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Advances in emerging technologies for the decontamination of the food contact surfaces

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Review

Advances in emerging technologies for the decontamination of the food contact surfaces

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ABSTRACT

Foodborne pathogens could be transferred to food from food contact surfaces contaminated by poor hygiene or biofilm formation. The food processing industry has various conditions favouring microbes' adherence, such as moisture, nutrients, and the microbial inoculums obtained from the raw material. The function of the ideal antimicrobial surface is preventing initial attachment of the microbes, killing the microbes or/and removing the dead bacteria. This review article provides detail about the challenges food industries are facing with respect to food contact materials. It also summarises the merits and demerits of several sanitizing methods developed for industrial use. Furthermore, it reviews the new and emerging techniques that enhance the efficiency of reducing microbial contamination. Techniques such as surface functionalisation, high-intensity ultrasound, cold plasma technologies etc. which have high potential to be used for the decontamination of food contact surfaces are discussed. The emerging designs of antibacterial surfaces provide the opportunity to reduce or eradicate the adhesion of microorganisms. The most important purpose of these surfaces is to prevent the attachment of bacteria and to kill the bacteria that come in contact. These emerging technologies have a high potential for developing safe and inert food contact materials for the food industry.

1. Introduction

Pathogenic microorganisms can be transferred to food through contact with a contaminated surface. Biofilms are generally composed of single or multiple species, forming multi-species biofilms, which have higher antimicrobial resistance and may contain spoiling and pathogenic bacteria (Galie et al., 2018). The characteristics of the involved bacteria (i.e., cell surface appendages, surface charge strain, metabolic activity), the attachment surface (material, wettability, roughness etc.) and the surrounding environment (pH, temperature etc.) all play a role in biofilm formation (Pagán and García-Gonzalo, 2015). In many studies, it was also observed that the biofilm pathogens were resistant to the anti-microbial agent, indicating that the food contact surface was not reacting against the microbes and needed to change its coating agent (Refaat, 2011; Pagán and García-Gonzalo, 2015; Rossi et al, 2020). To assure the quality and safety of food, the quality assurance systems enable the verification and application of control measures.

The way to limit the spread of these microorganisms is to restrict their survival on contact surfaces. However, the emerging designs of antibacterial surfaces provide the opportunity to reduce or eradicate the adhesion of microorganisms. The major purpose of these modified food contact surfaces (FCS) is to prevent microorganism attachment or eradication. The surface modification could be done via variable approaches like adsorption, covalent binding or surface topography modification. Several antimicrobial agents have been used to alter the properties of the surface, such as enzymes (Weerarathne et al., 2020), peptides (Hosseini et al., 2019), essential oils (Sharma et al., 2021) and polymers (Perera et al., 2021).

The development of the modified surface was done either utilizing the coating or by modifying the topography of the surface, and very few studies have focused on contamination through food contact surfaces. Such coatings mainly involve highly hydrated polymers like poly

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(ethylene glycol) (PEG), which have a high-water affinity and high entropy, leading to the exhibition of antifouling property. Polycationic peptides such as chitosan have been studied and proved as an efficient antibacterial agent as their positively charged cationic chain effectively disrupts the negatively charged walls of the bacteria. Schaer et al. (2012) demonstrated that the polycation-based surface coated with N-alkyl-polyethyleneimine or poly (N-alkyl-pyridinium) effectively kills a broad spectrum of bacteria. Srivastava and Kotov (2008) developed a cost-effective versatile technique for the layer-by-layer formation of a multilayer coating. These multilayer coatings have multifunctional properties such as antibiofilm, antibacterial, and antiadhesive activity. The antiadhesive property of the coatings was due to the incorporation of the hydrophilic polymer, and the polycationic content in the coating led to the antibacterial activity.

The present review article aims at providing a comprehensive overview of challenges the food industry is facing with respect to food contact materials. The article also summarises several cleaning methods developed for industrial use and their merits and drawbacks. It also discusses new and emerging techniques such as natural active agents, surface functionalisation, cold plasma technique etc. which have high potential to be used for the decontamination of food contact surfaces.

2. Challenges of the food industry with respect to food contact materials

Various conditions in the food processing industry, such as the availability of nutrients, moisture content, and microbial inoculum derived from the raw material, favour the adherence of microorganisms on the food contact surface. Biofilms are developed on the surfaces, escalating the complex ecosystem and causing contamination (Gutiérrez et al., 2016). Recent research discovered that the viable *L. monocytogenes* biofilm remained even after cleaning and disinfectant application (Gião and Keevil, 2014; Overney et al., 2017). Bio-deterioration is also considered as a major challenge for the food industry as all food will deteriorate to some extent once it is slaughtered or harvested. Any undesirable change in the property of a material because of a microorganism is known as bio-deterioration. The deterioration of food could be the loss of its nutritional value, change in colour and becoming vulnerable.

