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Hazard control through processing and preservation technologies for enhancing the food safety management of infant food chains

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ABSTRACT

Food safety of infant foods is of paramount importance due to the high vulnerability of this population. Food business operators guarantee safety of the products they put on the market by implementing control measures that prevent, eliminate, reduce, or keep relevant physical, microbiological and/or chemical hazards to an acceptable level. It is essential that the efficacy of control measures is validated during process design and on-line monitoring and periodic verification activities are implemented during the commercial production. Infant foods are usually processed through conservative thermal treatments that guarantee food safety but usually negatively affect the organoleptic properties, reduce vitamin and nutrient contents. Heat treatments can trigger the formation of process induced contaminants.The EU-SAFFI project aims to set and validate new/emerging processing and preservation technologies (i.e. pulse combustion drying, radiofrequency and high pressure processing) to control key contaminants and pathogens as efficiently as classical technologies and to provide a decision support system to manage food safety in infant food. This article describes how the project is addressing the research to control (i) furan, a key process-induced toxicant in infant food whose formation is induced during thermal preservation processes of foods such as infant formulas and jarred baby foods, (ii) tropane alkaloids, natural contaminants found in agricultural crops due to accidental harvesting of weeds whose presence above the maximum regulated levels have been documented in cereal-based foods for infants and children and (iii) different vegetative and spore forming bacterial pathogens, a group of microbiological hazards with product and technology-specific relevance and resistance.

1. Introduction

Within the food sector, infant foods are particularly relevant for food safety issues because of the high vulnerability of the target population and the wide variety of commodities. Processing and preservation processes are applied by manufacturers to treat different types of infant food.[1] Instead of reacting to foodborne outbreaks, the current regulation requires the food business operators to have a preventive systematic control of the processes implemented, namely the pre-requisite programs and Hazard Analysis and Critical Control Points (HACCP). The HACCP approach provides flexibility with the selection of control measures, enabling the accommodation of changes in food formulation, technology developments and innovations to meet the market and consumer demands. The implementation of HACCP-based programmes is audited by inspection agencies and regulatory authorities and enhances the food safety of produced food and promotes international trade by increasing confidence in food safety system.[2] The HACCP-based approaches focus on hazard control at specific critical control points (CCPs) applied to specific operations within the production process, storage and handling. Food business operators are responsible to obtain scientific and technical evidence that specific control measures (alone or combined) are effectively controlling the relevant identified hazards, either of physical, microbiological and/or chemical nature. Within the food safety management systems, control measures aim to prevent,

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eliminate, reduce, or keep a relevant hazard to an acceptable level that it is not likely to pose a public health risk under normal conditions of distribution and storage.[3,4]

In this context, validation of a control measure acquires a paramount importance and needs to be performed during the design of the process, prior to its rutinary implementation. A validation study aims to provide the evidence that the process and product parameters associated with the control measure, if properly implemented, can control the hazard under a worst-case scenario.[5] Conducting validation studies may be resource intensive. Several complementary approaches can be useful, including (i) the scientific and technical literature, international standards and recognised guidelines, gathering data from previous validation studies and the historical knowledge of the proper performance of the control measure; (ii) scientifically sound experimental approaches based on microbial challenge testing (either with pathogenic microorganisms or qualified surrogates), pilot plant or industrial trials designed and carried out to mimic process conditions and (iii) mathematical models that integrate scientific data on how product and processing factors affect the relevant hazards enabling the assessment on the ability of one or a combination of control measures to achieve the intended food safety outcome. Available data and mathematical models serve of part of the evidence that is being collected in a validation study, and often do not reflect the actual situation good enough, and one will precede with a challenge study to validate the control measure.

