Operating conditions for the electrolytic disinfection of process wash water from the fresh-cut industry contaminated with *E. coli* O157:H7

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The effect of operating conditions (current density, recirculation flow rate and electrode doping level) on the efficacy of boron-doped diamond (BDD) electrodes to inactivate microorganisms and decrease chemical oxygen demand (COD) was studied in lettuce process wash water with a COD of 725 mg/L and inoculated with a 5-strain cocktail of *Escherichia coli* O157:H7. Changes in pathogen population, COD, pH, temperature, redox potential, and free and total chlorine were monitored in process wash water during treatments. Considering the specific characteristics of the washing step included in the fresh-cut processing, the disinfection of process wash water should be of fast action. A biphasic with a shoulder model was used to estimate shoulder length (SI), log-linear inactivation rates (k$_{max1}$, k$_{max2}$), lowest population (N$_f$) and highest log reduction (HLR). Current density clearly influenced SI, and k$_{max2}$; recirculation flow rate influenced SI, k$_{max1}$, k$_{max2}$ and COD depletion; and doping level influenced N$_f$. No relationship was observed between inactivation parameters and chlorine concentration. Conditions including high current density (180 mA/cm$^2$), high flow rate (750 l/h) and high doping level (8 000 μmol/mol) seems to provide a disinfection efficiency suitable to decrease the chance of bacterial cross contamination in the fresh-cut industries while saving on water consumption and decreasing the amount of wastewater effluents.

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1. Introduction

Electrolyzed oxidizing water is a novel disinfectant that has been proposed as alternative to chlorination for washing of fresh and fresh-cut produce (Gómez-López et al., 2008). Its capability to achieve levels of microbial inactivation similar to those of conventional chlorination but with lower chlorine concentration and consequently less production of chlorinated disinfection by-products is one of its advantages (Issa-Zacharia, Kamitani, Miwa, Muhimbula, & Iwasaki, 2011).

It has been recently acknowledged that the primary role of disinfectants in washing fresh and fresh-cut produce is avoiding cross-contamination during washing (Gil, Selma, López-Gálvez, & Allende, 2009; López-Gálvez, Gil, Truchado, Selma, & Allende, 2010; Parish et al., 2003), since the decontaminant effect of the microbial reduction caused on produce is readily lost during storage (Allende, Selma, López-Gálvez, Villaescusa, & Gil, 2008) and once cross-contamination occurs it is not possible to eliminate the pathogen from produce (López-Gálvez et al., 2010; Luo et al., 2011).

This approach focuses the disinfection process towards the washing water rather than towards produce.

The chemical oxygen demand (COD) of wash water, which is used to estimate its amount of organic load, increases during washing due to the transfer of organic matter from produce to water through field soil, plant debris and exudates from vegetable surface fissures and cut surfaces. This phenomenon decreases the efficacy of most disinfectants, included those based on free chlorine such as electrolyzed water (Oomori, Oka, Inuta, & Arata, 2000). It also increases the amount of fresh water required for the fresh-cut industry and the pollution caused by wastewater disposal to the environment. Moreover, washing fresh-cut produce with water with high COD due to reuse impacts its quality; for example, Luo (2007) reported that washing lettuce in process water reduces tissue integrity and increase off-odor development.

The fresh and fresh-cut industry uses big amounts of water during washings. The minimization of water use and wastewater discharges is one of the big challenges of the fresh-cut industry (Ölmez & Kretzschmar, 2009). A water disinfection method that allows using the same water during longer periods or allows recycling will save costs to the industry and will be environmentally friendly. Therefore, a method that inactivates microorganisms...
in washing water to avoid cross-contamination and simultaneously decrease the accumulation of organic load will offer many advantages to the fresh-cut industry.

