Efficient management of the water resource in the fresh-cut industry: Current status and perspectives

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Efficient management of the water resource in the fresh-cut industry: current status and perspectives

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Abstract

Among the different food industries, fresh-cut produce manufacturing is one of the major water-intensive, due to the huge consumption of potable water to perform washing operations required to guarantee the safety and quality of the product. Reducing the water footprint of washing is thus a challenge for fresh-cut industries and food researchers. This review paper examines the current status of the water resource management in the fresh-cut industry and critically describes a comprehensive approach to the improvement of the water use efficiency by implementing strategies of water recirculation, reuse and recycling.

Keywords: fresh-cut, washing, water saving, decontamination, recycling

Introduction

Water is at the base of humankind's survival and living organisms depend upon it to complete their life cycle and further contribute to natural cycle (Hong-Bo, Li-Ye, Gang, Jin-Heng, & Zhao-Hua, 2007). Issues relevant to population increase, deterioration of surface water quality and climate changes are increasingly requiring to secure water supplies and alleviate environmental loads (EEC, 1991).

Food production and processing are known to account for the majority of water use globally (Foster et al., 2006). In this sector, the fresh-cut industry is one of the major water-intensive. Water consumption and wastewater volumes are generally in the range of 2-11 m^3/t and 11-23 m^3/t of fresh-cut product (FDM-BREF, 2006; Ölmez, 2014). These huge amounts of water are mainly discharged to surface water and make the fresh-cut industry difficulty fitting with nowadays global water scarcity. This issue is expected to become particularly critical in the next years, due to the intensification of the demand for fresh-cut produce in developing countries. The minimization of water use and wastewater discharges are thus big challenges for the fresh-cut industry that will be increasingly required to implement sustainable strategies for water saving (Ölmez & Kretzschmar, 2009; Gómez-López, Gobet, Selma, Gil, & Allende, 2013).

By focusing on the eco-efficient management of water, new opportunities and technologies for the environmental performance improvement, that can be also cost-effective, are increasingly under study and possibly applicable for water saving in fresh-cut production. In any case, the actual contribution of these interventions to the sustainable development of fresh-cut vegetable washing strictly depends on the benefits justifying their cost (Fig. 1).

Any innovation allowing washing operations with increased eco-efficiency is required to guarantee, or increase, the safety and quality characteristics of the product in line with industry norms. Yet there must be a return on the investment. Beside tangible profit, non tangible benefits could also come from the opportunity the company may have to build an eco-friendly image. In addition, there is the possibility that some countries will be more specific on the type and amount of certain chemicals allowed in the waste water discharges and known to be ecologically undesirable. This approach could eventually contribute to justify additional costs involved in water saving interventions.

This review paper analyses the current status of the water resource management in the fresh-cut industry, identifying possible strategies for improving water use efficiency and increase the overall sustainability of the production.

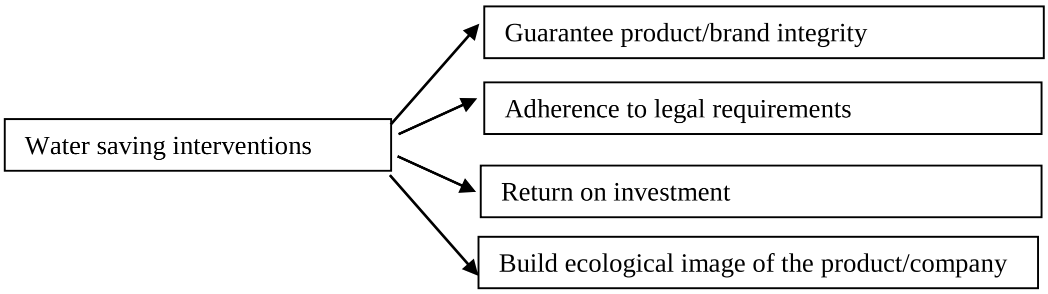


Fig. 1. Requirements for sustainable water saving intervention.

Water management in a typical fresh-cut vegetable production

Fig. 2 shows the flow of the product in a typical fresh-cut industry. The majority of water is used to perform washing operations, including primary washing to remove gross contamination, a number of consecutive immersions of the product in washing tanks and a final rinse step. Subsidiaries activities requiring water supply are cleaning and sanitizing operations as well as domestic necessities (toilets and staff usage). Current productions generally use water with different properties depending on the nature of the operation to be performed. Water added with chemical disinfectants, such as chlorine and its related compounds, is used to perform the washing steps. The latter include primary washing as well the consecutive passages in washing tanks. The number of passages depends on the organisation of the production flow. By contrast, the final rinsing of vegetables is performed with fresh tap water to remove disinfectant residues. Similarly, tap water is also used for plant cleaning and removal of disinfectants and detergents used to this aim.

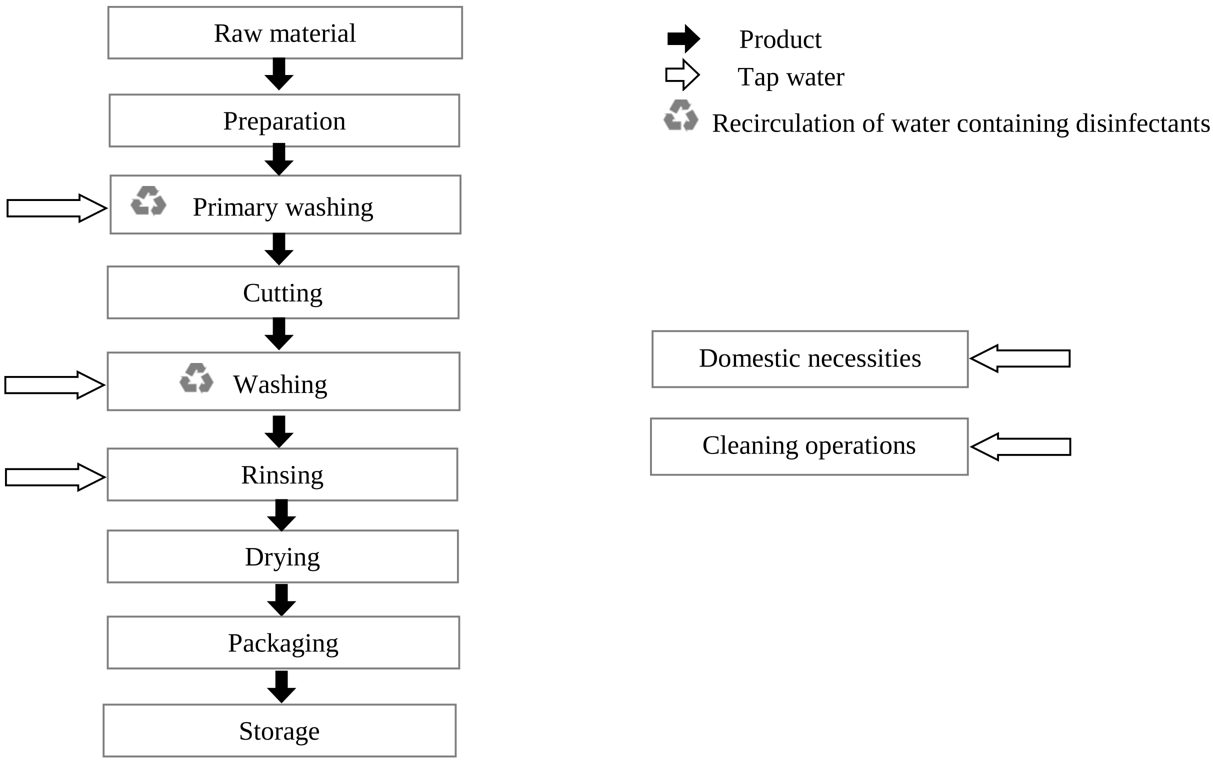


Fig. 2. Flows of product and water in a typical fresh-cut production process.

