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Power ultrasound decontamination of wastewater from fresh-cut lettuce washing for potential water recycling

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1 **Power ultrasound decontamination of wastewater from fresh-cut lettuce washing for potential water**  
2 **recycling**

3

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14

## 15    **Abstract**

16

17    The decontamination effect of pulsed and continuous power ultrasound, provided at either controlled or  
18    uncontrolled temperature regimes, was studied with reference to native microflora and inoculated pathogenic  
19    bacteria in wastewater obtained by fresh-cut lamb's lettuce washing. Results showed that decontamination  
20    efficacy increased with increasing specific energy and was higher when ultrasound treatment was  
21    provided under uncontrolled temperature regime. Continuous ultrasound supplied without  
22    temperature control allowed to achieve 3.2 Log reductions of native microflora during 20 min  
23    treatment, while 5 Log reductions of inoculated *Listeria monocytogenes*, *Escherichia coli* and  
24    *Salmonella enterica* were attained within 5 min of ultrasonication. The heat generated during  
25    continuous ultrasound accounted for approximately 58% of the total decontamination effect against  
26    *L. monocytogenes*, while it contributed for 100% to *E. coli* and *S. enterica* inactivation.

27

## 28    *Industrial relevance*

29    The application of power ultrasound combined with *in situ* generated heat could represent an effective  
30    tool for water decontamination and recycling in the fresh-cut industry. In addition, besides safety  
31    requirements, this technology would also meet cost-effectiveness criteria and existing standards.

32

33    **Keywords:** Ultrasounds, Wastewater disinfection, Water recycling, *In situ* generated heat, Fresh-cut  
34    industry

35

36

## 37 1. Introduction

38

39 Nowadays, water scarcity is a major issue at global level. It has been estimated that in the next 15-20 years the  
40 water supply-to-demand gap will be approximately 40%. Tackling the water gap is a challenge for EU research  
41 (Horizon 2020). The food sector greatly contributes to water scarcity. It has been estimated that about 20-50%  
42 reduction in water consumption in the food sector can be achieved by recycling and reuse of water (Hiddink,  
43 Schenkel, Buitelaar, & Rekswinkel, 1999).

44 The fresh-cut vegetables market has grown considerably in the last few decades in response to an increased  
45 demand for fresh-like, healthy and convenient foods. Fresh-cut vegetables production requires intensive use  
46 of water to both wash and move vegetables along the production line. In order to secure water supply and  
47 protect the environment from the adverse effects of the wastewater discharges (EEC 1991), water recycling in  
48 the fresh-cut industry has to be improved. Recycling of water that is intended to re-enter the washing step,  
49 implies wastewater disinfection. As well known, a 5 Log reduction of pathogenic bacteria is the generally  
50 accepted requirement for safe water disinfection. Wastewater decontamination may be accomplished by means  
51 of chemical and physical interventions (Casani, Rouhany, & Knøchel, 2005; Olmez & Kretzschmar, 2009).  
52 Among these, sodium hypochlorite is the most used due to its low cost and easy use (Olmez & Kretzschmar,  
53 2009; Gil, Selma, López-Gálvez, & Allende, 2009). However, not only wastewater containing chlorine has a  
54 great environmental impact, but also chlorination disinfection by-products are known to represent a potential  
55 risk for human health (Itoh, Gordon, Callan, & Bartram, 2011). Consequently, there is great effort to find  
56 suitable technologies to allow wastewater recycling (Casani et al., 2005; Olmez & Kretzschmar, 2009; Artés,  
57 Gómez, Aguayo, Escalona, Artés-Hernández, 2009). Power ultrasound has been suggested as a technology  
58 alternative to chlorination for wastewater decontamination (Neis & Blume, 2002; Piyasena, Mohareb, &  
59 McKellar, 2003). Ultrasound frequencies higher than 20 kHz are actually considered safe, non-toxic and  
60 environmentally friendly (Kentish & Ashokkumar, 2011). During ultrasound treatment, cavitation phenomena  
61 occur into the liquid medium causing a rapidly alternating compression and decompression zones, that are in  
62 turn responsible for generating shock waves with associated local very high temperatures and pressures, as  
63 well as free radicals and hydrogen peroxide (Leighton, 1994; Mason, Joyce, Phull, & Lorimer, 2003).  
64 Ultrasound effectiveness in wastewater decontamination was found to increase with the power input and

65 exposure time, and to depend on microorganism type (Scherba, Weigel, & O'Brien, 1991; Joyce, Phull,  
 66 Lorimer, & Mason, 2003; Hulsmans, Joris, Lambert, Rediers, Declerk, Delaedt, Olleveil, & Liers, 2010;  
 67 Elizaquivel, Sanchez, Selma, & Aznar, 2011; Gao, Lewis, Ashokkumar, & Hemar, 2014). Improved efficiency  
 68 of ultrasound technology can be obtained by its combination with other biocidal treatments, such as  
 69 chlorination (Drakopoulou, Terzakis, Fountoulakis, Mantzavinos, & Manios, 2009; Ayyildiz, Sanik, & Ileri,  
 70 2011), organic acids (Gómez-López, Gil, Allende, Vanhee, & Selma, 2015), and ultraviolet irradiation (Blume  
 71 & Neis, 2004; Mason et al., 2003; Naddeo, Land, Belgiorno, & Napoli, 2009; Gómez-López et al. 2015). An  
 72 increase of microbial sensitivity to ultrasound in combination with temperature increase, experienced with  
 73 ultrasonic treatment, for wastewater disinfection has been also reported (Madge & Jensen, 2002; Salleh-Mack  
 74 & Roberts, 2007; Gómez-López, Gil, Allende, Blancke, Schouteten, & Selma, 2014). It has been estimated  
 75 that the heat generated during ultrasound processing accounted for approximately 52% of the resulting  
 76 disinfection (Madge & Jensen, 2002).