One of the concerns for the management of microbiological food safety issues is to implement effective controls without increasing prices unnecessarily or compromising taste and nutritional value (Havelaar et al., 2010). As a result, microbial risk management necessitates a detailed awareness of the entire food supply chain. Screening the microbial load in the final product is often ineffective in terms of hazard control, as it is impossible to test enough samples to provide the statistical power required to identify pollutants at levels that pose unacceptable health hazards (Havelaar et al., 2010).

Raw material, such as raw meats, fish and poultry, may contain pathogenic bacteria. During storage or food preparation, pathogenic bacteria could be transmitted to other food materials, such as cooked or ready-to-eat foods. Various studies suggested the contamination of microbes such as *L. monocytogenes*, *S. aureus*, *E. coli,* etc. in food from the food contact surface (Colagiorgi et al., 2017; Møretrø and Langsrud, 2017; Ripolles-Avila et al., 2019). Contamination could also occur between the allergens and the allergen-free food commodities. Formation and dispersal of the biofilm are affected by various factors such as the surface material and its properties, specific bacterial strain (Borucki et al., 2003; Chae and Schraft, 2000), temperature (Donlan & Costerton, 2002), pH, and nutrient content. A proactive strategy is necessary, beginning with the manufacturer assuring a safe process and product design, as well as anticipating potential problems instead of detecting them after they have developed (Havelaar et al., 2010).

3. Microorganism transfer from food contact materials

It is a well-known fact that a high percentage of foodborne illnesses are caused by a failure to maintain hygiene during food preparation. A common practice that is the major cause of the contamination is the use of the same kitchen equipment for both raw material and ready-to-eat foods. It may lead to the contamination of fresh fruits and vegetables by the pathogenic microorganisms from the raw meat, which does not go through any thermal processing before consumption.

The consequence of contaminated surfaces as a mode of pathogen transfer to food is very common in domestic settings. However, according to a survey by Gkana, Lianou, and Nychas carried out in 2016, the majority of people realise the importance of cleaning and maintaining the hygiene of the food contact surfaces while preparing ready to eat food. A significant number of consumers also admit to being victims of poor food handling practices (Ehuwa et al., 2021;, Myintzaw et al., 2021). These inappropriate practices include the use of inefficient washed or unwashed cutting boards during food preparation, as well as the reuse of the same surfaces for handling both raw meat and ready-to-eat foods (Gkana, Chorianopoulos, et al., 2017; Gkana, Doulgeraki, et al., 2017).

The physicochemical properties of the food contact surface are modified to avoid the accumulation or attachment of the food particles on the surface, which could support microbial growth by providing them with nutrients. Some studies have evaluated the contamination of pathogens between cutting boards and meat. The studies which relate the effect of the surface material on microbial transfer mainly concentrate on stainless steel and polyethylene, as the majority of the food processing equipment is made of them (Cappitelli et al., 2014; Di Ciccio et al., 2015; Hamadi et al., 2014). In quantitative microbial risk assessment, the source, occurrence, and level of contamination are under consideration. Several studies have also reported that the microorganism could survive on the food contact material for hours and days (Gkana, Doulgeraki, et al., 2017). However, the risk of foodborne illness associated with contamination is not only dependent on the surface contamination, but also on the probability of transfer to other surfaces. Therefore, several studies include the examinination of different factors for the migration of bacteria from meat to contact surfaces and from surface to meat (Fagerlund et al., 2017; Giaouris et al., 2014; Lo et al., 2019). The surface ringing with tap water does not help to reduce the bacterial loads to safe levels. However, some studies revealed that the mechanical washing of surfaces, especially polyethylene and stainless-steel with detergent and water, is capable of reducing contamination between raw meat and fresh produce significantly (Gkana, Chorianopoulos, et al., 2017; Gkana, Doulgeraki, et al., 2017).

On the other hand, neither the spray disinfectant application nor mechanical washing with detergent and water are adequate to entirely avoid contamination and hence protect consumers from foodborne infections. Therefore, due to the absence of sufficient cleaning and disinfection procedures, the approach to prevent contamination is the use of different kitchen equipment for the preparation and handling of raw meat and fresh produce is inadequate (Gkana, Chorianopoulos, et al., 2017; Gkana, Doulgeraki, et al., 2017).