Efficient water management

In the attempt to develop efficient strategies for water saving, the first step is performing a review of the water used within the industry, considering each operation requiring water. This implies a holistic review of what water is actually used for the different applications and the characterisation of effluent water qualities, also in relation to legal requirements. The output is the description of the water flows to/from the production process and represents the water management plan of the industry. By analysing the water management plan, eventual corrective actions for water conservation can be identified and possibly tested. For instance, major savings could be generated by simply controlling leaks or improving on-site cleaning and operating practices. It is evident that the follow-up of any corrective actions should be performed to assess their effectiveness and eventual drawbacks. Following the implementation of the identified water saving interventions, a novel water management plan with improved efficiency is expected to be produced. The main steps for cost-effective use of water resource have been summarised by Williams and Anderson (2006).

It is clear that special attention should be paid when analysing water needs and developing possible water saving interventions potentially applicable to the washing operation. Contrarily to a commonly diffused belief, these huge amounts of water are not required to decrease the vegetable microbial count. The microbial load of vegetables entering the fresh-cut industry may range from 5 to 9 Log units, depending on type of salad, cultivation system, harvesting and handling procedures among other factors (Ölmez & Kretzschmar, 2009; Barth, Hankinson, Zhuang, & Breidt, 2010). Cutting operations, typically performed to produce fresh-cut vegetables, are well known to further increase microbial counts, with effects on both product safety and quality (Ragaert, Devlieghere, & Debevere, 2007). An average reduction of *circa* 1 Log unit in microflora is generally achieved upon washing, due to the sole mechanical removal of microorganisms from the vegetable surface by the water turbulent flow (Allende, Selma, López-Gálvez, Villaescusa, & Gil, 2008). If washing would be performed using tap water only, water would rapidly become highly contaminated, reaching microbial counts in the same order of magnitude of the unwashed salad. Tap water should thus be continuously renewed to avoid microbial proliferation and vegetable cross contamination by spoilage and pathogenic microorganisms. This risk is conventionally controlled by adding water with disinfection chemicals, thus allowing in-tank recirculation of wash water over a longer time. The addition of disinfectants in washing water has thus the sole objective of reducing the overall amounts of potable water required for this operation (Fig. 2).

The overall water print of washing largely depends on the rate of water turnover in the washing tanks. The more effective the disinfectant chemical, the lower the risk of cross-contamination. For this reason, the adoption of an efficient disinfectant could allow the water turnover flow, and thus the overall water consumption, to be significantly reduced. Based on these considerations, there has been a flurry of studies on the efficacy of disinfectant chemicals which are conventionally applied or potentially applicable to control microbial contamination of wash water during vegetable washing. These chemicals do not only include traditional chlorine but also additional chlorine compounds, which seem to exert specific advantages, as well as chlorine-free molecules. Following, a schematic description of the main criticisms and potentialities of these molecules is reported. A disinfection treatment is regarded as interesting when allowing at least 5 Log reductions on microbial load of wash water. Despite different chemicals reported in Table 1 are expected to achieve this target, no indications about the effect of the selected disinfectant on the water turnover in the washing tanks is available in the literature.

Chlorine disinfectants

Chlorine is the main disinfectant used worldwide because of its potency, low cost and easy use. As a consequence, chlorine and its related compounds are also the chemical oxidants most widely applied to disinfect washing water in the fresh-cut industry. Levels of 50-200 mg/L of free chlorine allow a 6 Log reduction of microbial load of water to be achieved and decrease the concentration of waterborne pathogens below the regulatory limits (EC, 1998; Codex, 2001; Gil, Selma, López-Gálvez, & Allende, 2009). Due to its oxidative potential, chlorinated water can corrode metal surfaces of processing equipment, reducing their overall life. In addition, as already mentioned, chlorine may react with dissolved organic matter to form carcinogenic and/or mutagenic disinfection by-products (DBP), including trihalomethans and haloacetic acid (Richardson & Ternes, 2005; Krasner et al., 2006). Further criticisms of these disinfectants also include toxicity towards operators as well as the necessity of introducing harmful molecules, such as hypochlorite, in food processing plants. A debate is thus on going on whether to ban chlorine and this decision was eventually taken by different European countries (Germany and Switzerland).

For this reason, any chlorine abuse should be avoided by using the minimum concentration required for the target sanitation level. This implies the knowledge of the chlorine speciation as a function of pH. In water disinfection, gaseous chlorine (Cl_2) and especially sodium hypochlorite ($NaClO$) are generally used as chlorine sources. Under typical wash water conditions (pH>4), hypochlorous acid is generated from gaseous chlorine and NaClO hydrolysis in water. Hypochlorous acid further dissociates into hypochlorite (ClO^-) and H^+ (Deborde & von Gunten, 2008). If the water pH is kept in the range of 6.5-7.5, only hypochlorous and hypochlorite ions are present, while gaseous chlorine concentration is negligible. As hypochlorous acid is the most reactive species against microorganisms, hypochlorite ions would represent a reservoir of HOCl. For this reason, chlorine usage under non-optimal conditions, as occurred in the past, was not only responsible for poor effectiveness in disinfection, but also resulted in an increase of chlorine dose in water up to abuse levels. Nowadays, the decrease in the overall use of chlorine compounds in washing water is simply obtained by their efficient use, following the awareness among operators of the importance of pH measurement and adjustment as well as total, combined and free chlorine concentration determination.

Following the necessity to balance the advantages/disadvantages of chlorination, chlorine based compounds, other than hypochlorite, have also been suggested. In Table 1, the advantages of the main non-hypochlorite alternative compounds (i.e. chloramines, chlorine dioxide and acidified sodium chlorite) as compared to chlorine usage as well as their main drawbacks are shown. More research is certainly required to fully understand their actual efficiency in fresh-cut washing.

More recently, the decrease in chlorine compounds in washing water has also been proposed by exploitation of electrolysed water. It is based on the electrochemical treatments of a diluted (0.5-2 g/L) sodium chloride solution to produce electrolyzed acidic water (pH 2.4-2.8) at the anode and electrolyzed basic solution (pH 11.2-11.6) at the cathode. The neutral electrolysed solution, obtained by mixing these solutions and adjusting pH at *circa* 7.0, is characterised by a redox potential between 600 and 700 mV. Under these conditions, chloride is mainly present as hypochlorous acid, leading to an intense antibacterial effect. Results obtained in the Stayfresh-Ager project has demonstrated that neutral electrolyzed water containing 30 mg/L of free chlorine allows more than 7 Log reductions of *Pseudomonas fluorescens* to be achieved whist the same result is obtained by conventional chlorination of water with hypochlorite at levels higher that 120 mg/L free chlorine (Fig. 3).