Once the validated control measure is implemented, it requires a real-time monitoring during processing of each batch though a planned sequence of measurements of control parameters that confirms that the control measure is operating as intended. In addition to monitoring, periodic verification is needed a posteriori, after the processing, to determine whether the control measure has been operating as intended.[3] Verification activities include reviewing production, maintenance and calibration reports, environmental sampling and product testing, amongst others. Sampling plans and analytical methodologies are frequently described in guidelines and regulations about microbiological criteria and maximum contaminant levels. The relevance of end-product testing as verification procedure depends on the type of product and process.[6]

Within the EU research project funded by Horizon Europe 2020, SAFFI (Safe Food for Infants in the EU and China, https://www.saffi.eu/), focused on foods for infants and children, a work package is currently in progress to develop a prototype of a decision support system for hazard control. The work package also aims to set and validate emerging processing and preservation technologies to control key contaminants and pathogens as efficiently as classical technologies and to set efficient sampling strategies at operational (infant food companies) and governmental (food safety authorities) level to enhance the effectiveness of food safety management options.

2. Infant food and new/emerging processing technologies

Infant food manufacturing involves one or more heating steps of raw materials or intermediate products. The end-products are generally microbiologically shelf stable. Shelf stability is achieved by the low water activity (a_w) of the end-product in the case of powdered infant formula and infant cereals or thanks to the microbial lethality achieved with the heating steps in case of ready-to-eat meals and fruit-based purees. To ensure the inactivation of spoilage and pathogenic microorganisms and enzymes, infant foods are usually processed using conservative time/temperature combinations as thermal treatments. Besides microbial inactivation, heating contributes to soften the raw materials. However, due to the intensive heating, less desirable flavour and colour changes may appear and the vitamin and nutrient contents are reduced.[7] Moreover, intensive thermal treatments trigger the formation of process induced contaminants such as acrylamide, furans, hydroxymethyl furfural (HMF), etc.[8]

The SAFFI project deals with four infant food chains chosen as case studies to cover infant nutrition while encompassing very different hazards (microbial, natural toxins, process contaminants and food packaging migrants), ingredients (of plant and animal origin), processing (including new or emerging technologies) and control steps. The case-studies include: (i) powdered infant formula, (ii) infant cereals, (iii) sterilized vegetables mixed with fish or meat meal and (iv) fruit-based purees. Besides the classical thermal technologies spray and drum drying processes, the pulse combustion drying (PCD) will be explored for case-studies (i) and (ii). The radiofrequency (RF) heating will be investigated as an alternative to classical retort sterilisation, while high pressure processing (HPP) will be the non-thermal alternative for pasteurisation.

2.1. Pulse combustion drying

Spray drying is the most commonly used technology to dry liquid foods, such as infant formula. Spray drying is very intensive on energy use, having a large impact in cost and sustainability. The use of direct heating systems has been eliminated due to the presence of undesirable gases after the fuel combustion, and only low efficient indirect heating is now being used for food processing. Pulse Combustion Drying (PCD) is a new drying technology that uses an engine to produce hot waves of air (3000 waves/minute, at 350–400 °C) that cause a very fast drying of the liquid droplets, resulting in a high-quality dried product, without the gas problems of the traditional direct heating systems.[9, 10] Another advantage of PCD is that it is more efficient than indirect heating spray drying for three main reasons. First, PC dryer can handle higher solid loading and viscosity than a conventional spray dryer. High viscosity fluids (such as infant cereals) are not possible to dry by spray drying, and a drum dryer must be used, with potential detrimental effects on final product quality. Secondly, in PCD the heat transfer is very high and drying is completed in a shorter time and at higher temperatures (air temperature between 350 and 500 °C) than classical drying technologies. As a consequence, a higher drying efficiency is achieved with PCD (20% less energy) compared with indirect heating spray drying.[10] Finally, due the smaller size of the equipment and lack of mobile parts inside the drying chamber, PCD requires lower investment and maintenance than classical spray drying equipment. Although the PCD technology is already working under industrial conditions it is not used for infant food production yet. Moreover, there is a need for scientific studies about thermal damage markers, accumulation of process contaminants and the microbial inactivation achieved to substantiate the beneficial potential within the food sector.