Boron-doped diamond (BDD) electrodes are attracting considerable attention for water and wastewater treatment due to generation of reactive oxygen species (ROS). They have several advantages over conventional anodes, which have been recently summarized (Martínez-Huitle & Brillas, 2008). BDD electrodes have been studied for chlorine-free disinfection processes, which will not give place to formation of chlorinated by-products (Ghernaout, Naceour, & Aouabed, 2010). Li, Zhu, and Ni (2010) proved the efficacy of BDD electrodes for inactivation of Escherichia coli K12 in Na₂SO₄ electrolyte, which was related to production of hydroxyl radical and other oxidants. As summarized previously (Panizza & Cerisola, 2009), numerous studies have demonstrated the efficacy of BDD electrodes to oxidize organic wastewaters.

We have previously reported the efficacy of BDD electrodes to inactivate E. coli O157:H7 and reduce COD of process water at several initial COD levels (López-Gálvez et al., 2012). The present study had as goals to study the effect of electric current density, recirculation flow rate and electrode boron doping level in the efficacy of electrolyzed water to inactivate a bacterial pathogen and decrease COD in process wash water.

2. Material and methods

2.1. Bacterial strains and inoculum preparation

A five-strain cocktail of E. coli O157:H7 strains (CECT 4267, 4076, 4782, 4783, and 5947), provided by the Hibro Group from the University of Cordoba (Spain), was used in the study. Cultures were rehydrated in Brain Heart Infusion broth (BHI, Oxoid, Basingstoke, United Kingdom). Nalidixic acid-resistant (NalR) E. coli O157:H7 cultures were obtained by consecutive 24 h transfers of BHI cultures to BHI with increasing concentrations of nalidixic acid (NaI) (Merck, Darmstadt, Germany) until strains were resistant to 50 μg of NaI per ml. NalR E. coli O157:H7 cultures were consecutively subcultured twice in 5 ml of BHI supplemented with NaI (Nal +, 50 μg/ml) at 37 °C for 20 h. After the second incubation, cultures were mixed, equal volumes of cell suspensions were combined to give approximately equal populations of each culture. Final concentrations of the inoculum solutions were confirmed by plating on Chromocult coliform agar (Merck, Barcelona, Spain) NaI (50 μg/ml).

2.2. Process wash water

Iceberg lettuce (Lactuca sativa L.) was purchased from a local wholesale market in Murcia (Spain) at the day of harvest and transported within 15 min under refrigerated conditions to the laboratory. Outer leaves were manually removed and discarded while internal leaves were cut into 3 cm pieces. Afterwards, batches of 67 g of lettuce each were placed into stomacher bags (Seward Limited, London, UK), 200 ml of water were added, and the mixture was homogenized for 2 min in a stomacher (AES Chemunex, Bruz, France). The obtained process wash water was filtered through a nylon mesh with gaps of 0.5 mm, in order to avoid obstruction of the electrolytic cell. The batch of process wash water was divided in portions and frozen at −20 °C until use. This process gives place to formation of chlorinated by-products (Ghernaout, Naceour, & Aouabed, 2010). Li, Zhu, and Ni (2010) proved the efficacy of BDD electrodes to oxidize organic wastewaters.

Disinfection experiments were performed using a pilot plant treatment system provided by Adamant-Technologies (La Chaux-de-Fonds, Switzerland). The treatment system included: power supply, control board, centrifuge pump, treatment tank, flowmeter, pipes, globe valve and electrolytic cells. Process temperature was controlled by pumping cold water through stainless steel heat exchangers immersed into the process water. An undivided electrolytic cell comprising two 100 mm BDD electrodes with an overall effective anode surface area of 67 cm² was used in all experiments (Diacell® 101 Adamant-Technologies, Switzerland). Amperage was set and controlled through the experiments by the power supply, which changed the polarity of electrodes every 20 min to minimize scale build-up on their surface.