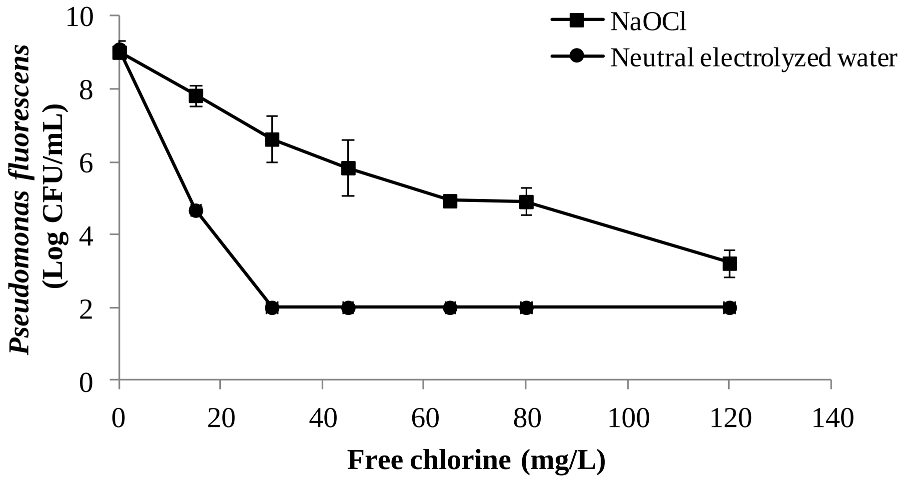


Fig. 3. Counts of *Pseudomonas fluorescens* as a function of free chlorine in water solutions added with sodium hypochlorite or produced by electrolysis of a solution containing sodium chloride.

These data suggest that neutral electrolysed solutions could be particularly interesting to decrease the overall presence of chlorine compounds in washing water without reducing the sanitation efficacy (Tomás-Callejas, Martínez-Hernández, Artés, & Artés-Hernández, 2011; López-Gálvez et al., 2012). In other words, the use of neutral electrolysed solutions could guarantee water turnover in washing tanks analogous to those obtained by using hypochlorite, while reducing the overall concentration of chlorine in water. It is noteworthy that solutions are generated on place, making not necessary the introduction of harmful compounds, such as hypochlorite, within the food industry. In addition, these solutions show minimum adverse effects on stainless steel but rapidly loss their antimicrobial activity. To this regard, investigations are need to either increase the solution stability or develop strategies for the renewal of its antimicrobial potential.

Although the trend of maximisation of the sustainable exploitation of the antimicrobial activity of chlorine compounds, their use is still controversial. Chlorine has been shown to fail killing some viruses and microbes, especially in highly contaminated waters. It has also demonstrated to be ineffective in controlling waterborne pathogens such as *Mycobacterium avium* that is ubiquitous in biofilms within water distribution systems (Shannon, Bohn, Elimelech, Georgiadis, Mariñas, &

Mayes, 2008). These aspects, together with the formation of toxic DBP, call for the development of new disinfection strategies based on chlorine combination or substitution with other chemical disinfectants or natural antimicrobials.

Chlorine-free disinfectants

The main chlorine-free disinfection strategies potentially applicable as alternative to the use of chlorine compounds are shown in Table 1. Among these, ozonation is nowadays the most interesting chlorine-free disinfection strategy for washing water. Ozone is a highly unstable molecule which easily forms hydroxyl radicals. This makes it a strong germicidal agent, used for killing pathogenic bacteria since the first industrial ozonation plant for drinking water was built over a century ago. Nowadays it is recognized as GRAS and widely used in Europe and United States. Due to its instability, ozone needs to be generated on-situ by ultraviolet irradiation of an oxygen containing gas or, more diffusely at industrial level, by corona discharge (Kim *et al.*, 2003). Being a gas at 20 °C, it is allowed to solubilise in the water phase by bubble diffusers, injectors or turbine mixers. During water treatment, ozone concentration may range from values lower than 0.1 to 1 mg/L, although higher concentrations can be also obtained under optimal condition. In water, it quickly decompose to form by-products having a very short life (Kim *et al*., 2003). Being a very strong oxidant, it can show adverse effects on equipment metal surfaces. Several studies have demonstrated the possibility to use ozonised water instead of chlorinated water to perform washing of fresh-cut vegetables (Kim *et al.*, 1999; Beltran, Selma, Marin, & Gil, 2005; Goodburn & Wallace, 2013).

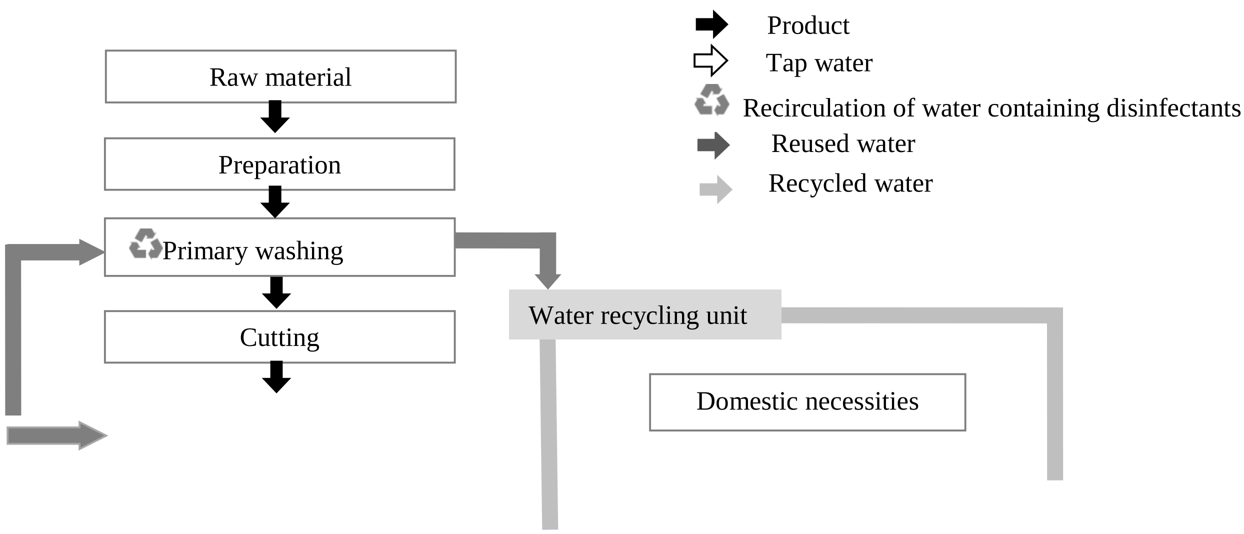
A number of different molecules, other than ozone, having oxidative power or characterised by specific antimicrobial activity have been proposed or are currently under study. A detailed description of their potentialities and criticisms is reported in the literature cited in Table 1.

Once the water management plan has been improved by optimising the rate of water turnover in the washing tanks, further water savings can be achieved by implementing strategies of water reuse and water recycling. Fig. 4 shows, beside the flow of the product, that of water according to these different saving strategies.

Water reuse

Water reuse is based on the exploitation of the water outflow from a given unit operation to perform another one. In this case, negligible changes in water characteristics are carried out before reuse. An efficient process based on water reuse through the different washing steps has been proposed (Gil *et al.,* 2009). Water is recommended to flow in the opposite direction to product advancement along the different washing steps (Fig. 4). For instance, water from rinsing could be incorporated in the washing tanks, and the latter reused in the pre-washing step. Adequate on-line monitoring of the water characteristics is required to keep the washing efficacy under control.