77 In contrast with the huge number of studies in the literature dealing with ultrasound decontamination of  
 78 municipal wastewater and effluents as well as model fluids, very few studies investigated ultrasound  
 79 effectiveness for water decontamination deriving from fresh-cut vegetable production (Elizaquível et al., 2012;  
 80 Gómez-López et al., 2014; Gómez-López et al., 2015). It has been demonstrated that power ultrasound was  
 81 effective in inactivating pathogenic bacteria inoculated in fresh-cut lettuce wash water (Elizaquível et al.,  
 82 2012), especially in the presence of the residual peroxyacetic acid concentration that can be found in the wash  
 83 water (Gómez-López et al., 2015). In these studies, ultrasonic treatments were carried out with temperature  
 84 control, allowing the inactivation effects of ultrasound alone to be evaluated. In another study, Gómez-López  
 85 et al. (2014) showed that ultrasound disinfection against *Escherichia coli* O157:H7 inoculated in fresh-cut  
 86 lettuce wash water can be increased by combination with heating. Reductions of 6 Log of this microorganism  
 87 were actually achieved after 60 and 20 min of ultrasonication with and without temperature control,  
 88 respectively.

89 In light of this, there is a lack of knowledge on the efficacy of power ultrasound in combination with *in situ*  
 90 generated heat against naturally occurring microflora and foodborne pathogens, other than *E. coli*, potentially  
 91 contaminating fresh-cut vegetable wash water.

92 In this study the efficacy of power ultrasound in decontaminating wastewater deriving from fresh-cut vegetable  
93 washing was investigated. To this aim, wastewater obtained by washing fresh-cut lamb's lettuce was subjected  
94 to power ultrasound, provided in pulsed or continuous modality, with or without temperature control. The  
95 decontamination efficacy of the treatments was evaluated on both the native microflora and inoculated  
96 pathogenic bacteria, i.e. *Listeria monocytogenes*, *Escherichia coli* and *Salmonella enterica*. These  
97 microorganisms were chosen due to their natural occurrence in a water environment and because they are  
98 generally considered indicators of fecal contamination (Szewzyk, Szewzyk, Manz, & Schleifer, 2000). The  
99 final goal was to find the potentiality of combined ultrasound with *in situ* generated heat in the attempt to  
100 implement strategies for efficient management of water resource in the fresh-cut industry. To this regard, the  
101 decontamination efficacy was related to the ultrasound cavitation and heat contributions.

102

## 103 **2. Materials and methods**

104

### 105 *2.1. Preparation of fresh-cut vegetable wash water*

106

107 Lamb's lettuce (*Valerianella locusta* Laterr.) was purchased from a local market. Lettuce leaves were placed  
108 into a beaker containing tap water at  $18\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$  (the vegetable-water ratio was 1:30 w/v). After 1 min of  
109 washing, water was separated from the leaves by using a domestic salad spinner.

110

### 111 *2.2. Bacterial strains and inoculum preparation*

112

113 The microorganisms used for inoculum were *Listeria monocytogenes*, *Escherichia coli* and *Salmonella enterica*  
114 subsp. *enterica* 9898 DSMZ, obtained from the bacterial culture collection of the Department of Food Science  
115 of the University of Udine (Italy). Strains were maintained at  $-80\text{ }^{\circ}\text{C}$  in Brain Heart Infusion broth (BHI, Oxoid,  
116 UK) with 30% sterile glycerol as cryoprotectant until use. Strains were incubated in BHI at  $37\text{ }^{\circ}\text{C}$  for 24 h,  
117 subsequently cultured in 5 mL of BHI at  $37\text{ }^{\circ}\text{C}$  for 24 h, and finally collected by centrifugation at 14170 g for  
118 10 min at  $4\text{ }^{\circ}\text{C}$  (Beckman, Avanti TM J-25, Palo Alto, CA, USA) and washed three times with Maximum

119 Recovery Diluent (MRD, Oxoid, UK). The final pellets were suspended in MRD and used as inoculum. A  
120 final concentration of approximately  $10^6$  CFU/mL was obtained for each bacteria suspension.

121

### 122 2.3. Power ultrasound treatment

123

124 An ultrasonic processor (Hieschler Ultrasonics GmbH, mod. UP400S, Teltow, Germany) with a titanium horn  
125 tip diameter of 22 mm was used. The instrument operated at constant ultrasound amplitude and frequency of  
126 100  $\mu$ m and 24 kHz, respectively. Aliquots of 200 mL of wash water inoculated or not with *L. monocytogenes*,  
127 *E. coli* and *S. enterica* were introduced into 250 mL capacity (110 mm height, 60 mm internal diameter) glass  
128 vessels. The tip of the sonicator horn was placed in the centre of the solution, with an immersion depth in the  
129 fluid of 10 mm. The ultrasound treatments were performed for increasing lengths of time up to 20 min. During  
130 the ultrasonication experiment, the temperature was either controlled using an ice bath, to dissipate the heat  
131 generated during treatment, or uncontrolled, leaving the temperature to rise due to heat dissipation. The  
132 sonicator operated either in pulsed mode or continuous mode. In the pulsed mode, the pulse duration period of  
133 0.5 s was followed by a pulse interval period of 0.5 s, during which the sonochemical reactor was switched  
134 off. Before and after each experiment, the ultrasound probe was disinfected by washing with ethanol followed  
135 by through rinsing with sterile water.

136

### 137 2.4. Thermal treatment

138

139 The total temperature-time combination received by water during continuous ultrasound under uncontrolled  
140 temperature regime was applied to the wastewater in the absence of the ultrasound treatment. To this purpose,  
141 aliquots of 200 mL of wash water were introduced into 250 mL capacity glass vessels and heated in a  
142 thermostatic water bath (Ika Werke, MST BC, Staufen, Germany) under continuous stirring, by mimicking the  
143 same temperature rise produced by the probe during continuous ultrasound treatment under the uncontrolled  
144 temperature regime.

145

### 146 2.5. Microbiological analysis

Both naturally present and inoculated microorganisms were quantified at different time intervals during the ultrasound and heat treatments. The wastewater samples were diluted 10 fold with MRD (Oxoid, UK). Total viable count of non inoculated water was enumerated by spreading onto plates with Plate Count Agar (PCA, Oxoid, UK) and incubating at 30 °C for 48 h. *L. monocytogenes* and *S. enterica* concentrations were determined by plating on Palcam Agar (PA, Oxoid, UK) and Xylose Lysine Desoxycholate agar (XLD, Oxoid, UK), respectively, at 37 °C for 48 h, while the Coli ID medium (BioMerieux, Mercy L'Etoile, France) was used for *E. coli* concentration determination, followed by incubation at 37 °C for 24 h.