Process wash water was inoculated with the NaI E. coli O157:H7 cocktail at an inoculum level of approximately 5 log cfu/ml just before the beginning of the electrolytic treatment. A volume of 5 L of inoculated water was placed in a polypropylene tank and recirculated through the electrolytic cell. Water recirculation flow rate was adjusted by means of the globe valve. In all cases pH of water was adjusted to ca. 6.5 before the treatments with 80 mg/L of citric acid. Initial water temperature was 8–10 °C and maintained within ±2 °C throughout our tests at 30–120 mA/cm². When the electrolytic cell was operated at 180 mA/cm² a maximum increase of 7 °C was observed at the end of the test.

2.4. Experimental design

A “reference” operating conditions was defined as a current density of 60 mA/cm², a flow rate of 300 l/h and a thin film diamond doping level (B/C, Boron/Carbon ratio) of 800 ppm (μmol/mol). These conditions were changed as indicated in Table 1. Two replicates were carried out by each of the tested conditions.

2.5. Microbiological and physicochemical analyses

Changes in levels of NaI E. coli O157:H7 were measured at different time intervals during 2 hours, with shorter intervals at the beginning of the experiments. Microbial enumeration was carried out as previously described (López-Gálvez et al., 2012).

Changes in levels of free and total chlorine (mg/L), pH, oxidation-reduction potential (ORP, in mV), temperature (°C), and COD (mg/L) were measured at different time intervals. Temperature, ORP, and pH were measured using a multimeter pH & redox 26

<table>
<thead>
<tr>
<th>Code</th>
<th>B/C ratio (μmol/mol)</th>
<th>Current density (mA/cm²)</th>
<th>Voltage</th>
<th>Recirculation flow rate (l/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>800</td>
<td>60</td>
<td>17</td>
<td>300</td>
</tr>
<tr>
<td>hCD30</td>
<td>800</td>
<td>30</td>
<td>12</td>
<td>300</td>
</tr>
<tr>
<td>CD120</td>
<td>120</td>
<td>30</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>CD180</td>
<td>180</td>
<td>24</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>tFR150</td>
<td>60</td>
<td>16</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>FR750</td>
<td>18</td>
<td>750</td>
<td></td>
<td></td>
</tr>
<tr>
<td>dD50</td>
<td>50</td>
<td>60</td>
<td>14</td>
<td>300</td>
</tr>
<tr>
<td>D3000</td>
<td>3000</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D8000</td>
<td>8000</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hH800</td>
<td>800</td>
<td>32</td>
<td>750</td>
<td></td>
</tr>
<tr>
<td>H8000</td>
<td>8000</td>
<td>29</td>
<td>750</td>
<td></td>
</tr>
</tbody>
</table>

| b CD: current density. |
| c FR: flow rate. |
| d D: doping level. |
| e H: highest current density and flow rate. |

Table 1 Experimental conditions for the inactivation of E. coli O157:H7 and chemical oxygen demand removal of process wash water.
(Crison, Barcelona, Spain). Free and total chlorine were determined based on the N,N-diethyl-p-phenyldiamine (DPD) method (APHA, 1998) using the Spectroquant NOVA 60 photometer (Merck, Darmstadt, Germany). COD was determined by the standard photometric method (APHA, 1998) using the Spectroquant NOVA 60 photometer.

Lettuce water was characterized for alkalinity by potentiometric titration until pH 4.3 with HCl, turbidimetry by a nephelometer Turbiquant 3000 IR (Merck), and conductivity by a CM 35 conductimeter (Crison).

2.6. Data processing

Microbial inactivation data were produced in duplicate and analyzed by GInaFIT tool (Geeraerd, Valdimidis, & Van Impe, 2005). GInaFIT is a freeware tool to assess non-log-linear microbial survivor curves. Modeling was not among the goals of this research, data were analyzed by GInaFIT tool (Geeraerd, Valdimidis, & Van Impe, 2005). The model, described at (Geeraerd et al., 2006), is as follows:

\[
\log_{10}(N) = \log_{10}(N_0) + \log_{10}\left(\frac{f e^{k_{max1} t} + \left(e^{k_{max1} Sl} - 1\right) e^{-k_{max1} t}}{1 + \left(e^{k_{max1} Sl} - 1\right) e^{-k_{max1} t}} + \left(1 - f\right) e^{-k_{max2} t} \left(\frac{e^{k_{max1} Sl}}{1 + \left(e^{k_{max1} Sl} - 1\right) e^{-k_{max1} t}}\right)^{k_{max2}}\right)
\]