In this case, the investment costs to implement water reuse are justified in terms of reduced fresh-water costs. Even if the return on the investment is not particularly interesting, the implementation of water reuse could be essential in countries experiencing systematic water shortage which would limit the production itself.



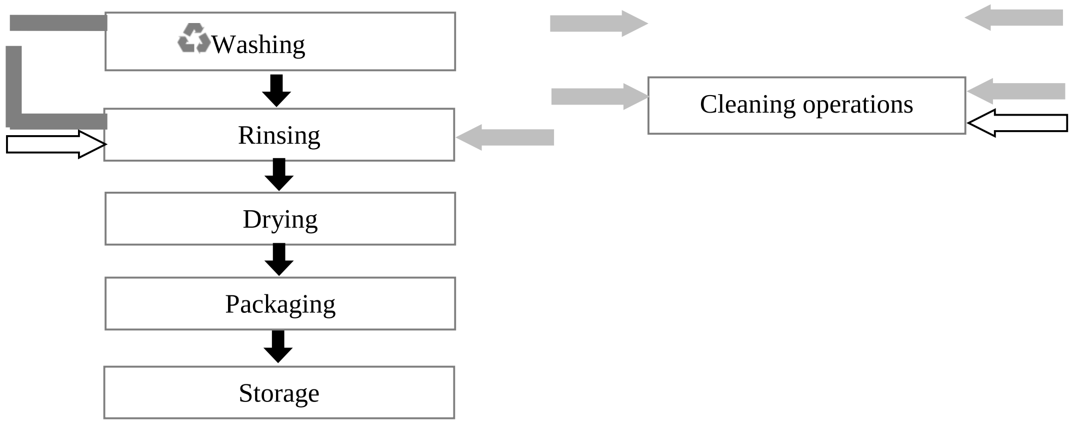


Fig. 4. Flows of product and water in a fresh-cut production process with efficient water management.

Water recycling

Even if water reuse among the washing tanks is performed, a huge amount of wastewater is however produced. It is noteworthy that the largest part of the cost of global wastewater management is pumping and transport from the usage site toward the water depuration treatment site and backwards. Thus, the most efficient solutions of wastewater recovery in any fresh-cut industry should be directly implemented at the production facilities. This concept is at the basis of the development of in-site water recycling strategies. The latter imply specific chemical or physical interventions aiming to modify water properties before re-entering in the production cycle (Fig. 4). Water recycling is more cost-effective than in-tank recirculation and water reuse, since it requires building and setting up of one or more water recycling units. This, in turn, generated the possibility to locally clean wash water and diverge it from municipal wastewater, decreasing the social costs for water treatment and the overall water footprint of the produce. Cleaned water can then be redirected to other internal uses, including not only washing but also plant cleaning and other domestic operations (Fig. 4). When waste water is recycled and intended to re-enter the washing process, microbial disinfection is definitely the main goal. To this regard, it is noteworthy that 5 Log reductions in pathogenic bacteria are generally considered to fulfil the requirement for safe water disinfection and its possible recycling as washing water.

Disinfection of wastewater may be accomplished by different strategies based on the exploitation of physical or chemical stresses, applied alone or in combination, or the physical removal of the contaminating microflora (Table 2).

Although many approaches are virtually exploitable, only a limited number of them actually shows a real applicability to develop water re-circulating units to be implemented in a fresh-cut production line. Among these, the exploitation of light radiation seems very promising. Its antimicrobial effect is due to the ability of ultraviolet light (UV) to damage microbial DNA, blocking DNA transcription and replication thus impairing the cellular functions, eventually leading to cell death (Rame, Chaloupeky, Soikova, & Bencko, 1997). UV light processing is confirmed to be easy to use and characterized by favourable costs of equipment, energy and maintenance (Bintsis, Litoupoulou-Tzanetaki, Robinson, 2000; Guerrero-Beltrán & Barbosa-Cánovas, 2004). It does not leave residues nor forms toxic products (Silva, Lima Filho, Palha, & Sarmento, 2013). In addition, photoreactor design and lamp technology are continuously improving. These aspects led the US Environmental Protection Agency to recognise UV-disinfection as the best current disinfection technology (Hijnen, Beerondonk, & Medena, 2006).

A huge amount of literature data on the germicidal activity of UV radiation is being accumulated since its first application as disinfecting process for drinking water in 1910 (Henry, Helbronner, & Recklinghausen, 1910). Most data refer to kinetics of disinfection of pathogens inoculated in water following its exposure to different doses of UV light (Sommer, Lhotsky, Haider, & Cabaj, 2000; Bintsis *et al.*, 2000). Depending on microorganisms and photoreactor design, a number of Log reductions from 4 to 7 can be easily obtained. Data about the water disinfection by UV-light are not directly applicable for the design of decontamination units for waste water from fresh-cut washing (McKinney, Williams, Boardman, Eifert, & Sumner, 2009; Mounaouer & Abdennaceur, 2012). To this regard, limited literature is available. A 60 min decontamination process of waste water collected from escarole washing in a closed unit was reported to reduce the microbial flora by 4 Log CFU/mL (Selma *et al.*, 2008). The research activity carried out in the Stayfresh-Ager project allowed demonstrating that higher decontamination levels in total viable count and *Pseudomonas* spp. can be achieved in less than 1 min by optimising the thickness of the waste water layer and the UV light dose during the treatment (Table 3). In particular, following the exposure of a 0.4 cm thick layer of wash water to 0.6 kJ/m^2 UV light, more than 4 Log reductions in total viable count were obtained. These levels of fluence completely inactivated pathogens (i.e. *Salmonella enterica*, *Escherichia coli* and *Listeria monocytogenes*) potentially contaminating wash water. The target value of 5 Log reduction in pathogenic bacteria was reached for the most photoresistant bacteria (*E. coli*) at a UV light dose corresponding to 0.4 kJ/m^2.

Although highly efficacious, water decontamination by UV light usually requires treatment times ranging from many seconds to min, depending on the photoreactor design and water thickness. This disadvantage could be overcome by using pulsed light, which can be considered an improved way of delivering ultraviolet radiation (Gómez-López, Devleghere, Bonduelle, & Debevere, 2005). It is based on exposure to xenon lamp flashes, which typically last from µs to ms. Light flashes are characterised by an intense broad spectrum of wavelength which includes not only ultraviolet but also visible and infrared light. The latter are known to strengthen the antimicrobial effects of the ultraviolet radiation by local photothermal effect and photophysical disturbance (Dunn, Ott, & Clark, 1995; Guerrero-Beltràn & Barbosa-Cànovas, 2004; Gómez-López *et al.*, 2005; Krishnamurthy, Tewari, Irudayaraj, & Demirci, 2008). Table 3 shows that, by choosing the proper pulsed light fluence (e.g. 11 kJ/m^2), a rapid disinfection of wash water can be obtained within few ms of treatment. In addition, it was also demonstrated that water recycling in multiple washing cycles significantly affected the spectral properties of wash water due to leaching of chlorophyllian pigments and organic matter (Ignat *et al.*, 2014). However, a significant amount of UV and pulsed light was able to penetrate wash water, yet allowing its efficacious disinfection. Based on this result, recycling up to 5 times of light disinfected wash water did not impair the overall efficacy of salad washing. Although both UV and pulsed light exert interesting potential for developing wash water recycling units, the use of ultraviolet light is nowadays more sustainable from an economic point of view. However, it is not excluded that technological advances in pulsed light processing could make it increasingly affordable in the next years.