Preliminary trials were carried out on the non inoculated wastewater to check for *Salmonella* spp. and *L. monocytogenes* presence and enumerate *E. coli*. For *Salmonella* spp., 25 mL of wastewater was diluted with 225 mL of Buffered Peptone Water (BPW, Oxoid, UK), homogenised in a Stomacher Lab-Blender 400 (VWR International PBI srl, Milano, Italy) for 2 min and incubated at 37 °C for 24 h. Aliquots of 0.1 mL of BPW were added with 9.9 mL Rappaport Vassiliadis (RV, Oxoid, UK) and incubated at 42-43 °C for 18-24 h. Presence/absence of *Salmonella* spp. was checked by spreading onto XLD agar plates and incubating at 37 °C for 24 h. For *L. monocytogenes*, 25 mL of wastewater were diluted with 225 mL of Fraser Broth (FB, Oxoid, UK), homogenised in a Stomacher for 2 min and incubated at 30 °C for 36-48 h. 1 mL of FB was added with 9 mL of FB and incubated at 37 °C for 24-48 h. Presence/absence of *L. monocytogenes* was checked by spreading onto PA plates and incubating at 37 °C for 24-48 h. To evaluate the presence of *E. coli* the Coli ID medium at 37 °C for 24 h was used.

In order to investigate whether treatments were responsible for bacteria sub-lethal injury, resuscitation trials were carried out. For each inoculated strain, 10 mL of wastewater was transferred into 10 mL of BHI broth and then incubated at 30 °C for 2h. Afterwards, presence/absence of *L. monocytogenes*, *E. coli* and *S. enterica* was checked by spreading onto PA, Coli ID and XLD agar media, respectively.

## 2.6. Temperature measurement

The temperature was recorded as a function of time using a copper-constantan thermocouple probe (Ellab, Denmark), connected to a data-Logger (CHY 502A1, Tersid, Milano, Italy).



## 175 2.7. *Specific power and energy computation*

176

177 The specific power or power density ( $P$ , W/L) transferred from either the probe or the water bath to the sample  
178 was determined calorimetrically by recording the temperature ( $T$ , K) increase against the time ( $t$ , s) of  
179 ultrasound or heat application (Raso, Manas, Pagan, & Sala, 1999). The following equation (1) was used:

180

$$181 \quad P = dc_p (\partial T / \partial t) \quad (1)$$

182

183 where  $c_p$  is the water heat capacity (4.18 J/kg K), and  $d$  is the sample density (kg/L). The specific energy (kJ/L)  
184 was calculated by multiplying the power density value by the duration of the treatment (Hulsmans et al., 2010).

185

## 186 2.8. *Statistical analysis*

187

188 Results are averages of two measurements carried out on two replicated samples and are reported as means  $\pm$   
189 SD. Analysis of variance (ANOVA) was performed with significance level set to  $p < 0.05$  (Statistica for  
190 Windows, ver. 5.1, Statsoft Inc. Tulsa, USA, 1997). The Tukey procedure was used to test for differences  
191 between means. Linear regression analysis was performed by using Microsoft Excel 2007. The goodness of  
192 fitting was evaluated based on visual inspection of residual plots and by the calculation of  $R^2$  and  $p$ .

193

## 194 3. **Results and discussion**

195

### 196 3.1. *Decontamination efficiency of continuous power ultrasound provided under controlled temperature* 197 *regime*

198

199 Initial total microbial count of wastewater deriving from fresh-cut lamb's lettuce wash water was  $4.92 \pm 0.15$   
200 Log CFU/mL. This value was in the same magnitude range of those reported in the literature for wastewater  
201 obtained by washing fresh-cut vegetable (Elizaquivel et al., 2011; Gomez-Lopez et al., 2015). As reported by  
202 Ignat, Manzocco, Bartolomeoli, Maifreni and Nicoli (2015) for wastewater obtained from lamb's lettuce

203 washed in analogous conditions as those performed in the present study, the microbial count was mainly  
 204 represented by *Pseudomonas* spp, Enterobacteriaceae and total coliforms. No presence of *L. monocytogenes*,  
 205 *E. coli* and *S. enterica* cells was detected in wastewater.

206 Wastewater obtained by washing fresh-cut lettuce was subjected to ultrasound treatment for up to 20 min in  
 207 continuous mode and controlled temperature regime. To avoid temperature increase, the vessel containing the  
 208 sample was placed into an ice bath to remove the heat generated during the ultrasound process into the fluid.  
 209 The controlled temperature regime allowed values never exceeding 35 °C to be obtained. The power density  
 210 transferred from the ultrasound probe into the fluid, quantified calorimetrically using eq. 1, was equal to 270  
 211 W/L. Accordingly, the specific acoustic energy values ranged between 15 kJ/L and 314 kJ/L, depending on  
 212 treatment time.

213 Fig. 1 shows the decontamination efficiency of continuous power ultrasound provided under controlled  
 214 temperature regime against the total microbial count as well as *L. monocytogenes*, *E. coli* and *S. enterica*  
 215 inoculated in the wastewater obtained by fresh-cut lettuce washing. Following the ultrasound treatments, Log  
 216 reductions of the total microbial count as well as *L. monocytogenes*, *E. coli* and *S. enterica* of the wash water  
 217 increased linearly with exposure time ( $p < 0.05$ ). In particular, the rate constants computed from the slopes of  
 218 the linear regression of the logarithm of microbial counts as a function of ultrasonication time were 0.127,  
 219 0.09, 0.195 and 0.226 min<sup>-1</sup> ( $0.783 < R^2 < 0.973$ ) for native microflora, *L. monocytogenes*, *E. coli* and *S. enterica*,  
 220 respectively. These differences in rate constants indicate different resistances to ultrasonication among the  
 221 microorganisms. A total microbial count reduction of approximately 2.8 Log units was obtained after 20 min  
 222 application of this treatment. Based on the above rate constants, a 5 Log reduction of *L. monocytogenes*, *E.*  
 223 *coli* and *S. enterica*, that is the minimum requirement for water disinfection, can be achieved by the application  
 224 of 56, 26 and 22 min of power ultrasound, respectively. It is noteworthy that these treatments are hardly  
 225 applicable at the industrial level because time and cost consuming. In our experimental conditions, higher  
 226 decontamination effects were achieved as compared with those of the literature. Neis and Blume (2002)  
 227 reported that reductions of 0.9 and 2.9 Log units of fecal streptococci and *E. coli*, respectively, were achieved  
 228 following 60 min at 400 W/L. Similar Log reductions of total coliforms and fecal streptococci in municipal  
 229 wastewater subjected to 1500 W/L power density were reported by Drakopoulou et al. (2009). Ayyildiz et al.  
 230 (2011) found that *E. coli* Log reductions ranged from approximately 0.5 and 1.1 for municipal wastewater

