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Models of microbial cross-contamination dynamics

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Cross-contamination can be understood as a systematic process where contaminated surfaces are involved in food contamination. However, in most cases, it is mainly referred as a sporadic event affecting the number of contaminated food samples in a lot rather than the concentration levels since bacterial transfer often occurs at low numbers. Bacterial transfer, although recently, has been considered as an important area to be modelled and several studies have made attempts to give insight in the transfer process to provide more reliable models and predictions. The use of compartmental mechanistic models could allow to better understand the influence of food processing factors and the indirect mechanisms involved in cross-contamination.

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Introduction

Microbial growth in foods reflects changes in concentration over time as a function of certain conditions. Over the last few years, the need to describe how microorganisms are transmitted throughout the food chain has led microbiologists to look at other bacterial processes than growth and death. Cross-contamination is reported to be an important factor strongly linked to food-borne diseases outbreaks and food spoilage. A limitation of existing predictive models in this regard is the lack of reproducibility in some cases to characterize variability associated to bacterial transfer from contaminated food surfaces to other recipient food surfaces in food-related environments. In recent years, understanding of the modelling transfer dynamics allows to provide quantifiable links between processing control parameters and microbial levels, simplifying the complexity of these relationships for implementation into risk assessment models.

The present paper aims at providing an updated overview of available cross-contamination modelling approaches in foods as well as the available evaluation methods for model robustness. Theoretical concepts are illustrated in two examples on the factors implicated in the modelling of cross-contamination dynamics in the produce and poultry production chains describing the underlying phenomena of transfer and survival of pathogens.

Overview of existing approaches of cross-contamination models in foods

Cross-contamination models have experienced a great development in the last years and different approaches have been adopted to explain the behavior of microorganisms during transfer through contact between different surfaces. Pérez-Rodríguez *et al.* [1••] published the state-of-the-art of bacterial transfer phenomenon, including a review of the transfer models developed so far and the factors affecting cross-contamination and recontamination phenomena. In their review, it was stated that the most popular models [2–4] are based on the so-called transfer rates (TR), as can be seen in Eq. (1).

$$N_r = \left(\frac{\mathrm{TR}}{100}\right) \cdot N_d \qquad (1)$$

where N_r is the quantity of cells transferred to the receptor surface; TR is transfer rate, that is, the percentage of cells transferred from one surface (donor) to another surface (receptor), and N_d is the quantity of cells contaminating the donor surface.

Refinement of this simple model has been proposed by other authors, assuming that there are variability and uncertainty components inherent to bacterial cells transfer. To capture this, various probability distributions have been evaluated to model transfer. Normal distribution was considered by Montville *et al.* [5]; Schaffner [6]; and Jensen *et al.* [7] as the most appropriate to describe the log-transformed TR data. Other distributions (*i. e.* Weibull, Beta) have been suggested [8] to describe TR between different surfaces during food process operations involving handlers and semi-elaborated foods.

Other models [9•] utilize the compartmental and dynamic cross-contamination approach based on the binomial process of bacterial transfer, as described by the parameters (n = *number of samples*, p = *probability of cells transfer*). Smid *et al.* [10] applied a Bayesian network model allowing the combination of uncertainty within one experiment and variability over multiple experiments; the posterior distribution of bacteria in the recipient surface was a Gamma distribution, while the variability of TR over all experiments was defined by a Beta distribution. The authors demonstrated the functionality of the model and provided more insight into the transfer probabilities of *Salmonella* between pork and stainless steel knife. They found a very large variability and a considerable uncertainty.

In some cases, events of 0% cells transfer between surfaces are observed. Some authors [11,12] attempted to model failed bacterial transfers applying cross contamination frequency values and TRs to describe microbial prevalence and concentration changes, respectively. Ariza *et al.* [9•] also explained this phenomenon by assuming very low values for the n and p parameters of the Binomial distribution.

The use of compartmental mechanistic models was illustrated by Møller *et al.* [13•] building a more complex transfer model for *Salmonella* during pork grinding inspired in a previous model [14•] developed for *Campylobacter* cross-contamination in poultry processing. Møller *et al.* [13•] hypothesized that the input of *Salmonella* is organized in two different matrices inside the grinder; one exhibiting high transfer ability, and a second where *Salmonella* demonstrated a low transfer from the grinder to the meat. The resulting model has seven parameters with biological significance; four of them are TR and the other three are cells inactivation. Some years later, they evaluated the model developed in other grinding conditions, that is, two microorganisms (*Salmonella* spp. and *Listeria monocytogenes*), two food matrices (pork and beef), two different grinders, different sizes and number of pieces of meats to be ground, and different temperatures [15••]. Regarding cross-contamination of pork through contact with an artificially inoculated slicing machine, other studies adjusted a log-linear model and Weibull model to transfer data, showing acceptable goodness-of-fit indexes [16] ($R^2 \geq 0.73$).

A recent study [17•] developed a mechanistic model focused on cross-contamination dynamics during produce washing, based on the previous experiments of Luo *et al.* [18]. Munther *et al.* [17•] provided a system of equations combining the dynamics of water chemistry and pathogen transmission from the wash water to shredded lettuce. Related also with cross-contamination via water, other complex approaches account for the transfer of *Escherichia coli* during chilling process of poultry in a water tank [19•]. It is overall concluded about the significance of processing factors on cross-contamination dynamics underlining the utility of the models proposed to quantify the effect of indirect mechanisms involved with cross-contamination [17•,19•].

Factors involved in the modelling of contamination dynamics

Environmental and intrinsic factors during processing affect the ability of microorganisms to be transferred from one surface to another. Intrinsic factors encompass the physiological characteristics and type of microorganisms, their degree of attachment, clustering and/or biofilm forming capacities. Moistness and roughness of the donor and receiving surfaces, as well as the contact time between them can be described as relevant environmental factors [1••].

When modelling cross-contamination dynamics in foods the contamination between food-equipment, food-water, water-equipment together with the reverse scenarios should be evaluated [20,21]. For instance, the transfer of *Salmonella* from meat to surfaces is more likely to occur when the meat skin moisture is high [22••]. The variability and uncertainty derived from the simultaneous action of several factors during transfer events make stochastic approaches using probability distributions more adequate when modelling the dynamics of cross-contamination [19•,20].

The influence of processing factors is illustrated through the following examples:

Produce chain

The washing water management in fresh-cut produce lines is of great importance concerning cross-contamination [23,24]. The binding rate, defined as the rate at which the microorganism present in the water binds to the produce, the free chlorine concentration and the washing holding time are factors that influence on the contamination dynamics [17•,24].

Considering the cross-contamination scenarios involving transfer from equipment to food (*i.e.*: cutting, shredding, *etc.*) the physicochemical characteristics and topography of the donor and receiving surfaces were highlighted as important factors while modelling microbial transfer [25,26•]. Zilelidou *et al.* [21] concluded that bacterial transfer might take place with higher TR from contaminated knives to fresh lettuce compared to the reverse scenario. Furthermore, higher residence times on the donor surface leads to lower TR, as it enables internalization or attachment of bacteria [1••,21,27].

The physiological characteristics and the susceptibility of different microorganisms to stressful environmental conditions can considerably influence on TR [1••,21]. *E. coli* O157:H7 was more susceptible to the desiccation stress caused by low relative humidity, with lower survival