2.2. Radiofrequency

Radiofrequency (RF) heating is a technology based on the absorption of electromagnetic waves by a dielectric material, similarly to microwaves in the 10–300 MHz range. When compared to microwaves, RF has a greater penetration into the product and better heating uniformity, minimizing irregular heating or hot spots.[11] Moreover, there is a minimal dirt deposition (less water and cleaning agents are needed for cleaning) due to the removal of hot heat transfer surfaces.[12] RF has a high heating efficiency (>80%) without losses to the surrounding environment.[13] As the heating rate is faster than in conventional heating technologies (such as UHT or retort), nutrient, vitamin and flavour damage is minimized[14] and the organoleptic characteristics of the product can be improved.[15] Different applications of RF for pasteurization can be found in the literature. In liquid or semi-liquid products, applications include orange juice,[16] tomato homogenate[17] and fish soup.[15] Some studies can also be found on the successful application of this technology to infant foods (milk powders) for the inactivation of *Cronobacter sakazakii*.[18]

2.3. High pressure processing

HPP is a non-thermal process applied once the product is in its final package to inactivate vegetative forms of pathogenic and spoilage microorganisms.[19] HPP is an alternative to heat processing that provides food safety and extended shelf-life while retaining nutrients and bioactive compounds.[20] Being non-thermal, HPP does not trigger the formation of thermal process contaminants that are formed at high temperature, such as 5-hydroxymethylfurfural (5-HMF).[21] In this sense, a study conducted on commercial heat-treated infant food showed that all tested jams contained 5-HMF, from traces to 72 mg/kg, as well as fruit-based food, whose contents ranged from not detectable to 8 mg/kg.[22] On the contrary, results from SAFFI showed that HPP (600 MPa for 6 min) can be used as non-thermal preservation technology, alternative to heat treatment, in apple and banana-based infant food without inducing the formation of 5-HMF (unpublished data).

It is worth to highlight that consumers perceive HPP as a natural process and more environmental friendly than conventional processes.[23] HPP innovative foods aim to meet consumer demands for minimally processed healthy products with better flavour and fresher appearance compared with the heated ones.[24] HPP of food is an emerging trend in the market of ready-to-eat food, including some infant food products (mainly acidic fruit purees). The current regulation sets microbiological criteria for ready-to-eat infant foods applying zero tolerance against *Listeria monocytogenes*, namely no detection for the pathogen in 10 samples of 25 g (Commission Regulation[25]No 2073/2005 of 15 November 2005 on microbiological criteria for foodstuffs 2005). Several guidance documents published by public health authorities recognise HPP as a technology contributing to the control of this pathogen in ready-to-eat food.[26], [27], [28], [29] HPP is also recognised as a suitable technology to design a control measure to inactivate the pertinent pathogens (e.g. *E. coli* O157:H7, *Salmonella* spp.) in fruit juices.[30]

To develop the case studies listed above, the SAFFI approach consists in the quantification of the fate of key chemicals (degradation, generation, migration) and the behaviour of the identified microbiological hazards (growth or inactivation) along the four infant food chains selected as case studies. Following, few examples on how the research is addressed are described.

2.4. Control of furan, a key process-induced toxicant in infant food

Furan is a highly volatile molecule, which is classified as a possible carcinogen for humans.[31]. The European Food Safety Authority[32] reported a high furan exposure in infants ϕ0.09–0.22 μg/kg.b.w/d) and toddlers 0.05–0.31 μg/kg.b.w/d). For toddlers, most of the exposure is related to consumption of jarred baby foods, fruit juices, milk-based products and cereals-based products; whereas for infants, the major sources of exposure would be infant formula and jarred baby foods. In 2016, ANSES published a report on the total diet for infants and toddlers.[33] In children under 3 years old, dietary exposure to furan was considered to be of concern, especially for breakfast cereals, jarred vegetable with or without meat or fish, placing furan at the top of the list of priority hazard.[34],[35] In the case of infant foods, furan can be formed from amino acids, carotenoids, ascorbic acid, lipids[33],[35] and carbohydrates[36] during thermal preservation processes such as pasteurization or sterilization (Fig.1). management rely on the availability of robust and reliable methods for quantifying furan in infant food in laboratories and monitoring on production lines. It would also require mitigation strategy to control its formation during industrial processes and suitable recommendations to limit child domestic exposure.