Where \(N\) (CFU/ml) is the number of survivors, \(N_0\) (CFU/ml) is the initial number of microorganisms, \(f\) is the fraction of the initial population in a major subpopulation, \(1 - f\) is the fraction of the initial population in a minor subpopulation, \(k_{max1}\) and \(k_{max2}\) (1/min) are the specific inactivation rates of the two populations, respectively, and \(Sl\) is the shoulder length (min) (Geeraerd et al., 2005). The Root Mean Sum of Squared Errors (RMSE) was used to evaluate the performance of the models (Geeraerd et al., 2005).

Non-kinetic curves were fitted using SPSS Statistics 19 (SPSS Inc., Chicago, ILL). Only curves with statistical significance (\(P < 0.05\)) are used for the discussion.

3. Results and discussion

3.1. Inactivation curves of Escherichia coli O157:H7

Table 2 shows the kinetic parameters of the inactivation curves for a cockpit of five strains of E. coli O157:H7 as influenced by diamond doping level (B/C, Boron/Carbon ratio), electrical current density and recirculation flow rate. In these experiments, current was fixed so that voltage was determined by the set current. Most of the inactivation curves exhibited a sigmoidal pattern, however at extreme conditions (e.g. maximum current density and recirculation flow rate), a second log-linear inactivation phase was observed (Fig. 1); specific cases will be discussed later. The biphasic with a shoulder model (Geeraerd et al., 2006) fit well the curves exhibiting a shoulder, one log-linear inactivation phase and then tailing as well as those with a shoulder and two log-linear inactivation phases, as it can be concluded from the low RMSE (Root Mean Sum of Squared Errors) values (Table 2). \(f\) values of all curves were higher than 0.99 indicating that the biggest part of the inactivation occurs in the first phase. Curves with shoulders have been reported for the inactivation of bacteria by BDD electrodes (in electrolyte solutions) (Jeong, Kim, & Yoon, 2009; Li et al., 2010); however no reports about tailing were found. It is possible that the high COD of the wash water used in our experiments caused depletion of oxidants before contacting bacteria at low populations under mild treatment conditions.

### 3.2. Changes in physicochemical parameters

As general trends, oxidation–reduction potential (ORP) increased slightly during electrolysis at all conditions with extreme values of 384 and 516 mV, and average values of 413 ± 31 mV at time zero and 495 ± 19 mV at the end of treatments. No relationship was observed between microbial inactivation trends and ORP evolution (data not shown) in spite of part of the early literature indicating a high ORP as the main factor for microbial inactivation by electrolyzed water (Kim, Hung, & Brackett, 2000; Oomori et al., 2000). However, this belief has been supported by studies that did not include the relatively new BDD electrodes, which could not depend on ORP for its disinfection action. Another important factor is pH, as it has been proved that the efficacy of water disinfection by BDD electrodes is greatly influenced by water pH (Jeong et al., 2009). The general trend was a stable pH during electrolysis.

Heat production is an undesirable side-effect of BDD electrolysis which generation depends on operating conditions. Temperature