As shown in Table 2, ozonation can also be used for decontamination of wastewater. Although several studies have been performed on the possibility to use ozonised water instead of chlorinated water to perform washing of fresh-cut vegetables (Table 1), to our knowledge no information is available on its use as disinfecting agent of waste water from fresh-cut vegetables. Zimmermann *et al.* (2011) evaluated the disinfection capacity of ozonation in a full-scale municipal wastewater treatment to be 0.5-2.5 Log reduction for *E.coli*. Indeed, the availability on the market of different devices to generate high ozone concentration at reasonable cost certainly focus the operators attention on this technology which is potentially implementable to recycle waste water in a fresh-cut line (Goncharuk *et al.*, 2008; Bialoszewski, Bocian, Bukovska, Czajkowska, Sokół-Leszczńska, & Tyski, 2010).

Power ultrasound has been suggested as a possible technology to achieve microbial decontamination of wastewater (Piyasena *et al.*, 2003; Blume & Neis, 2004). It is based on the application of ultrasound frequencies higher than 20 kHz, that can be regarded as safe, non-toxic and environmentally friendly (Kentish & Ashokkumar, 2011). Ultrasounds are known to promote cavitation phenomena into the liquid medium with formation of rapidly alternating compression and decompression zones. The latter lead to the development and collapse of small bubbles, thus generating: (i) shock waves associated to local very high temperatures and pressures; (ii) liquid micro-flow; (iii) formation of free radicals and hydrogen peroxide. The efficacy of water disinfection by ultrasound depends on power input, exposure time and microorganism nature (Hulsmans *et al.*, 2010). Literature data indicates that decontamination of water using ultrasound alone does occur but not very rapidly. Inactivation of pathogenic microorganisms is generally reported to be in the 1-2 Log reduction range, difficulty meeting the requirements for water potability. When ultrasound treatments were applied to inactivate *Escherichia coli* O157:H7 in fresh-cut vegetable wash water, a number of Log reduction approaching 5 was only obtained in treatments time not compatible with industrial processing (60 min) (Elizaquível *et al.*, 2011). Anese (2015) demonstrated that the decontamination efficacy of pathogenic microorganisms (*L. monocytogenes, E. coli, S. enterica*) in wash water derived from lettuce washing was the result of the contribution of two different effects: the acoustic stress to the microorganism and the ultrasound-induced thermal effect. The latter would largely prevail in the case of heat sensitive microorganisms, such as *E. coli* and *S. enterica*.

When a single technology fails in adequately disinfect waste water, decontamination could however be achieved by combining different processes, thus begetting hybrid technologies. For instance, ultrasounds could be applied in conjunction with other disinfection methodologies, such as light irradiation or ozonation (Mason *et al.*, 2003; Blume & Neis, 2004; Hulsmans *et al.*, 2010). Selma *et al.* (2008) proposed a hybrid process based on water decontamination in a UV-O_3 reactor, demonstrating a microbial reduction of 6.6 Log units after 60 min of water treatment. The disinfection efficacy was found to be higher than that of O_3 and UV applied separately. Paleologu *et al.* (2007) studied the possibility to apply H_2O_2-assisted UV/TiO_2 photo catalysis to completely inactivate *E. coli* in wastewater. Disinfection processes can also be combined with membrane separation techniques. The latter are based on the use of microfiltration or ultrafiltration to clean wastewater and redirect it to industrial use. In particular, reverse osmosis followed by UV disinfection or photo catalysis have been claimed to potentially produce water with potable characteristics (Shannon *et al.*, 2008). The development of a hybrid technology, although apparently more cost-effective as compared to individual techniques, may allow the application of each disinfection stress at a lower intensity level, potentially decreasing the operative cost over the long period. The discussion about the actual sustainability of hybrid technologies is the starting point of future research.

Conclusions

There has been much research into the quality and safety of fresh-cut produce. Production techniques, shelf life extension strategies, packaging technologies have mainly concentrate the efforts of the scientists in the last decades. Due to these advancements, produce with high quality standards is now available. Fresh-cut vegetables consumption seem to be stable in industrialised countries but dramatically increasingly in developing ones. Is the water footprint of such a production globally sustainable?

If the water consumption issue in industrial vegetable washing will be not carefully considered, a significant increase in the environmental (increase in waste water containing ecologically undesirable chemicals and characterised by high BOD and COD), social (waste water treatment cost) and health (toxicity of water disinfectants and by products) risks is expected in the future.

Fortunately, a recent flurry of activity in water treatment research is offering opportunities in mitigating the impact of this industrial sector. The expectation is that by focusing on the implementation of systems of efficient management of the water resource, sustainable, affordable, safe and robust methods to decrease water consumption in the fresh-cut industry can be developed and implemented. The time required for this to occur will not only depend on the capability to import knowledge and skills from the water purification sector but also on the availability of an adequate normative framework regulating the discharge of water waste.

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References

Aase, B., Sundheim, G., Langsrud, S., & Rørvik, L. M. (2000). Occurrence of and a possible mechanism for resistance to a quaternary ammonium compound in *Listeria monocytogenes. International Journal of Food Microbiology, 62,* 57-63.

Alexandre, E. M. C., Brandão, T. R. S., & Silva, C. L. M. (2012). Assessment of the impact of the hydrogen peroxide solutions on microbial loads and quality factors of red bell peppers, strawberries and watercress. *Food Control, 27,* 362-368.

Akbas, M. Y., Ölmez, H. (2007). Effectiveness of organic acid, ozonated water and chlorine dippings on microbial reduction and storage quality of fresh-cut Iceberg lettuce. *Journal of the Science of Food and Agriculture, 87,* 2609-2616.

Allende, A., Selma, M. V., López-Gálvez, F., Villaescusa, R., & Gil, M. I. (2008). Role of commercial sanitizer and washing systems on epiphytic microorganisms and sensory quality of fresh-cut escarole and lettuce. *Postharvest Biology and Technology, 49,* 155-163.

Allende, A., McEvoy, J., Tao, Y., & Luo, Y. (2009). Antimicrobial effect of acidified sodium chloride, sodium chloride, sodium hypochloride, and citric acid on *Escherichia coli* O157:H7 and natural microflora of fresh-cut cilantro. *Food Control, 20,* 230-234.

Anese, M. (2015). Unpublished data.

Artés, F., Gomez, P., Aguayo, E., Escalona, V., & Artés-Hernandez, F. (2009). Sustainable sanitation techniques for keeping quality and safety of fresh-cut plant commodities. *Postharvest Biology and Technology, 51,* 287-296.

Barth, M., Hankinson, T. R., Zhuang, H., & Breidt, F. (2010). Microbiological Spoilage of Fruits and Vegetables. In W. H. Sperber, & M. P. Doyle (Eds.), *Compendium of the Microbiological Spoilage of Foods and Beverages, Food Microbiology and Food Safety* (pp. 135-183). New York: Springer.

Baur, S., Klaiber, R., Wei, H., Hammes, W. P., & Carle, R. (2005). Effect of temperature and chlorination of pre-washing water on shelf life and physiological properties of ready-to-use Iceberg lettuce. *Innovative Food Science and Emerging Technologies, 6,* 171-182.

