# Electrolysed Water in the Food Industry as Supporting of Environmental Sustainability

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**Abstract** Food safety is a priority for the food industry and to achieve this result a correct plant sanitation programme is of the utmost importance. Among various disinfection techniques, an emerging one is represented by the use of electrolysed water (EW) as the disinfecting agent. The use of EW is compliant with the desire to find alternatives to chlorination and heat treatments, representing a green cleaning alternative to toxic disinfectants. EW is an activated liquid, obtained by passing a diluted saline solution (NaCl, KCl or $MgCl_2$) through an electrolytic cell, thus causing the production from the anode side of electrolysed oxidising water, containing high dissolved oxygen, free chlorine and characterised by a low pH (2.3–2.7) and a high oxidation–reduction potential (ORP > 1,000 mV). At the same time from the cathode side electrolysed reduced water is produced, with high pH (10.0–11.5), high dissolved hydrogen and low ORP (−800 to −900 mV). Unlike other chemical disinfectants, EW is not harmful for skin and mucous membranes and is quite easy to handle. Furthermore, the use of EW is relatively inexpensive and, above all, is a sustainable technique. Currently used sanitisers (e.g. glutaraldehyde, formaldehyde, etc.) are effective, but their adverse effects on the environment are well known. Differently from these chemicals, the use of EW has a reduced impact on the environment and because of its properties, it may find several applications in the food industry. In this work, the characteristics and some EW applications as sustainable sanitation technique applied in the food industry are reported and discussed.

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# 1 Introduction

Chlorine is commonly used as a disinfectant in food processing industries. However, the continuing outbreaks of food infection raise concerns and doubts about food safety. A large part of the food industry uses hypochlorite as disinfectant, but it is not often used under optimum conditions compromising its effectiveness. The excessive use of this disinfectant involves the presence of undesirable by-product residues on food (Gil et al. 2009). In addition, the chlorine-based disinfectants are a risk for human health and the environment (Ölmez and Kretzschmar 2009). In fact, it is known that from the reaction of chlorine with organic matter are generated carcinogenic halogenated by-products (DBP), for example trihalomethanes (THMs) and halogenated acids (HAAs) (Gil et al. 2009; Singer 1994). Moreover, the use of chlorine allows the production of large amounts of wastewater with high levels of biological oxygen demand (BOD). Chlorine dioxide, ozone, organic acids, peroxyacetic acid, hydrogen peroxide and EW are the main alternative sanitising agents that arouse interest (Ölmez and Kretzschmar 2009). In particular, EW represents a good alternative to chlorination and heat treatments, representing a green cleaning alternative to toxic disinfectants. Unlike other chemical disinfectants, EW is not harmful for skin and mucous membranes and is quite easy to handle. Furthermore, the use of EW is relatively inexpensive and, above all, is a sustainable technique. The cost of use is relatively low; the highest cost is the purchase of an electrolytic unit, but, after the initial investment, the costs are very low, requires only water, salt and electricity (Huang et al. 2008). Another important aspect is the low environmental impact which involves the use of EW. When the EW is in contact with the organic matter or is diluted with ordinary tap water by reverse osmosis, water becomes again "normal". As a result, the impact on the environment is much less negative compared to the use of chemical disinfectants, the use of which is also linked to the difficulties of transporting and storing potentially hazardous chemicals (Nakagawara et al. 1998; Tanaka et al. 1999). On the other hand, the main disadvantage is that EW rapidly loses its antimicrobial activity. The solutions REW and OEW maintain for a limited time their properties (12–21 days), if they are stored away from light and heat. Between the two solutions, the OEW loses its effectiveness more quickly, because the chlorine present in gaseous form is dispersed rapidly by volatilisation, so decays the bactericidal power (Kiura et al. 2002). This sustainable technology is already applied in various countries. Since 2002 in Japan EW is enclosed in the list of permitted food additives; moreover, in the USA the EPA (Environmental Protection Agency) has approved the use of electrolysed water in the food industry (Venturini 2013).