231 processed at 75 to 300 W/L for 10 min. Elizaquivel et al. (2011) reported 2.4 Log reductions of *E. coli* O157:H7  
 232 inoculated in fresh-cut vegetable wastewater following 30 min ultrasonication at 280 W/L, while 60 min were  
 233 required to achieve complete inactivation (5 Log reductions). Similarly, Gómez-López et al. (2015) reported  
 234 that 30 min ultrasound treatment at 280 W/L of wastewater obtained by lettuce washing allowed 2 Log  
 235 reductions for *E. coli* and *S. enterica*, and 1 Log reduction for *L. monocytogenes* to be achieved.  
 236 To actually quantify the effect of power ultrasound, the decimal reduction time  $D_{US}$  for the inoculated  
 237 pathogenic bacteria was calculated using procedures analogous to those employed in thermal death time  
 238 studies. In particular,  $D_{US}$  was defined as the ultrasonication time needed to reduce the number of  
 239 microorganisms by 90% at a given ultrasound power.  $D_{US}$  values of 11.1, 5.1 and 4.4 min were obtained for *L.*  
 240 *monocytogenes*, *E. coli* and *S. enterica*, respectively. According to the above mentioned definition, the higher  
 241 the  $D_{US}$  value, the less the microorganism susceptibility to the ultrasonication power. Therefore, *S. enterica*  
 242 resulted to be slightly more susceptible to the ultrasound treatment than *E. coli*, that in turn was more sensitive  
 243 than *L. monocytogenes*, in agreement with Gómez-López et al. (2015). The greater resistance of *L.*  
 244 *monocytogenes* to ultrasound treatments can be attributed to its Gram status. As known, the Gram-positive cell  
 245 wall of microorganisms presents a thicker and more tightly adherent peptidoglycan layer than that of the  
 246 Gram-negative microorganisms (Cummins, 1989). Thus, *L. monocytogenes* would be capable to better  
 247 withstand extreme pressure and temperature variations due to cavitation.  
 248

### 249 3.2. Decontamination efficiency of continuous and pulsed power ultrasound provided under uncontrolled 250 temperature regime

251  
 252 In order to study the decontamination potential of combined ultrasound processing with *in situ* generated heat,  
 253 wastewater obtained by washing fresh-cut lamb's lettuce was subjected to ultrasound treatments under  
 254 uncontrolled temperature regime. To this purpose, sample temperature was left to rise during the ultrasound  
 255 process due to heat dissipation. Trials without temperature control were performed in pulsed mode or  
 256 continuous mode. In the former case, samples were subjected to pulsing at 0.5/0.5 seconds on/off. This  
 257 modality has been already used to allow to contain the temperature rise during ultrasound process (Madge &  
 258 Jensen, 2002; Bermúdez-Aguirre & Barbosa-Cánovas, 2012). Fig. 2 shows the time-temperature profiles of

wash water during continuous or pulsed ultrasound without temperature control. As expected, temperature increased during treatments, reaching approximately 90 °C after 15 min of continuous ultrasound, whereas temperature values not exceeding 65 °C were recorded for the pulsed modality. In fact, pulsed ultrasound decreased the temperature rise compared with continuous ultrasound, because the “off” interval period allowed heat to be dissipated (Madge & Jensen, 2002). The power densities transferred into the wastewater sample during the pulsed and continuous power ultrasound processes were of 205 and 572 W/L, respectively. Accordingly, the specific acoustic energy values ranged between 60 and 244 kJ/L, and 32 and 687 kJ/L for the pulsed and continuous ultrasound modalities, respectively.

Fig. 3 shows the effect of pulsed and continuous power ultrasound provided under uncontrolled temperature regime on the total microbial count of the wastewater obtained by fresh-cut lettuce washing. The effect of heat alone, i.e. generated by providing the water sample the same time-temperature combinations received during the continuous ultrasound without temperature control, on the native microflora is also shown. The Log reductions of the total microbial count of wastewater increased linearly with exposure time ( $p < 0.05$ ). In particular, the rate constants computed from the slopes of the linear regression of the logarithm of total microbial count vs exposure time were 0.109, 0.147 and 0.142 min<sup>-1</sup> ( $0.711 < R^2 < 0.874$ ) for the pulsed ultrasound, continuous ultrasound and heating, respectively. It can be observed that the rate constants of the pulsed and continuous ultrasound increased with increasing levels of power density (205 and 572 W/L, respectively), in agreement with previous findings (Patil, Bourke, Kelly, Frias, & Cullen, 2009; Gao et al., 2014). Thus, the lowest Log reductions were attained during pulsed ultrasound. In fact, 20 min of this treatment resulted in 2.4 Log reductions of the total bacterial count. According to the classification suggested by Madge and Jensen (2002), this value accounts for a good disinfection efficiency of the pulsed ultrasound. It is noteworthy that the same Log reduction was achieved by applying continuous power ultrasound with temperature control (Fig. 1). It could be argued that the additional thermal effect produced during the pulsed treatment is likely to compensate the lower cavitation effect generated during the continuous ultrasound process at controlled temperature regime. Microorganisms responded similarly to the continuous ultrasound and heating alone (Fig. 3). Twenty min application of both treatments allowed a 3.2 Log reduction of the native microflora to be achieved, thus indicating that the *in situ* generated heat contributed to microbial inactivation, in agreement with previous findings (Madge & Jensen, 2002; Salleh-Mack & Roberts, 2007; Gómez-López et

287 al., 2015). Overall, data reported here suggest that cavitation may be not the only mechanism of microbial  
288 decontamination. Besides physical (i.e. extreme pressure variations and micro-streaming) and chemical (i.e.  
289 formation of free radicals and H<sub>2</sub>O<sub>2</sub>) mechanisms, temperature rise, occurring during ultrasound, plays an  
290 important role towards microbial inactivation.