Today, furan is generally quantified by solid phase micro-extraction (HS-SPME) coupled with gas chromatography-mass spectrometry (GC–MS).[37] In HS-SPME, a polymer attached to metal rod adsorbs the volatile molecules present in the headspace of the sample, and in particular the furan, which are then quantified by GC–MS. HS-SPME has the advantage of concentrating the analyte, which is very interesting when it is present at trace levels.[33] In counterpart, the competition phenomena between volatile species[36] resulting from the limited adsorption surface of the fibers[37] together with their poor manufacture reproducibility leads to a relatively poor precision of quantification based on this extraction mode. Two alternative options can be considered to overcome this problem. The first one is to circumvent the competition phenomena by using an extraction technique with similar advantages but implementing a fibre with a larger adsorption surface. With this in mind, Dynamic Headspace (DHS,[38]) is now automated and may represent a first valuable alternative to HS-SPME. The second option relies on using static headspace (SHS) extraction. Sampling is done with a syringe inserted at thermodynamic equilibrium between the headspace and the sample. As it does not involve an adsorbent trap, this method is reproducible because there is no competition phenomenon or composition variability. On the other hand, it does not allow the concentration of the analyte in the headspace inducing a significant drop in extraction yield. Presently, this limitation could be compensated by using modern mass spectrometer like Q Exactive-HRMS-Orbitrap®, which are much more sensitive than MS quadrupole.

The three previous analytical options are within the reach of reference laboratories but remain too costly and cumbersome to implement for routine self-monitoring by manufacturers. In this view, a non-targeted approach could be developed to determine compounds that are markers of furan formation, which would be much easier to analyse. By analogy with metabolomics, which consists in studying the variations in the metabolism of a biological organism in response to a stress factor, this new approach might consist in studying the variations in chemical reactions within a matrix in response to different process conditions and might be named procedomics. In the case of thermal preservation processes involved in the generation of furan, it could consist in identifying robust volatile marker of the generation of furan in the volatile fraction of transformed infant products.

Both furan quantification and procedomics would enable to study the effectiveness of furan mitigation by so-called non-thermal and alternative heating processes such as HPP and RF. This include determining the levels of furan generated during these processes, optimizing the influencing parameters and finally, benchmarking mild processes against conventional ones in terms of furan mitigation. It will also rely on setting appropriate recommendations in order to limit domestic exposure to furan via infant food consumption, by identifying hazardous practices by means of surveys on consumption practices (e.g. reheating with water bath, microwave), then determining the levels of furan generated by these practices, assess the risk of exposure in order, *in fine*, to propose the best practices to recommend.

2.5. Control of tropane alkaloids, natural contaminants from weeds

Tropane alkaloids are a class of plant toxins with more than 200 compounds that occur in a wide range of plants in the Solanaceae, Brassicaceae, Convolvulaceae and Moraceae families.[39] Some of these plants, such as potato, aubergine and tomato, are directly consumed by humans, while others can be found in agricultural crops due to accidental harvesting of weeds. For instance, it is well known that seeds of *Datura stramonium* with high levels of tropane alkaloids can be found in cereals such as millet, sorghum, buckwheat, sunflower and linseed.[40]

Most relevant tropane alkaloids are atropine (racemic mix of R- and L-hyoscyamine) and scopolamine. Intoxication by these compounds leads to anticholinergic effects such as dry mouth, blurred vision, muscle spasms, tachycardia, malfunction of the central nervous system, and death in most severe cases.[41] In the EU, the maximum levels of tropane alkaloids in food are set by the Commission Regulation (EC) No 1881/2006[42], namely 1.0 μg/kg atropine or scopolamine in processed cereal-based foods and baby foods for infants and young children, containing millet, sorghum, buckwheat or their derived products.

Nevertheless, the presence of tropane alkaloids above these limits has been documented in cereal-based foods for infants and children.