4. Existing solutions and their drawbacks

Planktonic cells of the same species are far more resistant to biocidal chemicals than bacteria that live in biofilms on surfaces. As a result, regular sanitation and disinfection treatments may fail to prevent contamination in some environments. To sanitize the material surface, it must be disinfected and cleaned effectively. Most commonly used, Clean-in-place (CIP) systems use rinse cycles and aqueous cleaning solutions to deactivate bacteria on equipment surfaces in commercial food processing plants. *Clostridium perfringens* attached to stainless steel, for example, was deactivated utilizing several CIP regimes that included the use of sodium hydroxide (NaOH) as an active cleaning agent. However, studies found CIP systems are sometimes not effective (Alzubeidi et al., 2018; Torres Dominguez et al., 2019). Khamisse et al. (2012) observed that the Ricotta facility's industrial cleaning and disinfection system did not substantially reduce total cell counts from stainless steel and PVC surfaces, despite the surfaces appearing clean after the cleaning procedure. In the food industry, many sanitizing processes are utilized such as radiation, heat, and chemicals. Electrolytic solutions' efficiency, strong bases or acids' effectiveness, and the effects of detergent concentration, water temperature, and surface material have been studied extensively (Torres Dominguez et al., 2019). Because of the high expense, radiation is used less frequently than heat and chemical treatment. Various chemicals, such as iodine and chlorine, react with food and dirt on the surface, becoming less effective and failing to disinfecting it properly (Table 1). Heat can be used to sanitize surfaces in three ways: hot air, steam, and hot water. As the temperature of the water in hot water treatment is around 75 ℃, it has the disadvantage of having limited efficacy and requiring a large amount of water. Similarly, steam has an effect on the surface's moisture and heat-sensitive areas, as well as causing oxidation. For the treatment with hot air, the surface material is heated to 82 °C for 20 min, which could also deteriorate the material.

Technologies such as steam spray, hot water and brushing are used in the food industry to maintain good hygiene practices. In these technologies, there is an indirect delivery of the physical energy and requires direct contact with the contaminated surface for effective decontamination. The boilers or pump provide steam spray in the spray system; the liquid is pressurized and sent to a nozzle, which increases the velocity of the steam and directs it towards the surface (Marriott and Gravani, 2006). To clean the surface, a high-velocity of steam is sprayed on it. Sprays are only effective on surfaces to which they have direct access; they are unable to reach hidden areas. Yang et al. (2017) studied the effect of hot water sanitation on egg processing. They performed the

Table 1
Technologies used for decontamination of the food contact surfaces.

