**Recent progress on the management of the industrial washing of fresh produce
with a focus on microbiological risks**

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Abstract

Sanitizers are an effective measure to maintain the microbiological safety of fresh produce process water. Proper water disinfection management is critical to avoid cross-contamination during the washing of fresh produce. Chlorine remains the most common sanitizer, and recent research deals, among other topics, with the comparison of different types of chlorine sources, optimization of doses for each product type and format, on-line monitoring systems, and mathematical modeling for process management. Peracetic acid (PAA) is the main industrial alternative but further research for the optimal dose and in-line monitoring and control systems is guaranteed. A plethora of other treatments are tested at a laboratory scale, but only a few are assessed under industrial conditions. Recent advances in the management of industrial fresh produce washing are presented and discussed.

Keywords: Wash water; Water reuse; Microbiological Hazard; Food safety; Disinfection

Introduction

Consumers perceive fresh produce as microbiologically safe [1]. However, fresh produce can get contaminated with pathogenic microorganisms at both the pre-harvest and post-harvest stages. Unfortunately, the source of contamination in most of the foodborne outbreaks linked to fresh produce cannot be identified [2]. In the cases where the source of contamination is known, the most important sources include the use of contaminated seeds and/or contaminated water and the handling by infected individuals [2,3]. Water has been identified as one of the most relevant risk factors at the pre-harvest level when used for irrigation or crop management products such as fertilizers [4], and at the post-harvest level facilitating cross-contamination during washing [5,6]. The selection of a suitable wash water treatment together with proper management are essential practices to avoid cross-contamination, reducing the microbial risk linked to the consumption of fresh produce. Novel approaches to the use of water disinfection treatments have been reported during the last years [7]. However, due to different reasons, including cost, complexity of implementation and management, workers' safety, deleterious effects in produce quality, legislation, and suitability to avoid cross-contamination in process water, only a few methods are currently used in commercial settings. Therefore, despite a large number of different water disinfection treatments available, current research approaches focus on the optimization of the use of industrially relevant methods, specifically chlorine and peroxyacetic acid (PAA) [8,9]. This review aims to compile the latest advances in the management of fresh produce washing in industrial settings, with a focus on microbiological safety.

Cross-contamination during the washing of fresh produce

For most fresh produce types, washing is a necessary step for the removal of dust, soil, debris, and pesticide residues [10]. Furthermore, washing can also be used to cool down the products and move them along the processing line [11]. The washing step, if properly managed, can also achieve some reductions in the microbial load of the product [8], including pathogenic microorganisms [12]. The washing procedures at the industrial scale can vary depending on: the type of product (leafy greens, berries, tomatoes) and the format (whole product, fresh-cut, microgreens). Furthermore, for the same product and cut size, there can be differences between facilities in equipment design and management practices including type of sanitizer and washing practice (pre-wash, single-wash, double-pass) [8,13"] (Figure 1).

The concept of microbial cross-contamination refers to the microbiological contamination of produce through contact with contaminated materials (e.g., water, produce, machinery) [14]. Process water recycling is necessary to increase the sustainability of the industry, but it can lead to a cross-contamination risk if inadequate practices are performed [15]. To avoid cross-contamination *via* process water at industrial settings, the proper use of antimicrobial treatments is a crucial strategy [16,17]. As in previous studies [5,18], Banach *et al.* [19] confirmed the need to disinfect fresh produce wash water to avoid microbial cross-contamination in a study testing chlorine dioxide at a pilot-plant scale. Apart from the use of sanitizers, other aspects of washing management can affect the risk of microbial cross-contamination. For example, it is necessary to confirm if produce/water ratios influence the likelihood of cross-contamination [20,21]. In addition, particulate material present in the wash water is a potential vector for cross-contamination with pathogens [22]. Interestingly, mathematical modeling is being used to gain insight into the cross-contamination problem [6,23"], indicating the most efficient interventions to mitigate it.