291 Fig. 4 shows the Log reductions of the total microbial count in the wastewater derived from washing fresh-cut  
292 lettuce as a function of the specific energy generated upon the pulsed and continuous power ultrasound  
293 processes without temperature control as well as heating alone. As the specific energy brings together  
294 transferred power, time of exposure and treated volume (Hulsmans et al., 2010), it was used as a reference  
295 parameter to make possible the comparison. It can be observed that the plots describing the effect of pulsed  
296 and continuous power ultrasound on the total bacterial count were almost overlapping, indicating that  
297 ultrasound modality (and thus power transferred into the fluid) had barely an effect on the microbial  
298 decontamination level, provided that the same energy (and temperature) was achieved. These two plots were  
299 in turn nearly on top of that describing the effect of the heating alone on the naturally present microflora. Our  
300 results are partially in disagreement with those reported by Madge and Jensen (2002) for fecal coliforms in  
301 domestic wastewater. In fact, according to these authors, the disinfection efficiency of pulsed and continuous  
302 ultrasound was similar up to 60 kJ/L, while the pulsed ultrasound resulted less effective than the continuous  
303 treatment at increasing doses. The results of the present study clearly show that the specific energy transferred  
304 to the system during power ultrasound without temperature control affected the microbial reduction, regardless  
305 the ultrasonication modality (pulsed or continuous), and confirmed that the *in situ* generated heat contributed  
306 to decontamination.

307 Fig. 5 shows the decontamination efficiency of continuous power ultrasound under uncontrolled temperature  
308 regime on wastewater inoculated with *L. monocytogenes*, *E. coli* and *S. enterica* suspensions having initial  
309 concentration of approximately 10<sup>6</sup> CFU/mL. Reductions of 1.0, 1.2 and 5 Log units of *L. monocytogenes*, *E.*  
310 *coli* and *S. enterica* were attained after 3 min of continuous ultrasound, respectively. Complete inactivation of  
311 *L. monocytogenes*, *E. coli* was achieved at 5 min of ultrasound exposure. By subjecting wastewater inoculated  
312 with *E. coli* and *S. enterica* to heating alone, by providing the same time-temperature combinations received  
313 during the continuous ultrasound, 5 Log reductions were also achieved within 5 min and 3 min, respectively.  
314 On the contrary, only 1.7 Log reductions *L. monocytogenes* were attained after 5 min heating, while complete

315 inactivation was achieved following 10 min treatment (Fig. 5). It must be pointed out that in our experimental  
316 conditions, temperature never exceeded 50 °C within 3 min of ultrasonication. At this sub-lethal temperature,  
317 *L. monocytogenes* cells were subjected to the ultrasound effect alone. On the contrary, as at 5 min of treatment  
318 the temperature rose to 65 °C, a contribution to *L. monocytogenes* reduction of the heat generated during the  
319 ultrasound process above this exposure time can be inferred, in agreement with previous studies (Pagan,  
320 Manas, Alvarez, & Condon, 1999; Bauman, Martin, & Feng, 2005; Salleh-Mack & Roberts, 2007; Gómez-  
321 López et al., 2014). Results indicate that the same decontamination efficiency against *E. coli* and *S. enterica*  
322 was achieved by providing either ultrasound or heating processes. Only in the case of *L. monocytogenes*  
323 different contributions to microbial reduction were found for ultrasound without temperature control and  
324 heating alone.

325 To actually differentiate cavitation and heat contributions to bacteria inactivation, *L. monocytogenes*, *E. coli*  
326 and *S. enterica* logarithmic cell numbers in wastewater samples were compared in terms of specific energy  
327 provided during either the continuous ultrasound treatments with or without temperature control or heating.  
328 Table 1 shows the rate constants computed from the slopes of the linear regression ( $p < 0.005$ ) of the logarithm  
329 of bacterial count vs energy values (kJ/L), and the correspondent determination coefficients. The estimated  
330 inactivation rate constant for *L. monocytogenes* in wastewater subjected to ultrasound without temperature  
331 control was greater than the inactivation rate constants obtained by either heating only or ultrasound under  
332 controlled temperature regime. According to Madge and Jensen (2002), these rate constants were used to  
333 determine the acoustic and thermal contributions to disinfection. In particular, the former was calculated as the  
334 percentage ratio of the rate constants of ultrasonication with and without temperature control; the thermal  
335 contribution was computed as the percentage ratio of the rate constants of thermal treatment and ultrasound  
336 process without temperature control. The acoustic and thermal contributions to *L. monocytogenes* inactivation  
337 were estimated to account for about 22 and 58%, respectively. The remaining 20% of unaccounted contribution  
338 can be attributed to synergistic effects. These results are in agreement with data reported by Madge and Jensen  
339 (2002) for fecal coliform bacteria in domestic wastewater subjected to ultrasound treatment at 700 W/L with  
340 or without temperature control and heating alone. Data of Table 1 also show that the estimated values of  
341 inactivation rate constants for *E. coli* and *S. enterica* subjected to continuous ultrasound without temperature  
342 control were almost the same of those accounting for the heat treatment alone. In other words, a small

temperature rise (i.e. from 30 °C to 50 °C for *S. enterica*; from 30°C to 63°C for *E. coli*) allowed the disinfection efficiency to be greatly increased. Therefore, in our experimental conditions, the effectiveness of continuous ultrasound carried out without temperature control compared with that provided under controlled temperature regime against *E. coli* and *S. enterica* was mainly due to the thermal contribution, while the acoustic mechanism was negligible. Differences in acoustic and heat contributions observed among *L. monocytogenes*, *E. coli* and *S. enterica* can be brought back to their different sensitivity to heat and ultrasounds, *L. monocytogenes* being the most resistant (Pagan, Manas, Raso, & Condon, 1999).

