently, authors have, for example, focused on CFI due to *Vibrio parahaemolyticus* in China (Chen et al. 2017). They highlighted that the epidemics were one out of two times due to meals in restaurants and were linked to cross-contamination in nearly 40% of cases.

1.2.1. L. monocytogenes

Numerous outbreaks have been attributed to the presence of *L. monocytogenes* in food, and it has sometimes been possible to incriminate contaminated surfaces as the source of these contaminations. This observation is likely to be contrasted with the fact that, in food-processing environments, *L. monocytogenes* can persist in niches for months or even years (Ferreira et al. 2014). A recent example involved a large-scale outbreak in South Africa between 2017 and 2018 (1060 laboratory-confirmed cases, 216 deaths). The source was a sausage factory of the Enterprise Food Group, a subsidiary of Tiger Brands Ltd. the largest packaged food company on the continent, where poor hygiene conditions were found. As a result of this outbreak, the estimated costs of damages for the victims were between 28 and 133 million euros, the estimated costs of recalls, destruction of products and production stoppages were 25 million euros and a fall in the company's stock market share reached 43% in one year (Olanya et al. 2019). Demand for pork (the raw material used by the company that caused the outbreak) fell by 50% and the price of pork fell by 20–40% during the outbreak. According to the South African National Agricultural Marketing Council (NAMC), the price of the sausage product that caused the outbreak dropped by 14%. More than a year later, the price of the product involved remained 3.8% lower than before the outbreak.

In other cases, the contaminated surfaces causing these outbreaks were clearly identified, such as a large-scale *L. monocytogenes* outbreak (2008, Toronto, Canada) involving ready-to-eat meat products produced by Maple Leaf Foods. Organic material was found to be trapped in the mechanical components of two meat slicers and harboring *Listeria*, despite sanitation procedures that met the equipment manufacturers' specifications (according to the company's CEO). However, according to federal inspection records, the monitoring of slicer cleaning operations had not been properly conducted in the months prior to the outbreak (see: https://www.cp24.com/inspector-found-problems-with-maple-leaf-plant-s-records-before-outbreak-1.393859). The outbreak resulted in 57 confirmed cases and 22 deaths in 2008, and a class-action lawsuit forced the company to pay $27 million in compensation, not including the cost of recalling the 220 foods produced at the plant.

Other foods have also caused outbreaks as a result of cross-contamination. A major *L. monocytogenes* outbreak in Quebec City, Canada, in 2008 (Gaulin et al. 2012) was associated with the consumption of retail pasteurized milk cheese. The strain that caused this outbreak was isolated from the cheese and also from environmental samples from the processing plant as well as from 22 retail stores. Cross-contamination was confirmed on knives, cutting boards and work surfaces. This event resulted in one of the largest product recalls ever conducted in the

province of Quebec involving 364 retailers. Another example of an outbreak due to *L. monocytogenes* (32 cases with mostly severe symptoms) occurred in 2013 and 2014 in Switzerland, due to ready-to-eat salads (Stephan et al. 2015). Analysis of swab samples taken before and after cleaning and disinfection were positive for *L. monocytogenes*, including a conveyor belt. Extensive inspection concluded that the design was poor (parts of the conveyor belt, such as the guide rods and spools that moved the belt, were not accessible for the daily cleaning and sanitizing process). Finally, a case of listeriosis contracted in the hospital was linked to milkshakes produced in a contaminated machine (Mazengia et al. 2017). This strain persisted in the machine for a year despite C&D operations.