88 **Industrial wash water treatments**

89 The regular practice of water recycling for fresh produce washing and the risk of
90 microbial cross-contamination highlight the need to use chemical sanitizers [24].
91 Chlorine is still the most used sanitizer in the fresh produce industry and has received
92 more attention than any other sanitizer [25^{**}]. The most critical disadvantage of the use
93 of chlorine is the formation and accumulation of disinfection by-products [26]. A
94 potential alternative is the use of chlorine dioxide, which is already used at the industrial
95 scale [27]. However, the use of chlorine dioxide can also lead to the presence of
96 disinfection by-products in the wash water and in the washed products [19]. Peracetic
97 acid would be the best alternative as a less controversial agent due to the public health
98 concerns of disinfection by-products [17,28]. PAA has shown efficacy in avoiding cross-
99 contamination with pathogenic microorganisms during the crisping of lettuce heads [29].
100 *Banach et al.* [30] confirmed the suitability of PAA for the washing of fresh-cut lettuce
101 at the industrial scale. PAA has a higher cost and slower microbial inactivation kinetics
102 compared to chlorine [31], but is less reactive than chlorine with the organic matter
103 present in the wash water [32]. In any case, the presence of substances other than PAA,
104 hydrogen peroxide, and acetic acid in the commercial solutions needs to be taken into
105 account (e.g., stabilizers; [33]).

106

107 **Water Disinfection Management**

108 Independently of the selected water disinfection treatment, the fresh produce
109 industry needs to use Standard Operating Procedures (SOPs) for the correct management
110 of process water. Such thorough control is required due to safety, economic, and
111 environmental reasons. For example, the concentration of the antimicrobial agent and (if

possible) its demand should be monitored regularly using appropriate sensors, as inaccurate measurements can result in overdosing with high-cost implications and health concerns or underdosing with unsafe washing practices [34]. In the case of chlorine, the concentration of free chlorine and the pH in the process water should be thoroughly monitored and fine-tuned. Different studies support a minimum operational limit of 10 mg/L free chlorine for leafy greens [5,25^{**}]. However, the operational limits are specific of each product and format [35^{*}]. According to Tudela *et al.* [35^{*}], high free chlorine is needed for baby leaves (>30 mg/L), medium levels for shredded lettuce and cabbage (20-25 mg/L) and low levels for diced onion (10 mg/L). Ideally, free chlorine levels would be managed through dosing strategies based on in-line measurements to be adjusted rapidly for each specific case [36,37].

The control of water sanitizers during produce washing relies on knowing how much sanitizer to use but how, where and when to accurately measure its amount/activity. If any water parameters are related to physicochemical and microbial water quality, they must be measured too. For example, the potential use of the oxidation-reduction potential (ORP) for the real-time monitoring of chlorine in fresh produce wash water was recently assessed by Van Haute *et al.* [38^{*}]. These authors concluded that the prediction of free chlorine levels based on the ORP is affected by many factors, limiting its usefulness for the monitoring of free chlorine in the process wash water. Other studies have observed a lack of correlation between ORP and the concentration of free chlorine [34]. For PAA, Ghostlaw *et al.* [39] suggested that organic load, temperature and pH are the parameters that should be monitored overtime to ensure that water quality and safety are maintained. Our results have shown that, being PAA an organic acid, the measurements of organic load and pH are not always useful for managing PAA residual concentrations. For chlorine, pH levels below 6.5 should be maintained, using appropriate pH regulators.

Citric acid should be avoided as it leads to the formation of DBPs [40]. Our group has studied in more detail the impact of different pH regulators (phosphoric, sulfuric, carbonic and citric acids) on the generation of chlorates, haloacetic acids (HAAs) and trihalomethanes (THMs) (A Marin *et al.*, unpublished). The authors recommend phosphoric acid as pH regulator based on the low levels of both THMs formation and emission of chlorine gas. Organic matter levels in water can have consequences for the efficacy of the sanitizers and the generation of halogenated disinfection by-products. Teng *et al.* [41] observed a direct negative effect of the presence of organic matter in the water in the inactivation efficacy of chlorine even when stable chlorine levels are maintained. Van Haute *et al.* [42*] concluded that the use of UV absorbance for the real-time estimation of the chlorine demand of fresh produce wash water is promising. However, the authors admit that the application of this parameter can be hindered by factors such as the variability in the correlation between chlorine demand and UV absorbance among crops of the same vegetable and due to the possible interference by the pH regulators. Srinivasan *et al.* [43*] developed a product-specific mechanistic model to predict free chlorine dynamics during the washing of fresh produce. Li *et al.* [44] proposed the measurement of total dissolved solids (TDS) for predicting organic load and chlorine reactivity. Qi *et al.* [45] also indicated the effect of organic matter and concluded that UV254 is the primary indicator of the organic load effect. For PAA, monitoring the demand in the wash water is difficult due to the organic nature of this disinfectant, that is detected by common organic matter measurements (e.g., chemical oxygen demand, COD). At the industrial level, PAA can be monitored in real time using amperometric sensors that should be calibrated and validated using suitable methods such as chronoamperometry [17, 34, 46]. In some cases, the measurement of turbidity could help for the assessment of the physicochemical quality of PAA-treated wash water [17].