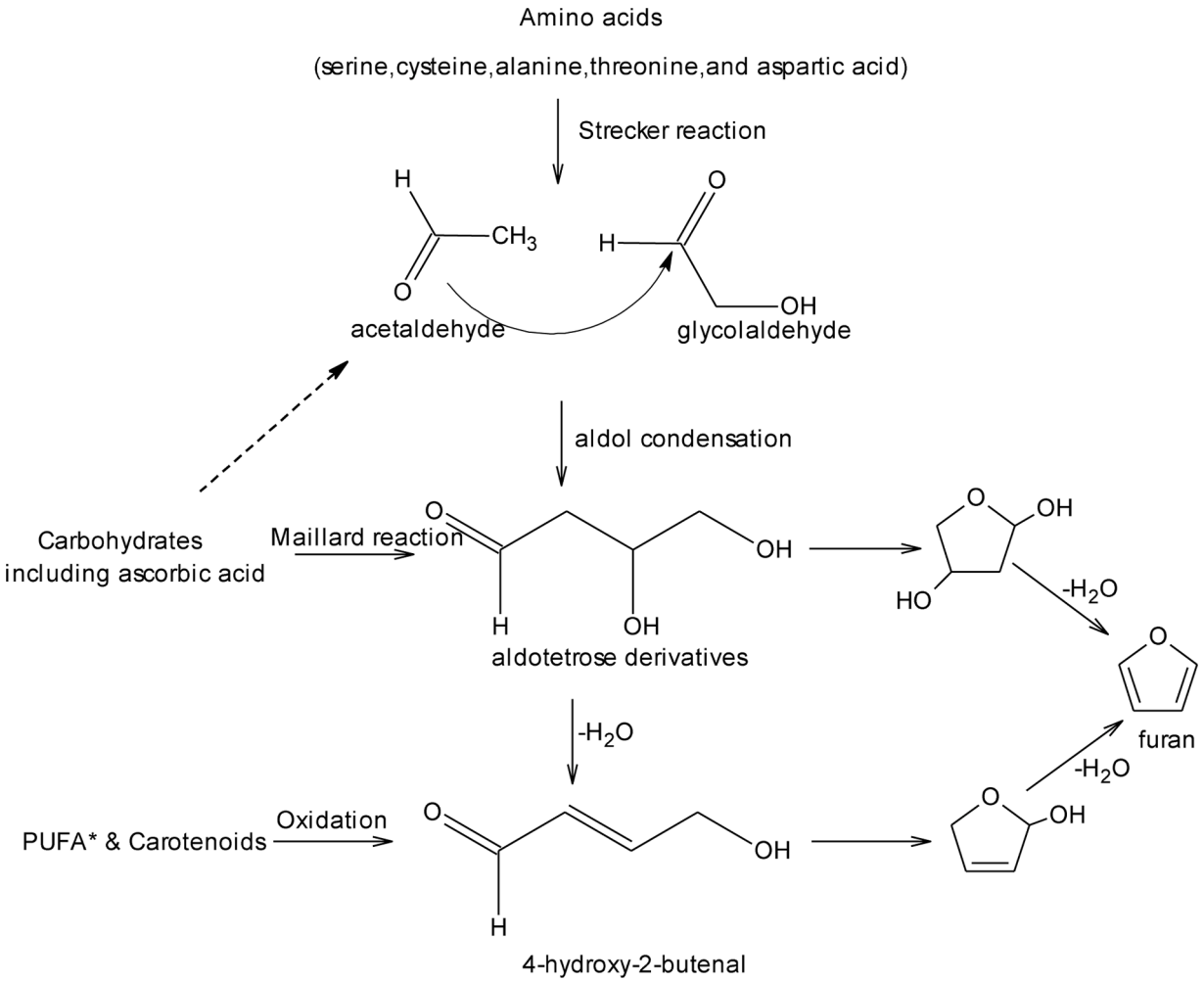

Fig. 1. Different origins of the parent furan formation. *PUFA = polyunsatured fatty acids.

