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Scale-up to pilot plant dimensions of plasma processed water generation for fresh-cut lettuce treatment

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ABSTRACT

The increasing demands of society for healthy nutrition in combination with continuously decreasing willingness to spend time for food preparation leads to a rising consumer demand for minimal processed ready-to-eat (RTE) products (convenient food).

The USA is the leading nation in the consumption and therefore, the biggest market for these kinds of products. Thus, the U.S. Food and Drug Administration (FDA) has long term experience in the evaluation of consequences of the consumption of minimal processed RTE products. This authority publicized a list of the ten riskiest foods with leafy greens on the top.

Sanitation steps based on plasma processes could be an promising addition to conventional cleaning procedures. Plasma, often introduced as forth state of matter, differs from the gaseous state of matter by a certain amount of free charge carriers caused by ionization processes of the gas atoms and molecules due to the supply of energy. The electrical conductivity allows supplying the energy needed to sustain this state electrically, giving access to a huge variety of plasma generation methods with excitation frequencies from DC to several GHz offering wide parameter ranges e.g. electron energies from 0.5 eV to 10 eV.

The treatment of natural products with changing parameters like size, shape or water content is a challenging task for design and optimization of plasma processes. The lack of effectiveness of sanitation processes on the surfaces of food products is a general problem of all discussed methods.

In order to overcome these problems a specific plasma process was established, based on a microwave plasma torch operated with compressed air delivering plasma processed air (PPA) as antimicrobial acting process gas. If PPA is brought into contact with water, plasma processed water (PPW) is generated which has antimicrobial properties. This PPW process was implemented into a pilot-plant scale salad-rinsing unit in order to demonstrate the scalability and applicability of this treatment procedure. During the trial 45 kg Endive (*Cichorium endivia*) and about 1.500 l of plasma generated disinfectant were consumed. Off the cuff, the process was competitive to industrial established chemical processes.

1. Introduction

A daily diet with fresh fruits and vegetables corresponds on the one hand with manifold health benefits and on the other hand with an increasing customers demand and significant growth in fresh produce industry (FDA, 2016). Fresh-cut produces are defined as fruit or vegetable which has been physically altered from its original form, but keeps its freshness (IFPA, 1999). Because of the fresh nature, mild processing technologies and increased surfaces as consequence of the cutting process, these products are more sensitive against microbial spoilage (Beaulieu & Gorny, 2002; Brackett, 1994). The microbial contamination may also cause foodborne illnesses, which occur annually and worldwide. Especially, produce like fresh-cut salad is frequently affected. The U.S. Food and Drug Administration (FDA) listed leafy greens under the ten riskiest foods in their Center for Science in the Public Interest (CSPI) Report 2009 on the top (The Ten Riskiest Foods Regulated, 2016). European institutions and customer organizations like the German Institute for Risk Assessment (BfR) are aware of the risk of food borne illnesses caused by fresh-cut salad, too (BfR, 2011; Consumer organization, 2013). Since fresh-cut lettuce is eaten raw, contaminations by pathogenic microorganisms at its surface in high concentrations are difficult to handle. The initial microbiological contamination of fresh-cut leafy vegetables can range between 10^5 to 10^7 cfu g^{-1} (Francis, Thomas, & O'beirne, 1999). It is important to note

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Table 1
Advantages and challenges of PPW (Plasma Process Water) used as gentle sanitation process compared to other commonly used liquid disinfectants.

sanitation process/disinfectant	advantages	challenges/disadvantage
conventional		
tap water	licensed application in water no chemical agents consumer acceptance inexpensive, economical	microbial reduction about one order of magnitude
ozone	licensed application in water microbial reduction about 2 to 4 orders of magnitude chemical reactions, reversible	high distorsion due to organic particles impairment of product quality high costs low consumer acceptance
chlorine	licensed (EU) application in water microbial reduction about 1 to 2 orders of magnitude	by-products like trihalomethanes storage of chemical agent impairment of product quality residues on the product prohibited very low consumer acceptance (EU partly)
chlorine dioxide	licensed application in water microbial reduction about 1 to 2 orders of magnitude	storage of chemical agent impairment of product quality possible chlorate residues possible; unclear and very low limit values by the EU low consumer acceptance
UV irradiation	licensed application in water (waste water)	investments for UV irradiation process necessary application only in water, not on the product cross-contaminations possible
innovative		
peracetic acid	licensed for surfaces, medical instruments and beverage industry application in water high efficiency chemical reactions, reversible	storage of chemical agent explosive in high concentrations (> 15%) consumer acceptance up to now, no license for food less investigations concerning food quality irritation of animal and human skin possible
electrically excited liquid water	microbicidal effect by hypochlorous acid, hydrochloric acid, chlorine dioxide, oxygen and ozone chemical reactions, reversible application in water microbial reduction up to 2 orders of magnitude optimising of process parameters possible	not licensed storage of chemical agent no sensorical or toxicological investigations known high consumer acceptance possible
Pulsed light	licensed (USA) application on polymer surfaces microbial reduction up to 7 orders of magnitude (polymers) no storage of chemical agent inexpensive, economical	application in water not investigated application for food surfaces under investigation microbicidal effects on food products unknown sensorical or toxicological investigations missing high consumer acceptance possible
PPW (Plasma processed water)	chemical reactions, reversible no storage of chemical agent application on fresh food surfaces eg lettuce application in water microbial reduction of 2 orders of magnitude minimum product quality minimal influenced (visual) optimising of process parameters possible on-demand production inexpensive, economical	not licensed sensorical or toxicological investigations missing high consumer acceptance possible

that high microbial levels *per se* are not necessarily of public health concerns. It is the presence and growth of pathogenic microbes that is the concern. Most of these microorganisms are gram-negative bacteria (Francis et al., 1999; Oliveira, Usall, Vinas, Solsona, & Abadias, 2011). The European Food Safety Authority (EFSA) described in their zoonosis report of 2011 (EFSA, 2013) 5648 reported food-borne outbreaks for 2011 with more than 200,000 confirmed human cases. The outbreaks were caused by *Bacillus* toxins, *Campylobacter*, *Clostridium*, *Escherichia coli* (mainly Verotoxin-producing *E. coli* (VTEC)), *Listeria*, *Yersinia* and some others. Furthermore, viruses like the norovirus or hepatitis A virus can cause disease outbreaks. Within this report, eggs and egg products were named as the most important food sources of the outbreaks, followed by mixed food and fish and fish products. However, the outbreak with most human cases was caused by *E. coli* (VTEC) and associated with sprouted seeds. Initial food contamination can occur during preharvest processing by manure, contaminated water and poor handling practices. The primary microbial load of fruits and vegetables can lead to cross contaminations during the production and processing (Ahvenainen, 1996). The postharvest biocidal wash to remove such contaminations or to disinfect may lead to more control of human pathogens on produce (Beuchat & Ryu, 1997; Beuchat, 1999). Therefore, disinfection and cleaning are the key operations of food processing to assure food quality and safety.

In general, a great demand regarding gentle sanitation in the production and processing of fresh produce exists because of the significant economic importance. Gentle sanitation supports a better food quality with higher consumer acceptance and higher product prices as well as environmental advantages and more handling safety by less use of