## 2 Electrolysed Water

EW is an activated liquid, obtained by passing a diluted saline solution (NaCl, KCl or $MgCl_2$) through an electrolytic cell, thus causing the production from the anode side of electrolysed oxidising water (OEW), containing high dissolved oxygen, free chlorine and characterised by a low pH (2.3–2.7) and a high oxidation–reduction potential (ORP > 1,000 mV). At the same time from the cathode side electrolysed reducing water is produced (REW), with high pH (10.0–11.5), high dissolved hydrogen and low ORP (−800 to −900 mV) (Huang et al. 2008; Venturini 2013; Rui et al. 2011). Of the two solutions, one, the acidic and oxidiser solution, contains hypochlorous acid (HOCl), hydrogen chloride (HCl) and free gas ($O_2$ and $Cl_2$); the other, the basic and the reductant solution, contains sodium hydroxide (NaOH), and, from this, $H_2$ gas is liberated. In Fig. 1, the electrolytic cell for the production of electrolysed water is schematically shown. Using a bath electrolysis without separation baffle, a solution with a pH close to neutral (6.2–6.5), with a low concentration of free chlorine (NEW), is obtained (Venturini 2013).

Due to its properties, and particularly for its bactericidal effect, EW may find several applications in the agriculture and food industry. The disinfectant action is due to several factors that act synergistically: pH; ORP; presence of free chlorine (the disinfecting action is mainly due to the presence of hypochlorous acid) (Venturini 2013). Additionally, the high redox potential induces the modification of the metabolic flows and influences the ATP production, probably due to the variation of the flow of electrons in the cell (McPherson 1993). HOCl, the most

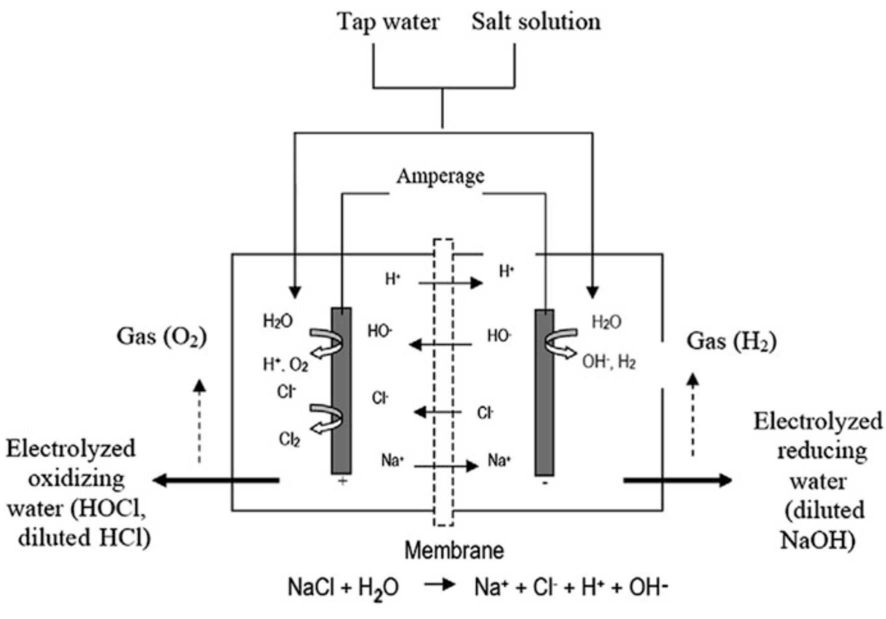


**Fig. 1** Scheme of the electrolytic cell for electrolysed water (Venturini 2013)

active of the compounds of chlorine, seems to be the main responsible for the death of the microbial cell, inhibiting the oxidation of glucose, due to the oxidation of the sulfhydryl groups of enzymes involved in carbohydrate metabolism (Marriott and Gravani 2006).

## 3 Application of EW as Surface Disinfectant

EW has been successfully utilised as surface disinfectant, for example for cutting surfaces made with different materials (glass, steel, glazed ceramic tiles). OEW can be used to reduce bacterial contamination on teflon, stainless steel and ceramic using short treatments (5 min) (Serraino et al. 2010; Park et al. 2002). However, the bactericidal efficacy of EW depends on the amount of organic matter present on the surfaces. In fact, many disinfectants, including hypochlorite, have a reduced effectiveness in presence of a large amount of organic substance (Bach et al. 2006; Liu et al. 2006). This effect can be reduced using the alkaline EW before application of the acidic solution. Alkaline water contains high concentrations of sodium hydroxide, which exerts a detergent action dissolving fats, proteins and polymeric compounds outside the bacterial membranes. In this manner the action of the acid solution will be greater (Ayebah et al. 2005). Møretrø et al. (2012) reported the effectiveness of EW for the disinfection of surfaces contaminated with *Salmonella*, even in the presence of biofilm. Bartolomé et al. (2011a) used EW for cleaning and disinfecting a circuit milking and cooling tank in a herd of dairy cattle by comparing its effectiveness with traditional cleaning chemicals. In this study, EW has been used as a replacement to a chlorinated alkaline detergent with phosphates and an acid descaling. The obtained results suggested that the EW not only preserves the integrity of the milking systems but also ensures a greater degree of sanitisation, compared to the traditional chemical products, besides being a clean and environmentally friendly system.