According to a survey in the Netherlands in 2011, 2012 and 2014, an average of 4.6, 4.4 and 0.5 μg/kg (respectively) was found in cereal-based food for infants and young children, with maximum levels of 80.8, 57.6 and 3.9 μg/kg, respectively.[43] Another survey found that 20% of cereal-based foods for young children (6–36 months) contained one or more tropane alkaloid, and amongst food groups, the highest mean concentration (130.7 μg/kg) was detected in cereal-based meals for children.[44]

Therefore, it is necessary to update or set up new strategies to control tropane alkaloids in infant food. In this sense, the SAFFI project is working in the assessment of the effect of food processing technologies, such as conventional spray drying or the emerging PCD technology, on the fate of tropane alkaloids in infant cereals. The effect of processing parameters such as pH, temperature and treatment time on the stability of these contaminants will be determined. Furthermore, the project aims to provide sampling, monitoring and analytical strategies to be implemented by infant food companies to establish an accurate and efficient control of these contaminants. A new analytical approach will be proposed, based on existing validated state-of-the-art methods for the determination of tropane alkaloids. These methods include extraction with acidified aqueous-organic solvents, purification steps and chromatographic analysis by LC-MS/MS.[44,45]

2.6. *Effect of infant food processing on bacterial pathogens*

Amongst the microbiological hazard identified in the infant food chains within the SAFFI project activities, both spore forming pathogens (*Bacillus cereus, Clostridium botulinum*) and vegetative bacterial pathogens (entero-haemorrhagic *Escherichia coli, Salmonella* spp. *Cronobacter sakazaki, Listeria monocytogenes*) are of relevance for different type of infant foods. The microbial resistance to heat and other processing technologies depends on several factors,[46,47] including:

- Microbial related factors such as type of microorganism (i.e. spores being much resistant than vegetative cells), though differences at species and strain level may also be considerable. The physiological state of the cells and the conditions to which a microorganism is exposed to prior to any treatment are also of paramount importance, as they may trigger resistance mechanisms and make bacteria more robust towards preservation and processing treatments.
- Product related (i.e. intrinsic) factors such as pH, water activity and specific compounds (natural or intentionally added as part of the product formulation) that may sensitize or protect microbial cells against other stresses.
- Extrinsic factors such as technological parameters associated with the processing and preservation technologies (temperature, pressure, etc.).

All these factors need to be considered when evaluating the efficacy of the control measures when both classical and new/emerging technologies are applied. With the aim of developing a prototype of a decision support system (DSS) for hazard control, the SAFFI project aims to collect information available in the scientific literature regarding the behaviour of relevant pathogen associated with specific processing and