1.2.2. *Other pathogens involved in epidemics due to cross-contamination*

Other pathogens have also been associated with foodborne outbreaks resulting from cross-contamination, such as *Campylobacter jejuni*, *Vibrio* spp., *Salmonella* spp. or even *Bacillus cereus*. For example, a salmonellosis cross-contamination was described in 2012, in the Netherlands, where 1149 cases were reported following the consumption of smoked salmon contaminated during the process by *Salmonella thompson* (Suijkerbuijk et al. 2017). Of the reported cases, 20% were hospitalized and four deaths occurred. The estimated number of cases in this outbreak (including reported and underestimated cases) was 21,123 for a total cost of 7.5 million euros including a cost of 6.8 million euros in lost productivity. Another *Salmonella* (*S. enterica*) outbreak in 2008 in Phoenix, Arizona, originated in a restaurant chain. While the primary source of these outbreaks was undoubtedly chicken, poor sanitation procedures, identified during routine inspections, most certainly played a significant role. For example, clean utensils and cutting boards were in close proximity to the area where the raw chicken was prepared and were therefore easily contaminated (Patel et al. 2010). In the same year, an outbreak of *Salmonella typhimurium* in the United States was linked to the consumption of peanut butter and paste (Finn et al. 2013) and was responsible for 714 cases and probably nine deaths. In the FDA inspection report for one of the manufacturing plants involved, major deficiencies were observed in the maintenance of equipment, containers and utensils, line hygiene procedures and ventilation systems (Finn et al. 2013). Finally, a *Salmonella* outbreak occurred in Brisbane during a convention in 2015 and resulted in at least 250 people becoming ill and 24 being hospitalized (see: https://www.foodsafety.com.au/news/brisbane-salmonella-outbreak-caused-by-cross-contamination). The epidemiological investigation proved that several kitchen utensils, including a portable blender, were the source of this contamination.

As for *L. monocytogenes*, utensils such as knives, cutting boards, and also work surfaces are often suspected to play a major role in cross-contamination. This is the case of a large-scale epidemic (237 cases, 53 hospitalizations) caused by *V. parahaemolyticus* in Korea in 2017 (Jung 2018). The epidemic occurred after residents consumed food at a welfare center. The epidemiological study found that eggs and squid were prepared with the same knife and cutting board, strongly suggesting cross-contamination. Another outbreak, occurring in July 2017, occurred in three auxiliary police squads in Seoul, Korea. The investigation identified the origin of the outbreak as a dish (or dishes) served during a lunch, consisting primarily of steamed rice with millet, chicken, radish kimchi and watermelon (Kang et al. 2019) contaminated with *C. jejuni*. However, it was not the chicken, as might have been expected, but the watermelon that showed the strongest association with the outbreak, suggesting cross-contamination from the chicken. The investigation revealed that the separation of raw and cooked foods was structurally satisfactory, but that the chicken wash water was leaking from the drain and spilling onto the floor, which likely resulted in contamination of the work surface on which the watermelon was cut.

1.3. Research of parameters affecting cross-contamination

The amount of bacteria transferred depends first on the bacterial species, as it has been demonstrated on different species such as *Campylobacter* spp. and *Salmonella* spp. (Sarjit and Dykes 2017), *L. monocytogenes* and *E. coli* (Zilelidou et al. 2015) or *S. aureus* and *E. coli* (Pérez-Rodríguez et al. 2007). Large differences are also sometimes observed between strains belonging to the same species, such as *Campylobacter jejuni* and *C. coli* (Guyard-Nicodème et al. 2013). These differences are probably related to the surface properties of the bacteria (physicochemistry, morphology) which affect the forms of adhesion to different materials. It has also been shown that the transfer rate was different for adherent cells (isolated) or biofilms. In fact, when the surface of the material is covered by a biofilm, bacteria can be transferred to the food either by an interfacial rupture of the bacteria in contact with the material or by a cohesive rupture within the biofilm and the properties of the materials are then no longer preponderant. It would be the transmission by cohesive rupture which would play a primordial role in the transfers of contamination (Gusnaniar et al. 2017). The differences observed may also be due to the complexity of the biofilms. A study on *L. monocytogenes* biofilms showed that the transfer rates were lower in mixed biofilms with *Pseudomonas fluorescens* than in mono-strain biofilms (Pang and Yuk 2019). Finally, contaminated surfaces can be subjected to drying periods in which some pathogens are able to survive, particularly within biofilms, but especially in the presence of food residues (Moore

et al. 2007). Different authors have therefore been interested in these biofilms subjected to desiccation. They observed that after 23 days of desiccation for a biofilm of *L. monocytogenes* (Truelstrup Hansen and Vogel 2011) and 30 days for a biofilm of *E. coli*-producing shigatoxins (Adator et al. 2018), a significant transfer still occurred after contact with food. It would even seem that the efficiency of transfer is increased after a period of drying, probably due to a decrease in the interaction forces between cells or between cells and materials (Rodríguez et al. 2007).