## 4 EW on Fruits and Vegetables

The use of EW could be useful also for the treatments of fruits and vegetables, in pre and post-harvest. In fact, in the various studies (Guentzel et al. 2010; Vandekinderen et al. 2009; Tomás-Callejas et al. 2011) is reported that the use of EW, NEW and OEW does not leave significant residues of chlorine and does not affect quality the sensory and nutritional of the fruits and vegetables. In pre-harvest, EW can be used for irrigation inhibiting the microbial growth in water (*Phytophthora* spp., *Fusarium* spp., *Algae*). The OEW can be used to protect products from deterioration post-harvest caused by fungal species, such as *Aspergillus*, *Cladosporium*, *Penicillium*, and from the presence of mycotoxins produced by these fungal species. OEW, diluted with water in a 1:4 ratio, is effective to prevent the gray rot of peaches due to the germination of *Botrytis cinerea* (Venturini 2013). Guentzel et al. (2010) reported about the use of near-neutral EW (pH 6.3–6.5) on surfaces of peaches and grapes to inactivate pure cultures of *B. cinerea* and *Monilinia fructicola* responsible of gray mould and brown rot on fruits surfaces. From the study resulted that the dipping and daily spraying treatments prevent the microbial growth better than dipping alone. Moreover, EW is effective for washing and disinfection of fresh-cut fruits and vegetables. The water can represent a vehicle of cross-contamination; for this reason chlorine is usually added to the washing water but EW represents a valid alternative to this practice (Graça et al. 2010; Yudin et al. 2010). Yang et al. (2003) reported that a reduction of *Salmonella typhimurium*, *Escherichia coli* O157:H7 and *Listeria monocytogenes* of 2 log CFU/g can be obtained by plunging fresh-cut lettuce in EW at pH 7, containing 300 mg/L of free chlorine, for 5 min. Also Abadías et al. (2008) indicated that diluted NEW (50 mg/L free chlorine) has a bactericidal power against *E. coli*, *Salmonella*, *Listeria innocua* and *Erwinia carotovara* on fresh-cut lettuce, carrot, endive, corn salad and Four season salad. In addition, the result obtained showed that the NEW has an efficacy comparable with NaClO (120 mg/L free chlorine). Tomás-Callejas et al. (2011) used neutral and acidic electrolysed water (AEW) for fresh-cut mizuna baby leaves. The results of the study suggests that EW has a disinfecting power equal to NaClO. Furthermore, NEW has a higher effect against enterobacteria and mesophilic bacteria, while AEW against psychrotrophic and lactic acid bacteria. In another study (Graça et al. 2010) NEW and AEW were used to inactivate food-borne pathogens on the surface of fresh-cut apples, pears and oranges. From this study emerged that both solutions (NEW and AEW) are able to reduce the microbial population, but AEW has a higher efficacy. Deza et al. (2003) reported that the neutral solution had the same or greater efficacy than AEW on the surface of tomatoes. Koide et al. (2009) reported about the use of slightly acidic EW (pH 6, 1.20 mg/L available chlorine) on fresh cut cabbage. This study showed that slightly acidic EW has a disinfectant efficacy equivalent or higher than NaClO. Gómez-López et al. (2013) investigated about the production of trihalomethanes in baby spinach washed with EW. According to this study, although the EW contains a certain amount of chlorine, it is not involved in the production of dangerous levels of THMs. Even in the washing and cleaning of mushrooms (*Pleurotus ostreatus*), EW has been useful for the purpose of removing *E. coli* O157:H7, *Listeria*, *S. typhimurium* and *Bacillus cereus*, which hardly were eliminated with normal washing procedures (Venturini 2013). Ding et al. (2011) also reported about the use of EW with a neutral pH (6.2–6.5) value and low concentration of free chlorine (5 mg/L) on oyster mushroom to eliminate food-borne pathogens. The study showed that the EW with neutral pH and low concentration of free chlorine allows to obtain the same results of using strong acid electrolysed water (pH 2.5–2.7, 50 mg/L available chlorine), with less dangers for human health. Pangloli and Hung (2013) reported that EW with 30 mg/L of free chlorine can be successfully used to wash blueberries reducing the population of *E. coli* O157:H7 that may be present. Nimitkeatkai and Kim (2009) observed the effect of EW on washing apples. For the test were used strong acidic EW (pH 2.8) and weak acidic EW (pH 6.5). The authors assessed the efficacy of the two sanitising solutions, and the better choice is to wash apple with weak acidic EW (either 2 or 5 min) or strong acidic EW for 2 min to preserve sensory quality of apples. Liu et al. (2013) used EW during the production of germinated brown rice (GBR). In fact, although the production of GBR is quite simple, the growth of contaminating microorganisms may constitute a problem. The EW (with different parameters) was used to wash the brown rice. The study showed that the acidic EW promotes the accumulation of gamma-aminobutyric acid (GABA) during the germination of brown rice. The accumulation of GABA is positive because it has many beneficial properties for human health (Liu et al. 2013). Moreover, both strong acidic EW and slightly acidic EW were more effective in inhibiting microbial growth during germination and also promoted the growth of GBR compared with alkaline EW. This aspect has been confirmed in a previous study in which the alkaline EW inhibited the growth of mung bean sprouts; on the contrary, strong acidic EW promoted the growth of mung bean sprouts (Liu et al. 2011). In addition, Rui et al. (2011) studied the application of EW for the washing of mung bean sprouts. The use of EW as washing water, but also of irrigation, was effective for the reduction of populations of *Salmonella* and *E. coli*. Issa-Zacharia et al. (2011) used slightly acidic EW (pH 5.6–5.8) on Chinese celery, lettuce and daikon sprouts. The efficacy of the electrolysed solution was compared to sodium hypochlorite solution. It was found that slightly acidic EW is efficacy, as much as the sodium hypochlorite, to reduce the population of indigenous aerobic mesophilic bacteria.