Beltran, D., Selma, M. V., Marin, A., & Gil, M. I. (2005). Ozonated water extends the shelf life of fresh-cut lettuce. *Journal of Agriculture and Food Chemistry, 53,* 5654-5663.

Beuchat, L. R. (1998). Surface decontamination of fruits and vegetables eaten raw: a review. Food Safety Unit. World Health Organisation. WHO/FSF/FOS/98.2,42.

Bialoszewski, D., Bocian, E., Bukovska, B., Czajkowska, M., Sokół-Leszczńska B., & Tyski, S. (2010). Antimicrobial activity of ozonated water. *Medical Science Monitor, 16,* MT71-MT75.

Bintsis, T., Litopoulou-Tzanetaki, E., & Robinson, R. K. (2000). Review: Existing and potential applications of ultraviolet light in the food industry-a critical review. *Journal of the Science of Food and Agriculture 80,* 637-645.

Blume, T., & Neis, U. (2004). Improved wastewater disinfection by ultrasonic pre-treatment. *Ultrasonics Sonochemistry, 11,* 333-336.

Casani, S., Rouhany, M., & Knochel, S. (2005). A discussion paper on challenges and limitations to water reuse and hygiene in the food industry. *Water research, 39,* 1134-1146.

Casteel, M. J., Schmidt, C. E., & Sobsey, M. D. (2008). Chlorine disinfection of produce to inactivate hepatitis A virus and coliphage MS2. *International Journal of Food Microbiology, 125,* 267-273.

Codex Alimentarius Commission (2001). Codex Committee on Food Hygiene, Proposed Draft Guidelines for the Hygienic Reuse of Processing Water in Food Plants. Joint FAO/WHO Food Standards Programme, 34th Session, Bangkok, Thailand.

Dasgupta, J., Sikder, J., Chakraborty, S., Curcio, S., & Drioli, E. (2015). Remediation of textile effluents by membrane based treatment techniques: A state of the art review. *Journal of Environmental Management, 147,* 55-72.

Deborde, M., & von Gunten, U. (2008). Reactions of chlorine with inorganic and organic compounds during water treatments – kinetics and mechanisms: A critical review. *Water Research 42,* 13-51.

Dunn, J., Ott, T., & Clark, W. (1995). Pulsed-light treatment of food and packaging. *Food Technology, 49,* 95-98.

EC, 1998. Council Directive 98/83/EC relating to the quality of water intended for human consumption. Official Journal of the European Communities, No. L 330, 32-54.

EEC, 1991. Council Directive 91/271/EEC concerning urban wastewater treatment. Official Journal of the European Communities, No. L 135, 40-52.

Efligenir, A., Déon, S., Fievet, P., Druart, C., Morin-Crini, N., & Crini, G. (2014) Decontamination of polluted discharge waters from surface treatment industries by pressure-driven membranes: Removal performances and environmental impact. *Chemical Engineering Journal, 258*, 309–319.

Elizaquível, P., Sánchez, G., Selma, M. V., Aznar, R. (2012). Application of propidium monoazide-qPCR to evaluate the ultrasonic inactivation of *Escherichia coli* O157:H7 in fresh-cut vegetable wash water. *Food Microbiology, 30,* 316-320.

FDM-BREF, 2006. Integrated Pollution and Control. Reference Document of Best Available Techniques in the Food, Drink and Milk Industries. The European Commission – JRC Joint Research Center, Institute for Prospective Technological Studies, Seville-Spain.

Foster, C., Green, K., Bleda, M., Dewick, P., Evans, B., Flynn, A., et al. (2006). Environmental impacts of food production and consumption. A Final Report to the Department of Environmental, Food and Rural Affairs, Manchester Business Scholl, Defra, London.

García-Fernández, I., Fernández-Calderero, I., Polo-López, M. I., & Fernández-Ibáñez, P. (2015). Disinfection of urban effluents using solar TiO_2 photocatalysis: A study of significance of dissolved oxygen, temperature, type of microorganism and water matrix. *Catalysis Today, 240,* 30-38.

Gil, M. I., Selma, M. V., López-Gálvez, F., & Allende, A. (2009). Fresh-cut product sanitation and wash water disinfection: Problems and solutions. *International Journal of Food Microbiology, 134*, 37-45.

Gogate, P. R., & Pandit, A. B. (2004a). A review of imperative technologies for wastewater treatment I: oxidation technologies at ambient conditions. *Advances in Environmental Research, 8,* 501-551.

Gogate, P. R., & Pandit, A. B. (2004b). A review of imperative technologies for wastewater treatment I: hybrid methods. *Advances in Environmental Research, 8,* 553–597.

Gómez-López, V. M., Devlieghere, F., Bonduelle, V., & Debevere, J. (2005). Intense light pulses decontamination of minimally processed vegetables and their shelf life. *International Journal of Food Microbiology*, *103*, 79-89.

Gómez-López, V., M., Rajkovic A., Ragaer P., Smigic N., & Devlieghere F. (2009). Chlorine dioxide for minimally processed produce preservation: a review. *Trends in Food Science and Technology, 20,* 17-26.

Goncharuk, V. V., Vakulenko,V. F., Shvadchina, Y. O., Sova, A. N., Sitnichenko, T. N., & Kalinichenko, I. E. (2008). Formation and decomposition of hydrogen peroxide during UV-radiation, ozonization, and O_3/UV treatment of river water. *Journal of Water Chemistry and Technology 30,* 335-343.

Goodburn, C., & Wallace, C. (2013). The microbiological efficacy of decontamination methodologies for fresh produce: A review. *Food Control, 32,* 418-427.

Guerrero-Beltrán, J. A., & Barbosa-Cánovas, G. V. (2004). Review: Advantages and limitations on processing food by UV light. *Food Science and Technology International*, *10*, 137-147.

Henry, V., Helbronner, A., Recklinghausen, M. (1910). Nouvelles recherches sur la sterilization de grandes quantites d'eau par les rayons ultraviolets. *Comptes Rendus de l'Académie des Sciences*, *151*, 677-683.

Hijnen, W. A. W., Beerondonk, E. F., & Medena, G. J. (2006). Inactivation credit of UV radiation for viruses, bacteria and protozoan (oo)cysts in water: a review. *Water research 40,* 3-22.

Hong-Bo, S., Li-Ye, C., Gang, W., Jin-Heng Z., & Zhao-Hua, L. (2007). Where is the road to bio-water-saving for the globe? *Colloids and Surfaces B: Biointerfaces, 55*, 251-255.

Hulsmans, A., Joris, K., Lambert, N., Rediers, H., Declerk, P., Delaedt, Y., Olleveir, F., & Liers, S. (2010). Evaluation of process parameters of ultrasonic treatment of bacterial suspensions in a pilot scale water disinfection system. *Ultrasonics Sonochemestry*, *17*, 1004-1009.

Ignat, A., Manzocco, L., Bartolomeoli, I., Maifreni, M., & Nicoli, M. C. (2014). Minimization of water consumption in fresh-cut salad washing by UV-C light. *Food Control*. In press.

Kentish, M., & Ashokkumar, M. (2011). The physical and chemical effects of ultrasound. In H. Fengh, G. V. Barbosa-Cánovas, & J. Weiss (Eds.), Ultrasound Technologies for Food and Bioprocessing (pp. 1-12). London: Springer.

Kim, J. G., Yousef, A. E., Chism, G. W. (1999). Use of ozone to inactivate microorganisms on lettuce. *Journal of Food Safety, 19,* 17-34.