Alternative methods

Alternative antimicrobial treatments that have received considerable attention in recent years include the use of natural compounds, bacteriophages, and cold plasma. Although lab-scale research on essential oils and other natural compounds as antimicrobial treatments has proven potential application as wash water sanitizers [47], their application in the washing stage at an industrial scale is improbable due to reasons such as the high cost and the lack of monitoring methods. Bacteriophages are being proposed as a tool for the biocontrol of pathogenic bacteria in fresh produce, but their use as a wash water treatment in the produce industry is not realistic [48^{*}]. Although plasma activated water has been tested at a scale relevant to the produce industry [49^{*}], more information on the safety of this technology is needed [50]. Cross-contamination *via* water can also be minimized by using systems alternative to the usual flume systems. For example, a single-pass immersion-free washing system for fresh-cut leafy vegetables has been successfully tested [13^{**}].

Hurdle technology

The hurdle approach consists of the application of different mild treatments to ensure microbial safety while avoiding deleterious effects in the quality and the chemical safety of the product [51]. The use of various low-intensity treatments can make the operation more sustainable regarding its energy costs and production of residues. Low ultrasound doses can be applied in combination with other treatments (e.g., natural compounds), to treat wash water without causing sensory damage to the product [52,53]. According to Pietrysiak *et al.* [54], the use of hurdle technology would give the best results for controlling *Listeria monocytogenes* in the fresh apple industry. For apple

187 packing, the authors suggest the use of the following sequence of treatments (hurdles): 1)
188 water rinse, 2) brush cleaning using surfactants, 3) rinse with sanitizer solution, 4)
189 application of antimicrobial wax. In spite of the potential benefits, the application of
190 combined treatments is not common at industrial scale, probably due to the complex
191 management and the additional cost.

193 **Conclusions**

194 For most fresh produce, washing is a necessary step in processing plants and
195 packinghouses. Due to sustainability reasons, the wash water is usually recycled, leading
196 to a cross-contamination risk with pathogenic microorganisms. As a consequence,
197 measures to avoid cross-contamination *via* water at industrial scale are needed. Although
198 many methods are tested at laboratory scale, due to different reasons (legislation,
199 technical issues, affordability), only a few are actually used by the industry. Chlorine is
200 still the most used wash water treatment, with abundant new research devoted to
201 optimizing its use. Peracetic acid is the more consistent alternative to chlorine and is
202 already being applied at industrial scale. Future research should deepen on different
203 relevant aspects for PAA use, such as the monitoring and control of PAA levels in wash
204 water by in-line sensors, the presence of stabilizers in the washed product, and the
205 minimum levels needed to avoid cross-contamination. In the topic of fresh produce
206 washing as well as in others (e.g., pre-harvest contamination), the continuous effort and
207 the collaboration between the industry and the research community is improving the
208 safety of fresh produce for the benefit of society.

210 **Declaration of interest**

211 None

Author contributions

Francisco López-Gálvez: Writing- Original draft preparation, Writing- Reviewing and Editing. Maria Isabel Gil & Ana Allende: Supervision, Writing- Reviewing and Editing.

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460 **Figure captions**

461 **Figure 1.** Illustration of different washing procedures used for different types of products.
462 Top: immersion in an open system for the washing of fresh-cut leafy greens; bottom left:
463 shower+waterfall in an open system for bell pepper washing; bottom right: immersion in
464 a closed system for the washing of shredded vegetables (e.g., carrot).

465 **Figure 1.**

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