## 5 EW on Animal Products

EW is also effective on animal products against pathogenic microorganisms. For example, the EW can be used to reduce the concentration of *E. coli* O157:H7, *Salmonella* spp., *L. monocytogenes* and *Yersinia enterocolitica,* conveyed through the faeces, on shell eggs. Normally, prior to incubation, the eggs are subjected to a disinfection treatment that involves the use of formaldehyde, glutaraldehyde or hydrogen peroxide. Although effective, these treatments may have toxic effects, not only on the operator who uses them but also on the chick. The EW achieves the same results in terms of disinfection without toxicity (Favier et al. 2000; Ni et al. 2013; Cao et al. 2009). The washing with EW of chicken carcasses before plucking and evisceration was useful to reduce the risk of cross-contamination and to remove *Campylobacter jejuni* from the surface of carcasses (Park et al. 2002; Fabrizio and Cutter 2004). Rahman et al. (2012) used both slightly acidic EW (pH 6.2–6.5, 10 mg/L of available chlorine) and strong acidic EW (pH 2.5–2.7, 50 mg/L of available chlorine) for dipping treatment of fresh chicken breast meat. The results showed that the two solutions have similar antimicrobial activity and not affect negatively the overall sensory quality of meat. On the contrary, EW treatment improved sensory attributes of meat (freshness, texture, odour) and extended the shelf life of the product. Azad et al. (2013) also reported about the use of EW, as drinking water, to reduce the oxidative damage to skeletal muscle of broiler chickens exposed to heat stress. The oxidative damage is due to the production of ROS (reactive oxygen species). From the study resulted that the chickens treated with EW water and exposed to a temperature of 34 °C for 5 days showed higher feed consumption, considerable improved growth performance and lower ROS production compared with the control with normal drinking water. Moreover, Bartolomé et al. (2011b) evaluated the possibility of using EW as drinking water of dairy cattle, and the effects on the quality of milk produced. In milk from cows that had ingested EW, there was a significant reduction in the number of somatic cells and the concentration of coagulase-positive microorganisms. The use of EW for the washing of fresh meat was also investigated. Bosilevac et al. (2005), Fabrizio and Cutter (2004) and Fabrizio et al. (2002) compared the effectiveness of EW with the chlorinated water, ozonated water, acetic acid and trisodium phosphate in reducing the bacterial population on fresh meat. From the studies resulted that the low pH of acidic EW allows a greater reduction, compared to the common chlorinated water, of the phenomenon of cross-contamination due to the sequential washes of carcasses. The EW is also effective to inactivate the bacteria present on fish and seafoods. In fact, it is the efficacy to reduce the population of *E. coli* O157:H7 on salmon raw or to prolong the shelf life of yellow fin tuna during chilled and frozen storage (Huang et al. 2006). Phuvasate and Su (2010) also evaluated the possibility of using EW and EW ice to minimise the growth of histamine-producing bacteria on fish skin and food contact surface. High levels of histamine cause scombroid syndrome, a common illness due to consumption of highly contaminated fish. From this study it resulted that soaking fish skin inoculated with histamine-producing bacteria in EOW (50 ppm) for 120 min can be obtained a reduction of bacteria slightly higher compared with distilled water treatment, but using EW containing 100 ppm of chlorine resulted in a better reduction of bacteria. The treatment with EW ice (100 ppm) was very effective to reduce bacteria on fish skin. This result suggested that EW ice treatment, reducing microbial load on fish skin, can reduce the possibility of cross-contamination when fish fillet is prepared. In the same study, EW containing 50 ppm of chlorine resulted in a good sanitiser to eliminate histamine-producing bacteria on food-contact