To find whether these treatments had reversible or irreversible effects, resuscitation trials were carried out on *L. monocytogenes*, *E. coli* and *S. enterica* inoculated wastewater already subjected to continuous ultrasound without temperature control or heat treatment. Results showed that *E. coli* and *S. enterica* were irreversibly inactivated by 5 min of both treatments, whereas *L. monocytogenes* cells, although stressed, were able to re-grow, indicating their ability to repair the cellular damage. However, no resuscitation was observed for *L. monocytogenes* cells subjected to longer treatments.

#### 4. Conclusions

The results acquired in this study highlighted the effectiveness of pulsed and continuous power ultrasound in decontaminating wastewater derived from fresh-cut production. When ultrasound was provided with temperature control, different capabilities were found among the microorganisms considered (i.e. native microflora as well as inoculated *L. monocytogenes*, *E. coli* and *S. enterica*) to withstand physical and chemical effects of cavitation, *L. monocytogenes* and *S. enterica* being the most and the least resistant, respectively. When ultrasound was applied without temperature control, a 5 Log reduction of the pathogenic bacteria was achieved within 5 min. Such a rapid decontamination was attributed to the contribution of *in situ* generated heat during ultrasound treatment. The thermal contribution accounted for 58% for *L. monocytogenes*, while it represented the prevalent mechanism for *E. coli* and *S. enterica*, that are more heat sensitive bacteria. In light of this, instead of increasing ultrasound power input and dissipate the heat produced during the treatment, it seems more feasible to apply lower acoustic power densities and exploit the *in situ* generated thermal effect to decontaminate wastewater obtained by fresh-cut vegetable washing from heat resistant microorganisms. In the

371 attempt to optimize the wastewater management in the fresh-cut sector, application of power ultrasound in  
372 combination with *in situ* generated heat to wastewater decontamination could represent a promising tool for  
373 water recycling inside a fresh-cut production. Moreover, besides safety requirements, this technology would  
374 also meet cost-effectiveness criteria and existing standards.

375

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377

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 467

468 **Figure captions**

469

470 **Fig. 1.** Log reductions of total microbial count, *L. monocytogenes*, *E. coli* and *S. enterica* in wastewater  
471 obtained by fresh-cut lamb's lettuce washing, subjected to continuous power ultrasound under controlled  
472 temperature regime.

473

474 **Fig. 2.** Time-temperature profiles of wastewater from fresh-cut lamb's lettuce washing during pulsed or  
475 continuous power ultrasound provided under uncontrolled temperature regime.

476

477 **Fig. 3.** Log reductions of total microbial count in wastewater fresh-cut lamb's lettuce washing subjected to  
478 pulsed or continuous power ultrasound under uncontrolled temperature regime, or heating. The latter provided  
479 the water sample the same time-temperature combinations received during the continuous ultrasound.

480

481 **Fig. 4.** Log reductions of total microbial count in wastewater from fresh-cut lamb's lettuce washing as a  
482 function of the specific energy generated upon pulsed and continuous power ultrasound without temperature  
483 control as well as upon heating provided according to the same time-temperature combinations received during  
484 the continuous ultrasound.

485

486 **Fig. 5.** Log reductions of *L. monocytogenes*, *E. coli* and *S. enterica* inoculated in wastewater from fresh-cut  
487 lamb's lettuce washing as a function of time for continuous power ultrasound under uncontrolled temperature  
488 regime. Dashed lines: microbial reduction obtained by subjecting wash water to the sole heat generated by  
489 providing the water sample the same time-temperature combinations received during the continuous  
490 ultrasound. Asterisk: counts below the detection limit of 1 Log CFU/mL.

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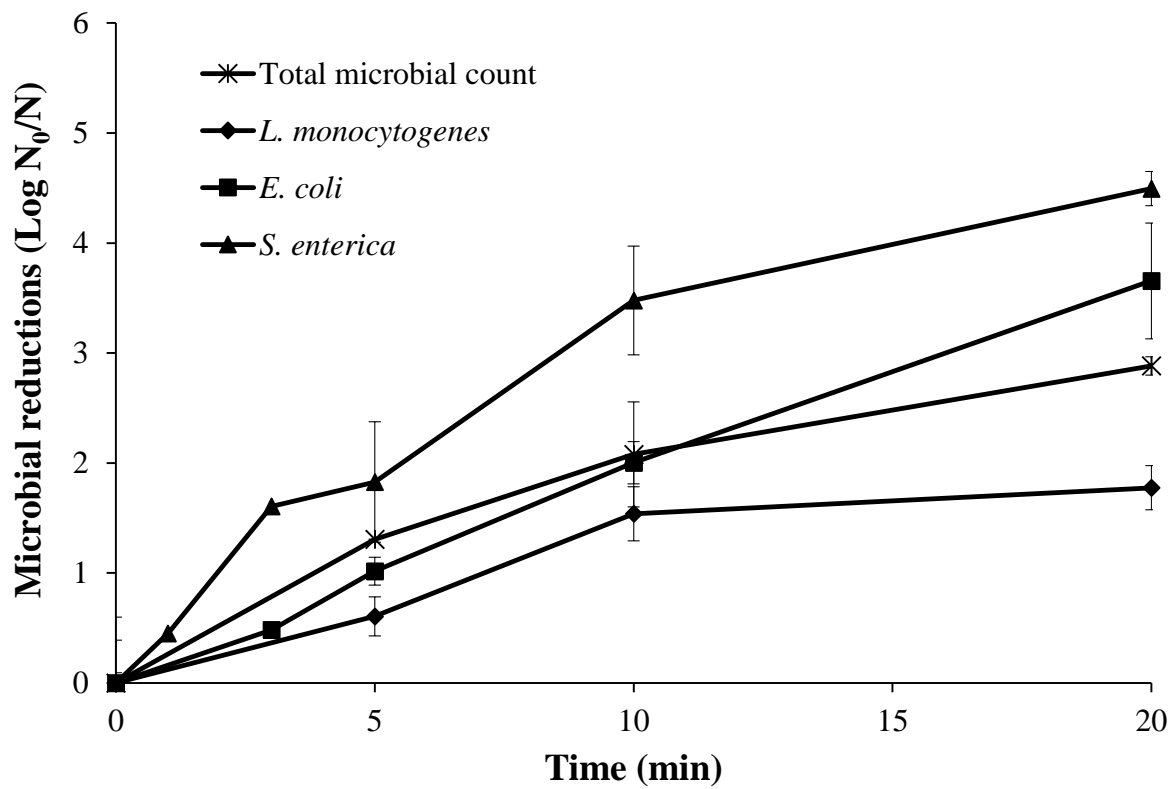
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**Table 1**