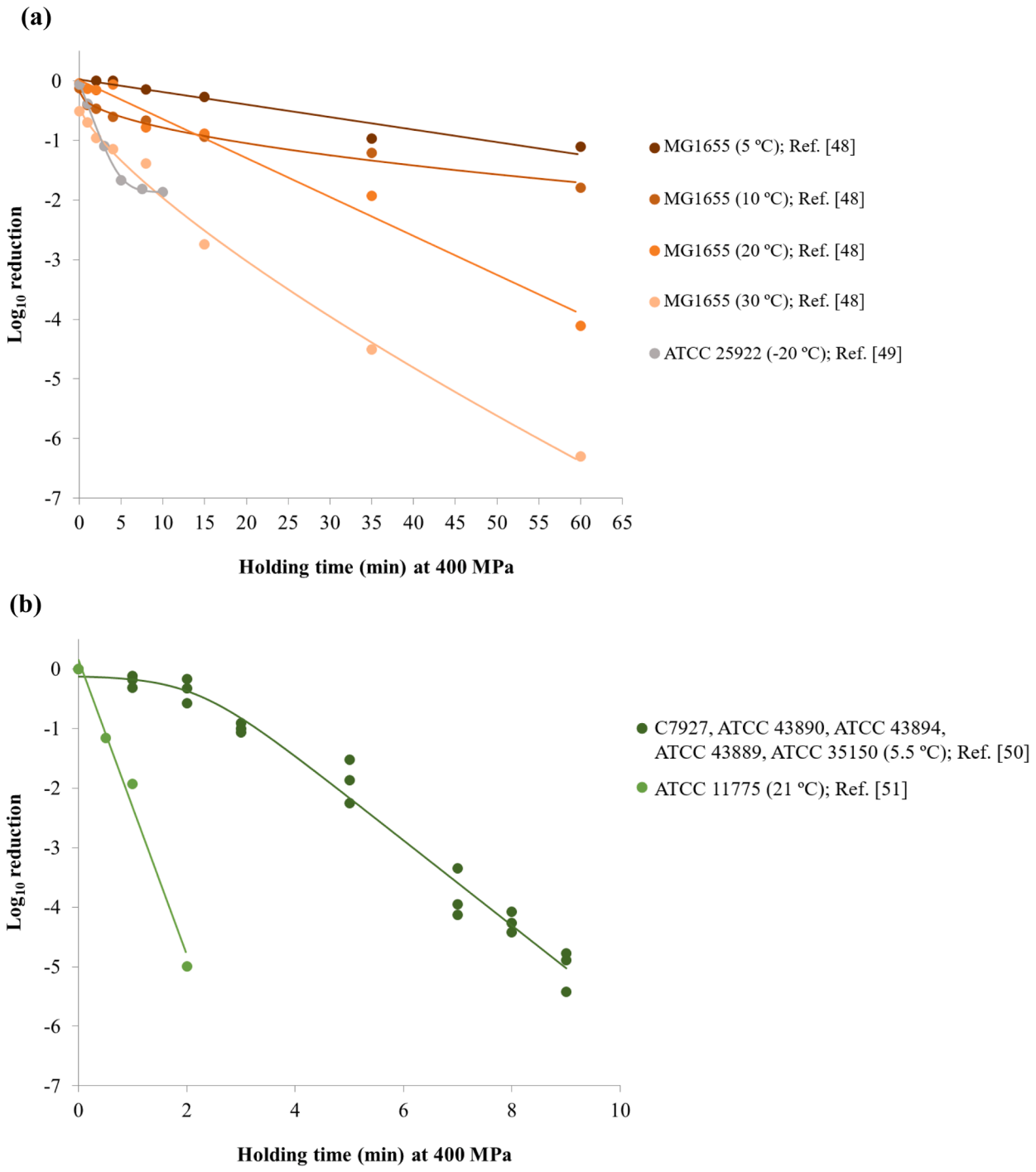

Fig. 2. Inactivation (Log_{10} reduction) of different strains of *E. coli* in apple (a) and carrot (b) juice during high pressure processing at 400 MPa at different temperatures. Data extracted form References[48–51].

preservation technologies considered in each case-study. A wide variability of the microbial response is usually recorded when different studies are gathered, which can be related to the differences in the used methods and design of experiments, covering different factors and ranges of conditions. For instance, Fig. 2 shows the inactivation of *E. coli* reported in different scientific articles during HPP of apple and carrot juice, and inactivation kinetics depend on the product, the strain and the temperature.[48–51] Statistical meta-analysis and mathematical modelling strategies can be useful to integrate the results of individual studies and find global estimate of kinetic parameters with their corresponding variability.[52] A meta-analysis can also point to factors that have a significant and main impact on the kinetic parameter.[53] The outputs of meta-analysis are also useful to guide the design of new inactivation experiments and can give a first impression on the efficacy of a processing or preservation treatment. SAFFI will further build on the meta-analyses, and also perform validation studies on pilot plant scale. In these cases, appropriate non-pathogenic microbial surrogates are often used to mimic the behaviour of the target relevant pathogen in the evaluated process.[5] Also here the meta-analyses can give guidance and can be used as benchmark to evaluate whether the surrogate of choice is a good alternative for the target pathogen. In the SAFFI project, experimental work will also address the occurrence of sublethal injury of

pathogens upon product treatment, because sublethally injured cells might recover and growth out in the food product during shelf lifeFig. 1.

This complementary approach, collecting targeted experimental data using a well-designed experimental approach and combine these data with available literature will result in project outcomes with more confidence then when only based on experimental efforts.

Declaration of Competing Interest

Authors declare no conflicts of interest

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