surface. Feliciano et al. (2010) evaluated the efficacy of sanitised ice in reducing bacterial load on fish fillet and in the water collected from the melted ice. The results of this study showed that the sanitised ice allows to reduce the microbial load on raw fish fillet and minimise the microbial growth in water collected from the melted ice. In fact, melting ice may be a reason of cross-contamination if not discarded properly. Furthermore, according to Doi (2002), using a non-diaphragm cell can be produced sterile seawater by filtered seawater and adding HCl solution. The sterile solution obtained in this manner can be used for the treatment of fish and seafood without affecting taste and smell. In the study of Lin et al. (2014), shrimps were stored under acidic EW ice. From the observations, it appeared that the shrimps in EW ice maintained longer, compared to the sample under traditional ice, their initial characteristics. Particularly, a delay in colour change, a slight variation in the pH, a lower production of volatile basic nitrogen, and no negative effect on the texture of the product have been observed. In addition, Wang et al. (2014) reported that using acidic EW ice in dark condition can be obtained a stronger bactericidal effect compared with light condition; in fact, in light condition acidic EW had the highest chlorine loss rate. In this condition, acidic EW ice caused a lower change of pH compared with the control treated with tap water ice, lower accumulation of alkaline compounds and nitrogenous materials.

## 6 Combined Treatments

In order to increase the efficacy of EW has been proposed its use in combination with other treatments on different foods, without damaging the eco-friendly character of the treatments. Martínez-Hernández et al. (2015) investigated about the use of NEW combined with ultraviolet C light (UV-C) and with superatmospheric $O_2$ packaging (HO) to reduce *Salmonella enteritidis* and *E. coli* on fresh-cut kalian-hybrid broccoli. The results showed that NEW + UV-C or NEW + OH is more effective in reducing pathogens compared with NaClO or NEW and UV-C alone. On the contrary, the use of triple combination (NEW + UV-C + OH) did not improve the bacteriostatic effect of double combination. Liu et al. (2013) attested that EW in combination with ultrasound has better antimicrobial properties than EW alone. Zhou et al. (2011) used EW in combination with chitosan or carboxymethyl chitosan (CMC) to preserve the characteristics of the puffer fish (*Takifugu obscurus*) during refrigerated storage. On the product treated with EW + chitosan and EW + CMC was detected a microbial load significantly lower than control (untreated) or than the sample treated with EW alone. However, the combination of EW with chitosan showed better antimicrobial efficacy than the combination of EW with CMC. Rahman et al. (2011) investigated about the combination treatment of alkaline EW and citric acid with mild heat to ensure microbial safety and sensory quality of shredded carrots. The results showed that the dipping in sanitiser solution for 3 min at 50 °C is effective to reduce the microbial count but did not influence the tissue, pH and surface colour of shredded carrots, compared to the untreated control. Similar results were obtained on cabbage, in which the combination of alkaline EW with 1 % of citric acid for 5 min of dipping at 50 °C has a strong sanitising effect on total count on cabbage (Rahman et al. 2010). Zhou et al. (2012) indicated that the immersion of Nanhui peaches in EW or in EW and 1-methylcyclopropene (MCP) contributes to maintain the colour of peach flesh during storage. In fact, peaches treated with EW or EW-MCP showed lower flesh colour changes, lower production of ethylene, lower changes in polyphenol oxidase and peroxidase activity, compared with untreated fruits. Therefore, was also detected a lower production of malondialdehyde, one of the compounds resulting from oxidation processes. In Table 1 are summarised the main applications of EW on different foods.