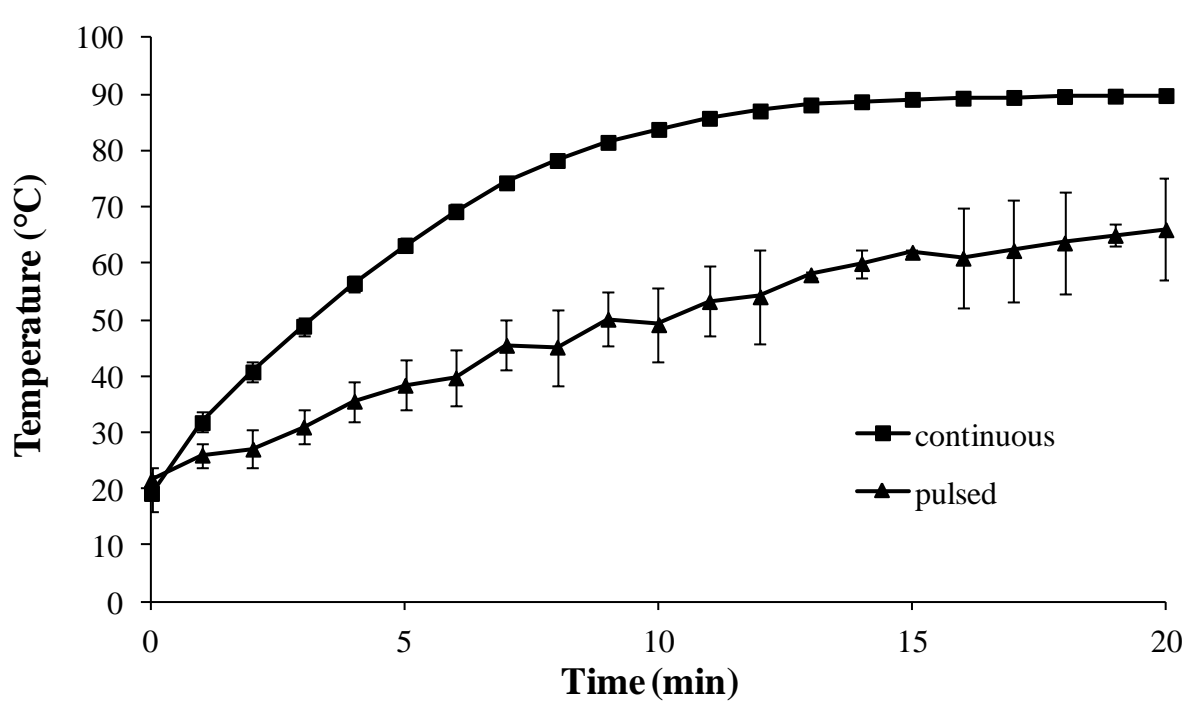
Rate constants computed from the slopes of the linear regression of the logarithmic cell number of *L. monocytogenes*, *E. coli* and *S. enterica* in wastewater from fresh-cut lamb's lettuce washing subjected to continuous ultrasound processing (US) with or without temperature control or heating *vs* energy values (kJ/L), and correspondent determination coefficients.

	US with temperature control		US without temperature control		Heat only	
	k (L/kJ)	R <sup>2</sup>	k (L/kJ)	R <sup>2</sup>	k (L/kJ)	R <sup>2</sup>
<i>L. monocytogenes</i>	0.0057	0.830	0.0263	0.858	0.0152	0.967
<i>E. coli</i>	0.0125	0.979	0.0278	0.892	0.0298	0.843
<i>S. enterica</i>	0.0144	0.889	0.0449	0.965	0.0477	0.963