Kim, J. G., Yousef, A. E., Khadre, M. A. (2003). Ozone and its current and future application in the food industry. *Advances in Food and Nutrition Research, 45,* 167-218.

Krasner, S. W., Weinberg, H. S., Richardson, S. D., Pastor, S. J., Chinn, R., Sclimenti, M. J., et al. (2006). Occurrence of a new generation of disinfection by-products. *Environmental Science and Technology, 40,* 7175-7185.

Krishnamurthy, K., Tewari, J. C., Irudayaraj, J., & Demirci, A. (2008). Microscopic and spectroscopic evaluation of inactivation of *Staphylococcus aureus* by pulsed UV light and infrared heating. *Food and Bioprocess Technology, 3,* 93-104.

López-Gálvez, F., Posada-Izquierdo, G. D., Selma, M. V., Perz-Rodriguez, F., Gobet, J., Gil, M.I., et al. (2012). Electrochemical disinfection: an efficient treatment to inactivate *Escherichia coli* O157:H7 in process wash water containing organic matter. *Food Microbiology, 30,* 146-156.

Manzocco, L., Ignat, A., Bartolomeoli, I., Maifreni, M., & Nicoli, M. C. (2015). Water saving in fresh-cut salad washing by pulsed light. *Emerging Technologies and Innovative Food Science.* In press.

Martín-Diana, A. B., Rico, D., Barry-Ryan, C., Frías, J. M., Mulcahy, J., & Henehan, G. T. M. (2005). Comparison of calcium lactate with chlorine as a washing treatment for fresh-cut lettuce and carrots: Quality and nutritional parameters. *Journal of the Science of Food and Agriculture, 85,* 2260-2268.

Mason, T. J., Joyce, E., Phull, S. S., & Lorimer, J. P. (2003). Potential uses of ultrasound in the biological decontamination of water. *Ultrasonics Sonochemistry, 10,* 319–323.

McKinney, J., Williams, R. C., Boardman, G. D., Eifert, J. D., & Sumner, S. S. (2009). Dose of UV light required to inactivate *Listeria monocytogenes* in distilled water, fresh brine, and spent brine. *Journal of Food Protection, 72*, 2144-2150.

Mounaouer, B., & Abdennaceur, H. (2012). Ultraviolet radiation for microorganism inactivation in wastewater. *Journal of Environmental Protection, 13,* 194-202.

Ölmez, H., & Kretzschmar U. (2009). Potential alternative disinfection methods for organic fresh-cut industry for minimizing water consumption and environmental impact. *LWT-Food Science and Technology 42,* 686-693.

Ölmez, H. (2014). Water consumption, reuse and reduction strategies in food processing. In B. K. Tiwari, T. Norton, & N. M. Holden (Eds.), *Sustainable Food* Processing, (pp. 401-434). Chichester: Wiley-Blackwell.

Parish, M. E., Beuchat, L. R., Suslow, T. V., Harris, L. J., Garrett, E. H., Farber, J. N., et al. (2003). Method to reduce/decontaminate pathogens from fresh-cut produce. *Comprehensive Reviews in Food Science and Food Safety, 2,* 161-173.

Paleologou, A., Marakas H., Xekoukouloutakis, N. P., Moya, A., Vergara, Y., Kalogerakis, N., et al. (2007). Disinfection of water and wastewater by TiO_2 photocatalysis sonolysis and UV-C irradiation. *Catalysis Today, 129,* 136-142.ù

Piyasena, P., Mohareb, E., & McKellar, R. C. (2003). Inactivation of microbes using ultrasound: a review. *International Journal of Food Microbiology, 87,* 207-216.

Ragaert, P., Devlieghere, F., & Debevere, J. (2007). Role of microbiological and physiological spoilage mechanisms during storage of minimally processed vegetables. *Postharvest Biology and Technology*, *44*, 185-194.

Rame, J., Chaloupeky, V., Soikova, N., & Bencko, V. (1997). An attempt to demonstrate the increase resistance of selected bacterial strains during repeated exposure to UV radiation at 254 nm. *Central European Journal of Public Health, 4, 30*-31.

Ramos, B., Miller, F. A., Brandão, T. R. S., Teixeira, P., & Silva, C. L. M. (2013). Fresh fruits and vegetables-An overview on applied methodologies to improve its quality and safety. *Innovative Food Science and Emerging Technologies, 20,* 1-15.

Richardson, S. D., & Ternes, T. A. (2005). Water analysis: Emerging contaminants and current issues. *Analytical Chemistry, 77*, 3807-3838.

Sanz, S., Gimenez, M., Olarte, C., Lomas, C., & Portu, G. (2002). Effectiveness of chlorine washing disinfection and effects on the appearance of artichokes and borage. *Journal of Applied Microbiology, 93,* 986-993.

Segat, A., Biasutti, M., Iacumin, L., Comi, G., Baruzzi, F., Carboni, C., et al. (2014). Use of ozone in production chain of high moisture Mozzarella cheese. *LWT-Food Science and Technology, 55,* 513-520.

Selma, M. V., Allende, A., López-Gálvez, F., Conesa, M. A., & Gil, M. I. (2008). Disinfection potential of ozone, ultraviolet-C and their combination in wash water for the fresh-cut industry. *Food Microbiology*, *25,* 809-814.

Shannon, M. A., Bohn, P. W., Elimelech, M., Georgiadis, J. G., Mariñas, B. J., & Mayes, A. M. (2008). Science and Technology for water purification in the coming decades. *Nature, 452,* 301-310.

Shere, L., Kelly, M. J., & Richardson, J. H. (1962). Effect of bromide hypochlorite bactericides on microorganisms. *Applied Microbiology, 10,* 538-541.

Silva, A. B., Lima Filho, N. M., Palha, M. A. P. F, & Sarmento, S. M. (2013). Kinetics of water disinfection using UV-C radiation. *Fuel*. doi: 10.1016/J.fuel.2012.11.026.

Sommer, R., Lhotsky, M., Haider, T., & Cabaj, A. (2000). UV inactivation, liquid-holding recovery, and photo reactivation of *Escherichia coli* O157 and other pathogenic *Escherichia coli* strains in water. *Journal of Food Protection, 63,* 1015-1020.

Tomás-Callejas, A., Martínez-Hernández, G. B., Artés, F., & Artés-Hernández, F. (2011). Neutral and acidic electrolysed water as emergent sanitizers for fresh-cut mizuna baby leaves. *Postharvest*

Biology and Technology, 59, 298-306.

Vandekinderen, I., Devlieghere, F., De Muelenaer, B. K, Ragaert, P., & Van Camp, J. (2009). Optimization and evaluation of a decontamination step with peroxyacetic acid for fresh-cut produce. *Food Microbiology, 26,* 882-888.

Williams, P. J., Anderson, P. A. (2006). Operational cost savings in dairy plant water usage. *International Journal of Dairy Technology, 59,* 147-154.

Zimmermann, S. G., Wittenwiler, M., Hollender, J., Krauss, M., Ort, C., Siegrist, H., et al. (2011). Kinetic assessment of modelling of an ozonation step for full-scale municipal wastewater treatment: micro pollutant oxidation, by-product formation and disinfection. *Water Research, 45,* 605-617.

Figure captions

Fig. 1. Requirements for sustainable water saving intervention.