**Table 1** Main applications of EW on different foods

| Food | Results of treatment | Combined treatment | References |
|---|---|---|---|
| Fresh-cut fruit and vegetables | EW with different parameters was used for washing or dipping treatment. It was found that EW is a good sanitiser and did not affect the sensory and nutritional quality of products. | For fresh cut broccoli was used EW combined with UV-C (ultraviolet C light) and HO (superatmospheric $O_2$ packaging). The combined treatment was more effective in reducing pathogens compared with single treatment. | Vandekinderen et al. (2009), Tomás-Callejas et al. (2011), Graça et al. (2010), Yang et al. (2003), Abadías et al. (2008), Deza et al. (2003), Koide et al. (2009), Martínez-Hernández et al. (2015) |
| Germinated brown rice (GBR) Mung bean sprouts | EW with different parameters was used as washing water but also for irrigation. It resulted that AEW was more effective in inhibiting microbial growth during germination and promoted the growth of GBR and mung bean sprouts. | On GBR EW in combination with ultrasound had better antimicrobial properties than EW alone. | Rui et al. (2011), Liu et al. (2011, 2013) |
| Shredded carrots and cabbage | | EW + citric acid is effective to reduce the microbial count but did not influence the tissue, pH and colour, compared to untreated control. | Rahman et al. (2010, 2011) |
| Peaches and grapes blueberries apples | The washing treatment with EW was effective to preserve the overall quality of the products and reduce the population of microorganism that cause loss in quality. | EW + MCP (1-methylcyclopropene) was used for washing of Nanhui peaches. It was observed lower flesh colour changes and lower production of ethylene and peroxidase activity, compared with untreated fruits. | Guentzel et al. (2010), Pangloli and Hung (2013), Nimitkeatkai and Kim (2009), Issa-Zacharia et al. (2011), Zhou et al. (2012) |
| Chinese celery, lettuce, daikon sprouts | The slightly AEW was effective, as much as the sodium hypochlorite, to reduce the population of indigenous aerobic mesophilic bacteria. | | Issa-Zacharia et al. (2011) |
| Baby spinach | The EW is not involved in the production of dangerous levels of THM. | | Gómez-López et al. (2013) |

(continued)

**Table 1** (continued)

| Food | Results of treatment | Combined treatment | References |
|---|---|---|---|
| Oyster mushroom | EW with a neutral pH (6.2–6.5) was used to wash mushroom. The treatment had the same disinfectant efficacy of strong acidic EW. | | Graça et al. (2010) |
| Eggs | The EW gave good results in terms of disinfection without toxicity for chick compared to the treatment with formaldehyde, glutaraldehyde or hydrogen peroxide. | | Favier et al. (2000), Ni et al. (2013) |
| Meat | Reduction of microorganisms from the surface of carcasses. The treatment did not affect the overall sensory quality, compared with the common chlorinated water. | | Fabrizio and Cutter (2004), Rahman et al. (2012), Bosilevac et al. (2005), Fabrizio et al. (2002) |
| Milk and poultry | EW was used as drinking water for cows and broiler chickens. The treatment positively affected the quality of milk from cows that had ingested EW and the growth of chickens. | | Azad et al. (2013), Bartolomé et al. (2011b) |
| Fish and seafoods | The EW ice was effective to reduce the histamine-producing bacteria on fish skin and to preserve the quality of seafood flesh. | The combined treatment of EW + Chitosan was better than EW + CMC (carboxymethyl chitosan) for reducing microbial load and improving the overall quality of puffer fish. | Huang et al. (2006), Phuvasate and Su (2010), Feliciano et al. (2010), Lin et al. (2014), Wang et al. (2014), Zhou et al. (2011) |

## 7 Conclusions

From the reported studies, it is evident that the EW represents a sanitising technique as supporting of environmental sustainability. It can be used as disinfectant surface but also for the treatment of food products. In particular, from the cited studies, it resulted that AEW has a better antimicrobial activity compared with NEW. However, in order to preserve the sensory and nutritional quality of food, it is advantageous to use the NEW or slightly AEW. In any case, the effects of EW used in different conditions have to be further investigated depending on the type of food.

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