The material also plays a major role in the efficiency of the transfer of adherent bacteria, probably because of the very different interaction forces between bacteria and material depending on the physicochemistry and/or the topography of the materials (Midelet and Carpentier 2002; Midelet and Carpentier 2004; Midelet and Carpentier 2006). For example, the transfer efficiency of a biofilm of *Listeria innocua* (Jeon et al. 2018) or *S. typhimurium* (Moore et al. 2007) is higher on polypropylene than on stainless steel.

Other factors such as contact time and food or surface contamination rate significantly affect bacterial transfers. First, the characteristics of the contacts between contaminated surfaces and food, such as their duration or number, obviously profoundly affect the efficiency of the transfer. For example, the efficiency of transfer of *Enterobacter aerogenes* from steel or wood to different foods increases with the duration of contact (Miranda and Schaffner 2016). Other works have shown that the number of detached bacteria decreases with the number of successive contacts with a food, which can be high, as in slicers (Eginton et al. 1998; Midelet and Carpentier 2002). Indeed, studies on the transfer of *L. monocytogenes* from a slicer blade to ham (Chaitiemwong et al. 2014) or different meat products (Vorst et al. 2006) have shown a linear reduction in the logarithmic concentration of the bacteria on consecutive ham slices. Similar results have been obtained for other bacterial species, such as *E. coli* O157:H7 and *L. monocytogenes* (Zilelidou et al. 2015) or *E. coli* O157:H7 and *S. aureus* (Pérez-Rodríguez et al. 2007).

Other environmental factors can also affect the rate of biofilm transfer to food in contact. These include the composition of the food, which has been the subject of many studies. For example, *E. aerogenes* cells are transferred more rapidly from a steel surface to watermelon than to bread or butter, but especially than to candy, which suggests a major role of the water content in the food (Miranda and Schaffner 2016). In case of successive contacts, as when using slicers, the fat content of the food and also its moisture content would facilitate the transfer of contamination, in particular by the formation of a layer of fat on the blade of the slicer (in other words, a surface conditioning of the material). This has been demonstrated on the

cross-contamination of blades contaminated with *L. monocytogenes* on meat foods such as salami, mortadella or turkey (Vorst et al. 2006; Keskinen et al. 2008) or cheese (Rodríguez and McLandsborough 2007; Rodríguez et al. 2007). A lower temperature would limit the efficiency of the transfer of *L. monocytogenes* when slicing salmon (Aarnisalo et al. 2007).

Obviously, the implementation of cleaning procedures limits the risk of cross-contamination from contaminated surfaces. Yet, various authors have noted that these procedures are often unable to completely eliminate this surface contamination, for example, by *Campylobacter* and *Salmonella* on cutting boards (Cogan et al. 1999; Ravishankar et al. 2010; Soares et al. 2012).

1.4. Conclusion

It is therefore clear that further work is needed to allow for a better assessment of the potential hazard of inert surfaces in industrial environments for food contact contamination. Work on improving the hygienic design of processing tools (new materials and surfaces, resistance and evolution of properties) and their environment (design of processing sites and factories) must be developed to limit the contamination of surfaces, and therefore the bacterial transfer to food. Indeed, the ease of hygiene is one of the keys to consider the use of more gentle and more environmentally friendly hygiene procedures, and less consumption of water, energy and chemicals (green chemistry with enzymes or antimicrobial peptides, physical methods with or without chemistry, microbial ecology via the development of positive biofilms). A direct consequence will be the reduction of induced impacts on the environment (greenhouse gases, drinking water consumption, discharge of detergents/surfactants into surface waters despite wastewater treatment, etc.).

1.5. References

Aarnisalo, K., Sheen, S., Raaska, L., Tamplin, M. (2007). Modelling transfer of *Listeria monocytogenes* during slicing of "gravid" salmon. *International Journal of Food Microbiology*, 118(1), 69–78.

Adator, E.H., Cheng, M., Holley, R., McAllister, T., Narvaez-Bravo, C. (2018). Ability of Shiga toxigenic *Escherichia coli* to survive within dry-surface biofilms and transfer to fresh lettuce. *International Journal of Food Microbiology*, 269, 52–59.

Asao, T., Kumeda, Y., Kawai, T., Shibata, T., Oda, H., Haruki, K., Nakazawa, H., Kozaki, S. (2003). An extensive outbreak of staphylococcal food poisoning due to low-fat milk in Japan: Estimation of enterotoxin A in the incriminated milk and powdered skim milk. *Epidemiology and Infection*, 130(1), 33–40.