<table>
<thead>
<tr>
<th>Code</th>
<th>SI (min)</th>
<th>(k_{max1}) (1/min)</th>
<th>(k_{max2}) (1/min)</th>
<th>RMSE</th>
<th>(N_0) (log CFU/ml)</th>
<th>HLR (^a) (log CFU/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>19.55 ± 1.24</td>
<td>0.25 ± 0.02</td>
<td>0.00 ± 0.00</td>
<td>0.0927</td>
<td>2.33</td>
<td>2.37</td>
</tr>
<tr>
<td>CD30</td>
<td>22.44 ± 2.25</td>
<td>0.33 ± 0.07</td>
<td>0.00 ± 0.00</td>
<td>0.2042</td>
<td>2.11</td>
<td>2.67</td>
</tr>
<tr>
<td>CD120</td>
<td>18.26 ± 1.95</td>
<td>0.38 ± 0.06</td>
<td>0.03 ± 0.01</td>
<td>0.2174</td>
<td>0.24</td>
<td>4.21</td>
</tr>
<tr>
<td>CD180</td>
<td>11.14 ± 1.19</td>
<td>0.56 ± 0.10</td>
<td>0.08 ± 0.01</td>
<td>0.1327</td>
<td>0.00</td>
<td>4.75</td>
</tr>
<tr>
<td>FR150</td>
<td>22.80 ± 2.71</td>
<td>0.16 ± 0.03</td>
<td>0.00 ± 0.00</td>
<td>0.1037</td>
<td>1.90</td>
<td>2.98</td>
</tr>
<tr>
<td>FR750</td>
<td>13.79 ± 1.55</td>
<td>0.49 ± 0.09</td>
<td>0.04 ± 0.01</td>
<td>0.1821</td>
<td>0.68</td>
<td>4.23</td>
</tr>
<tr>
<td>D50</td>
<td>14.64 ± 3.45</td>
<td>0.22 ± 0.04</td>
<td>0.01 ± 0.01</td>
<td>0.2120</td>
<td>2.10</td>
<td>2.89</td>
</tr>
<tr>
<td>D3000</td>
<td>22.17 ± 2.50</td>
<td>0.28 ± 0.05</td>
<td>0.00 ± 0.00</td>
<td>0.2182</td>
<td>1.81</td>
<td>2.87</td>
</tr>
<tr>
<td>DB000</td>
<td>16.45 ± 2.29</td>
<td>0.23 ± 0.02</td>
<td>0.00 ± 0.01</td>
<td>0.1852</td>
<td>0.52</td>
<td>3.99</td>
</tr>
<tr>
<td>HB000</td>
<td>3.36 ± 2.43</td>
<td>0.77 ± 0.30</td>
<td>0.09 ± 0.03</td>
<td>0.3837</td>
<td>0.00</td>
<td>4.80</td>
</tr>
<tr>
<td>HB000</td>
<td>4.89 ± 0.68</td>
<td>1.58 ± 0.58</td>
<td>0.26 ± 0.02</td>
<td>0.1803</td>
<td>0.00</td>
<td>4.73</td>
</tr>
</tbody>
</table>

Parameters correspond to the biphasic with a preceding shoulder model of Geeraerd et al. (2005, 2006).

\(^a\) SI: shoulder length.
\(^b\) \(k_{max1}, k_{max2}\): Specific inactivation rate of subpopulations 1 and 2 respectively.
\(^c\) RMSE: root mean sum of squared errors.
\(^d\) \(N_0\): minimal estimated count.
\(^e\) HLR: highest log reduction based on estimated values.
increase was around ±2 °C with a maximum of 10 °C throughout our tests at 30–120 mA/cm²; when the electrolytic cell was operated at 180 mA/cm² the temperature changed from 10 to 17 °C.

3.3. Effect of current density on Escherichia coli O157:H7 inactivation and COD depletion

It can be observed in Fig. 2 that the length of the shoulder of the inactivation curves decreases with current density increase, as it has been previously reported (Jeong et al., 2009; Li et al., 2010). Shoulders occur in inactivation curves when the damage inflicted to microbial cells during the corresponding treatment time has not been enough to cause inactivation, and does not exist when the damage to microbial cells is strong enough to cause immediate inactivation. Cross-contamination of fresh and fresh-cut produce during washings occurs when a contaminated piece of fruit or vegetable releases microorganisms to the washing water, which allows them to reach other pieces. Once the cross-contamination has occurred, the disinfection of the newly contaminated pieces is not possible (López-Gálvez et al., 2010; Luo et al., 2011). In order to avoid this process, the disinfectant should act without delay. Therefore, it would be advisable to produce electrolyzed water at high current densities in order to minimize delay in the inactivation of microorganisms in process wash water. No pattern was however observed for the $k_{max1}$ as function of current density (Table 2). $k_{max2}$ values were zero at low current densities, which corresponds with the tailing observed in those inactivation curves; and become higher than zero with increasing current densities, which corresponds to a second log-linear inactivation phase. It seems that at low current densities, the treatment is not enough to overcome the resistance of a persistent subpopulation, which is broke down at high current densities. When $k_{max2} > 0$, $k_{max2}$ is smaller than $k_{max1}$, showing that the inactivation proceeds slower after the second inflection point.