Fig. 2. Flows of product and water in a typical fresh-cut production process.

Fig. 3. Counts of *Pseudomonas fluorescens* as a function of free chlorine in water solutions added with sodium hypochlorite or produced by electrolysis of a solution containing sodium chloride.

Fig. 4. Flows of product and water in a fresh-cut production process with efficient water management.

Table 1. Advantages and limitations of chlorine and-chlorine-free disinfectants, currently used or potentially applicable, in fresh-cut vegetable washing.

	Molecule	Advantages	Limitations/disadvantages	References
Chlorine compounds	**Hypochlorite and related compounds**	Easily measured and controlled Low cost and easily available	Sensory changes Formation of unhealthy DBP (THMs, HAAs) pH dependant activity Sensitive to temperature, light, air Efficacy affected by the presence of organic matter Corrosive Liberation of chlorine vapours during production Forbidden in some European countries	Sanz, Gimenez, Olarte, Lomas, & Portu (2002) Baur, Klaiber, Wei, Hammes, & Carle (2005) Casteel, Schmidt, & Sobsey (2008) Goodburn and Wallace (2013)
	Chloramines	Few unhealthy DBP Active for long time	Poor biocidal effect Long contact time	Casani,Rouhany & Knochel (2005)
	Chlorine dioxide	Less reactive to organic compounds Higher antimicrobial activity at neutral pH Stable over a wide pH range Minimal contact time High solubility in cold water More stable Less corrosive	Generation on site required Explosive at concentrations > 10% in air Not permitted for fresh-cut produce in US and not regulated in EU Formation of specific DBP Rinsing necessary after washing	Gómez-López, Rajkovic, Ragaer, Smigc, & Devlieghere (2009) Goodburn and Wallace (2013)
	Acidified sodium chlorite	Greater efficacy (due to low pH)	Little information on DBP produced	Allende, McEvoy, Tao, & Luo, (2009)

				Ramos, Miller, Brandão, Teixeira, & Silva (2013)
Chlorine-free compounds	**Ozone**	GRAS Lower running cost Active at low concentration No pH dependence Short contact time No residues or DBP	Dependence on organic matter No residual disinfection activity High initial investment cost Toxic when inhaled Damages to product surface Corrosive On-site generation required	Kim, Jousef, & Chism (1999) Kim, Jousef, & Khadre (2003)
	Peracetic or Peroxyacetic acid	Efficacy independent on water organic load, temperature and pH Active at low concentrations Not corrosive (< 80 mg/L) No DBP harmful to human and ecosystem	Low antimicrobial efficacy at permitted levels	Artés, Gomez, Aguayo, Escalona, & Artés-Hernandez (2009) Vandekinderen, Devlieghere, De Muelenaer, Ragaert, & Van Camp (2009)
	Bromine	Possible synergism with chlorine	Little information on brominated DBP produced	Shere, Kelley, & Richardson (1962)
	Trisodium phosphate	Low corrosivity	High pH (11-12) Limited antimicrobial efficacy towards *Listeria monocytogenes*	Beuchat (1998)
	Quaternary ammonium compounds	Colourless, odourless Not corrosive Good penetrating ability Limited reactivity with organic compounds	Cost effective	Aase, Sundheim, Langsrud, & Rørvik (2000) Parish *et al.* (2003)

Calcium based compounds	Increase calcium content of the final product	Bitterness and off-flavours if used in association with chlorine Limited antimicrobial efficacy	Martín-Diana, Rico, Barry-Ryan, Frías, Mulcahy, & Henehan (2005)
Hydrogen peroxide	No harmful DBP Low cost Easy to use	Phytotoxic Impairs product quality: browning/bleaching effect Low antimicrobial efficacy at permitted levels Long contact time Requires the removal of H_2O_2 after processing Potential product toxicity if used in association with silver	Akbas and Ölmez (2007) Alexandre, Brandão, & Silva, (2012)
Organic acids (citric lactic, acetic)	Easy to use No toxicity GRAS	Very long exposure time Affect product taste and flavour Relatively low antimicrobial efficacy High COD and BOD values of wastewater Antimicrobial effect dependent on nature of acid and microbial strain	Akbas and Ölmez (2007) Ölmez and Kretzschmar (2009)

DBP: Disinfection by-products.

Table 2. Main strategies for water disinfection, potentially applicable to wastewater deriving from fresh-cut washing.

Technology	Principle	Process	Disinfection application	References
Single	Physical stress	UV PL	Salad wash water	Selma, Allende, López-Gálvez, Conesa, & Gil (2008) Ignat, Manzocco, Bartolomeoli, Maifreni, & Nicoli (2014) Manzocco, Ignat, Bartolomeoli, Maifreni, & Nicoli (2015)
	Chemical stress	O_3	Waste water from wine distillery, dairy industries	Gogate and Pandit (2004a) Segat *et al.* (2014)
	Physical and chemical stress	US	Waste water from salad and degradation of pollutants (e.g. chlorinated compounds)	Piyasena, Mohareb, & McKellar (2003) Gogate and Pandit (2004b) Elizaquivel *et al.* (2012)
Hybrid	Physical/ chemical stress/ separation	UV + O_3 UV + H_2O_2 UV + US O_3 + US H_2O_2 +UV/TiO_2	Wastewater from distillery and tomato industry	Mason, Joyce, Phull, & Lorimer (2003) Blume and Neis (2004) Hulsmans *et al.* (2010) Gogate and Pandit (2004a) Goncharuk, Vakulenko, Shvadchina, Sova, Sitnichenko, & Kalinichenko (2008) García-Fernández, Fernández-Calderero,

			Polo-López, & Fernández-Ibáñez (2015)
	RO+ UV	Textile wastewater	Paleologu et al. (2007)
	RO + UV/TiO_2	Water produced in petroleum industry	Shannon *et al.* (2008)
		Remove toxic compounds from industrial discharge waters	Efligenir, Déon, Fievet, Druart, Morin-Crini, & Crini (2014) Dasgupta, Sikder, Chakraborty, Curcio, & Drioli (2015)

UV: Ultraviolet light

PL: Pulsed light

US: Ultrasonication

O_3: Ozonation

H_2O_2: Addition of hydrogen peroxide

UV-A/TiO_2: Photocatalysis using titanium dioxide

RO: Reverse osmosis

Table 3. Log reductions of native and inoculated microorganisms in lamb's lettuce wash water exposed to increasing fluence of UV and pulsed light (modified from Ignat *et al., 2014* and Manzocco *et al., 2015*).

Light	Fluence (kJ/m^2)	Microrganisms				
		Native		Inoculated		
		Total viable count	*Pseudomonas* spp.	*S. enterica*	*L. monocytogenes*	*E.coli*
UV	0.1	3.2	>4.0	>6.0	>7.0	3.7
	0.2	3.6	>4.0	>6.0	>7.0	4.8
	0.4	3.8	>4.0	>6.0	>7.0	5.2
	0.6	>4.0	>4.0	>6.0	>7.0	5.7
	1.2	>4.0	>4.0	>6.0	>7.0	>7.0
Pulsed	2.6	0.5	0.6	0.9	0.6	0.5
	4.4	1.3	1.9	2.9	2.0	3.0
	7.0	2.5	3.6	4.3	4.8	5.6
	11.0	4.9	4.8	>5.0	>6.0	5.4
	17.5	4.9	4.8	>5.0	>6.0	6.3