p<0.005

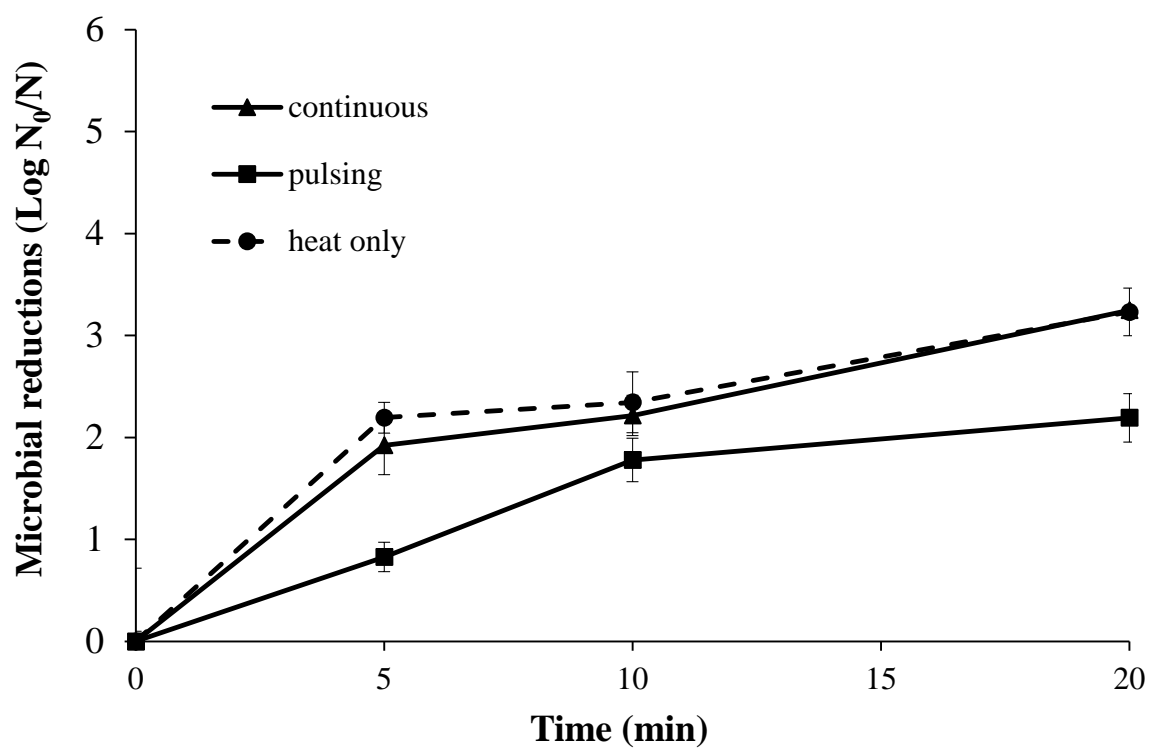


**Fig. 1**



**Fig. 2**

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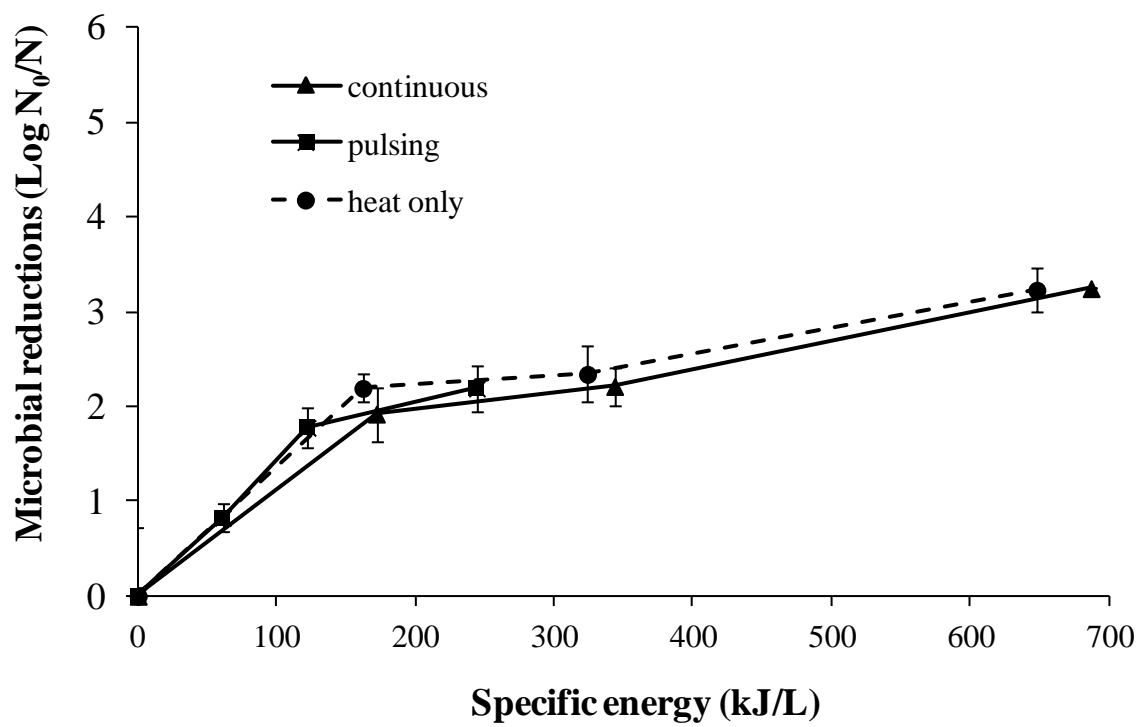
534 **Fig. 3**

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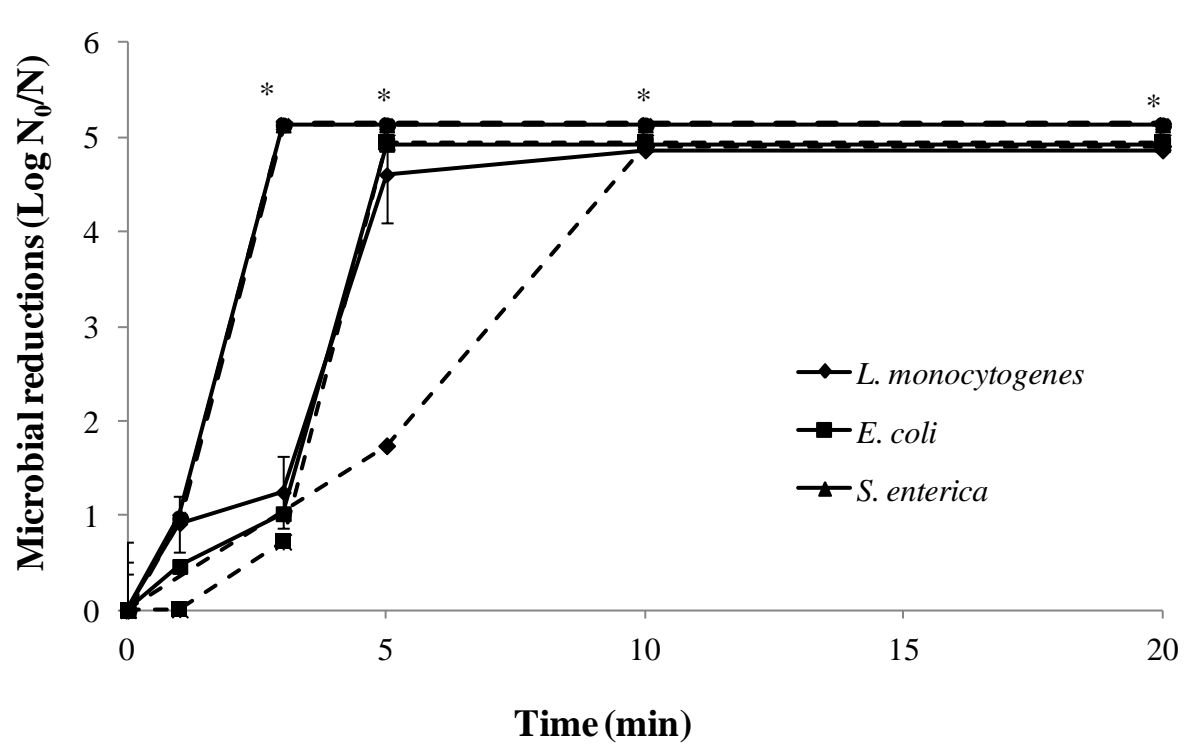
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**Fig. 4**



**Fig. 5**