Increasing the current density linearly increased the highest log reduction (HLR) (Fig. 2). Our results agree with those of Gusmão, Moraes, and Bidoia (2010), who reported a higher $E. coli$ inactivation at higher current densities in sodium sulfate electrolyte, and with the results of Li et al. (2010) for $E. coli$ inactivation in sodium sulfate electrolyte as well, but using a BDD anode as in the present research. In the present study, the limit of detection (1 CFU/ml) was reached at 180 mA/cm². These facts indicate that the use of high current densities to treat process water is advisable for fresh-cut industry.

Free chlorine is the form of chlorine responsible for most of the microbial inactivation in classical electrolyzed water. It was detected only in very low concentrations thorough these experiments, reaching a maximum level of 0.71 mg/L through these experiments and the highest concentration detected at the end of any experiment was 0.40 mg/L. The low free chlorine to total chlorine ratio was expected given the low chloride concentration present in the water (115 mg/l), the high amount of organic load of the process wash water and the presence of nitrogen compounds that react with free chlorine to form chloramines. The measured low free chlorine concentration can contribute to kill microorganisms, although, as BDD electrodes have demonstrated chlorine-free disinfection efficiency (Martínez-Huitl & Brillas, 2008), it is believed that the inactivation is mainly caused by the wide range of ROS produced on BDD electrodes. For example, Jeong et al. (2009) compared five anode materials for non-pathogenic $E. coli$ inactivation in a chlorine-free electrolyte. They found that a BDD anode was more effective for microbial inactivation, which was associated to a higher production of hydroxyl radicals. A lower potential for generation of toxic halogenated disinfection by-products is expected giving the low levels of free chlorine generated in these experiments.

The total chlorine evolution during electrolysis exhibited a parabolic increase (Fig. 3), with faster increment at higher current density for the range 30–120 mA/cm². This result is in line with Len, Hung, Erickson, and Kim (2000), who reported higher chlorine production at higher current densities. Comparing bacterial inactivation constants with the total chlorine evolution, the higher the total chlorine concentration the higher the inactivation up to 120 mA/cm², but the HLR at 180 mA/cm² is not related to a higher total chlorine concentration. At 180 mA/cm², the evolution was similar than that at 120 mA/cm², however, after 40 min became slower until decrease at long times. This behavior is consistent with results from other tests performed at 180 mA/cm² that will be presented later in this article. It is possible that the high current density favored the breakdown of chloramines, which can account for most of the total chlorine measured. It has been reported that electro-generated free chlorine reacts with chloramines in the vicinity of the surface of BDD electrodes to N₂ (Kapalka, Joss, Anglada, Comninellis, & Udert, 2010) and NCl₃.

The first-order rate of (chemical oxygen demand) COD depletion as function of different operating parameters is shown in Table 3. COD depletion rates do not depend on current density within the...
High current densities are beneficial for fast microbial inactivation. Nevertheless, high current densities are less efficient from the point of view of energy consumption required to achieve a given COD removal. As shown in Fig. 4, it can be observed that the amount of energy consumption required to achieve a given COD removal follows the order: 180 > 120 > 60 > 30 mA/cm².

3.4. Effect of recirculation flow rate on Escherichia coli O157:H7 inactivation and COD depletion

As observed at high charge densities, $k_{\text{max}, 2} > 0$ only at high recirculation flow rate (Table 2). Similarly, high recirculation flow rates increase COD rate depletion due to better material transport towards the electrode in the diffusion limited operation regime of the cell. During electrolysis, a boundary layer rich in newly produced oxidants and poor in precursors is formed on anodes. Under static conditions, the boundary layer increases thickness, which precludes de novo formation of oxidants and decreases disinfection efficacy. A higher recirculation flow rate decreases the boundary layer thickness on the electrode surface. This results in a higher rate of transport of the organic material towards the electrode (larger transfer coefficient) and therefore in a higher oxidation rate. It also favors the diffusion of short lived reactive oxygen species towards the bulk of the solution, therefore increasing the disinfection efficiency. These findings suggest that a high recirculation flow rate is beneficial for a faster microbial inactivation and COD depletion in process wash water from the fresh and fresh-cut produce industry.

3.5. Effect of B/C ratio on Escherichia coli O157:H7 inactivation and COD depletion

Pure diamond is an insulator and it must be made conductive by doping, usually with boron. The influence of the doping level on the electrochemical disinfection process cannot be easily predicted and has never been evaluated. It was therefore considered important to check the effect of this parameter. As shown in Fig. 6, E. coli O157:H7 final counts decreased when the doping level is increased to 8000 μmol/mol. No effect of the B/C ratio (diamond doping level)
was observed for the other parameters of the inactivation model. Likewise the doping level does not affect COD depletion (Table 3). Therefore, a higher B/C ratio seems to benefit microbial inactivation without affecting negatively COD depletion, and it might be suitable for a more efficient decontamination of process wash water in the fresh and fresh-cut produce industry.

3.6. Selection of operating conditions

The synergy of a high current density, a high flow rate and a high doping level was expected to give a superior inactivation rate. Consequently this condition was assayed also including the reference 800 μmol/mol doping level. The results demonstrate a major improvement in efficiency (Table 2, Fig. 7), with shorter shoulders, higher inactivation rates and microbial counts also dropping to null.

Similarly, the levels of total chlorine for both experiments also decreased after reaching a maximum (data not shown). COD depletion rate under these treatment conditions is twice that of the standard treatment. Taking into account only the data for 180 mA/cm², it is interesting to notice that counts became zero earlier in process wash water treated at 8000 μmol/mol B/C ratio (at 35 min), and also earlier at 750 l/h (at 55 min) than at 300 l/h (at 90 min) as it can be deducted from k_max1 and k_max2 values presented in Table 2. Therefore, as it could be expected, 8000 μmol/mol B/C ratio, 750 l/h recirculation flow rate and 180 mA/cm² gives the best conditions for a faster and more complete microbial inactivation and COD depletion.

As conclusion, when suitable operating conditions are applied, wash water electrolysis with BDD electrodes is a promising technology for the fresh-cut industries to decrease the chance of bacterial cross-contamination, save water consumption and decrease wastewater effluents. Further work is needed to evaluate the efficiency in a dynamic system where microbial and COD loads are changing with time.

Acknowledgments

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Fig. 5. Effect of recirculation flow rate on the shoulder length and the first-phase log-linear inactivation rate for E. coli O157:H7 in process wash water electrolyzed by 800 μmol/mol B/C ratio boron doped diamond electrodes at 60 mA/cm².

Fig. 6. Effect of electrode boron doping level (μmol/mol) on the final E. coli O157:H7 counts after 120 min in process wash water electrolyzed at 60 mA/cm² and 300 l/h recirculation flow rate.

Fig. 7. Inactivation curve for a five-strain cocktail of E. coli O157:H7 in process wash water electrolyzed under the following conditions: CD180: 800 μmol/mol boron doping level, 180 mA/cm², 300 l/h; H800: 8000 μmol/mol boron doping level, 180 mA/cm², 750 l/h; and H8000: 8000 μmol/mol boron doping level, 180 mA/cm², 750 l/h.

References