No	Method	Specify (Temperature and Concentration)	Result	Disadvantages	Reference
	Heat				
1.	Hot Air	82 °C for 20 mins	Dry air treatment resulted in a more than two log reductions of the examined microorganism	Affect heat sensitive material	(Brooks & Flint, 2008; Schmidt, 1997; Valdramidis et al., 2005)
2.	Hot Water	75 °C for 30 mins	Reductions of initial counts for *E. coli* O157:H7 and *S. typhimurium* of 3.7 and 3.8 log	Limited Efficacy, High water usage	(Brooks & Flint, 2008; Castillo et al., 1998; Yang et al., 2017)
3	Steam	100 °C	Steam reduced the number of different indicator organisms but spread the bacterial contamination to surface area adjoining to the contaminated sites	Affect heat and moisture sensitive equipment.	(Brooks & Flint, 2008; Castillo et al., 1999; Meireles et al., 2016; Schmidt, 1997)
	Radiation				
4	Ionizing Radiations	Maximum level of 1.0 kGy for 30 s	Log reduction of 5.3, 4.1, 4.9 and 4.6 for *L. Monocytogenes,* 6.7 log for *E. coli 0157:H 7*	Destroy those microbes which are in direct contact with the radiation	(Bari et al., 2005; Goodburn & Wallace, 2013; Ramos et al., 2013)
5	UV Rays	254 nm	1.75, 1.27, 1.39 and 1.21 log CFU/g the populations of E. coli, L. innocua, S. *enteritidis* and S. aureus, respectively	Depends on the material of the surfaces and should be free from any dirt which would absorb the radiation and hence protect the bacteria	(Bintsis et al., 2000; Birmpa et al., 2013; Katara et al., 2008; Petersson et al., 2014)
6.	Combination of UV and Infrared Radiation Heating	60 sec of UV with IRH at 50 °C	*B. subtilis* spores were inactivated 0.5–0.9 log more effectively by UV-IRH for 60 sec	Absorption characteristics depends on the specific microbial properties	(Hamanaka et al., 2011; Marquenie et al., 2002)
7.	Aqueous ozone	6.0 ppm for 1 min	*B. subtilis* and *P. fluorescence* were eliminated from stainless steel surfaces	May be toxic to the Human who handle Ozone in the industry	(Guzel-Seydim et al., 2004; Khadre & Yousef, 2001)
	Chemicals				
8.	Nisin	6.75 × 10^{-3} ppm, 5 min, 20 °C	Reduction of 2.58 log CFU/cm2 of *L. monocytogenes* on Stainless steel surfaces	Low solubility of nisin in water	(Arevalos-Sánchez et al., 2012; Meireles et al., 2016)
9.	Carvacrol	0.05 to 0.1%, 1 h	Reduction of 7 log CFU of *Salmonella sp*. on Polystyrene and Stainless-Steel surfaces and Reduction of 2–3 log CFU of bacteria (*listeriae and salmonellae*) on the surface of Stainless Steel at 2 mM.	Efficiency varies on different species of pathogen	(Meireles et al., 2016; Soni et al., 2013)
10.	Hydrogen Peroxide	0.5% hydrogen peroxide	Reductions ≥ 4 log$_{10}$CFU/mL against *Escherichia coli*, *Staphylococcus aureus*, *Enterococcus hirae*, and *Pseudomonas aeruginosa*	Depends on the concentration, May cause browning of fresh food in contact	(Barbut et al., 2013; Briñez et al., 2006; Ríos-Castillo et al., 2017)
11	Chlorine	50 ppm for 7 sec	E. coli O157:H7, S. Typhimurium, and L. Monocytogenes reduction observed is in between *4.12 and 5.43* log *reductions*	Corrosive, deteriorates during storage and when exposed to light; dissipates rapidly;	(Bang et al., 2014; Park & Kang, 2017; Schmidt, 1997)
12.	Chlorine dioxide (ClO$_2$).	200 µg/mL or 5% for 10 min.	Reduction of 4.42 log CFU of *B. cereus* on Stainless Steel surfaces. ClO2 (5%, 10 min) Reduction of 4.14 log CFU/chip of *L. monocytogenes* biofilm.	Could change the colour of the fresh produce fruits and vegetable when in contact.	(Kreske et al., 2006; Meireles et al., 2016)
13.	Iodine	12.5–25 ppm for 30 s	Achieve a 10^5 log reduction of selected test organisms in a given contact time	Effectiveness decreases as pH increases; discolour the surface	(Cooper, 2007)
14	Quaternary Ammonium Compounds	200–500 ppm for 30 s	Reductions on polystyrene, with average 2.7 log CFU/cm^2. On stainless steel surface, biofilm populations were reduced by average 3.9 log CFU/cm^2	Slow destruction of microbe, not compatible with detergents	(Poimenidou et al., 2016; Weber and Rutala, 2013)
15	Triclosan	0.2% to 2%	0.5- to 1.0-log10 *for S aureus* and *Serratia* species and 1.5- to 1.7-log10 for *E coli* and *Salmonella* species	Concentration dependent, microbes develop resistance	(Møretrø et al., 2012; Weber and Rutala, 2013)

treatment at 71 °C for the 30 s and observed the reduction of *S. enteritidis* biofilms by 4.3–7.08 log CFU/cm^2. Also, they had observed that the hot water treatment was more efficient at removing the *S. enteritidis* biofilms than chlorine (Yang et al., 2017). However, various studies have observed no effect of heat on the microbes due to resistance (Bae et al., 2009; Kim et al., 2017; Rico-Munoz, 2017). However, brushing has limited efficacy in terms of the approachable area for the bristles of the brush. The surface where bristles are unable to reach will not be cleaned (Fuchs, 2015).

The antimicrobial efficacy of chemicals is mainly influenced by three factors: concentration, temperature and contact time. The concentration of the chemical agent must be optimised thoroughly as less concentration will reduce harmful microorganisms inadequately and too much concentration could be toxic. Chemical sanitisers are said to work best between 13 °C and 49 °C in water. The recommended length of contact time must be maintained in order to kill the microorganism effectively. Chlorine, iodine, hydrogen peroxide and quaternary ammonium are the approved chemicals used as a sanitiser. In bacteria, hydrogen peroxide causes the release of reactive oxygen species, which causes the oxidation of the cytoplasmic content or cell wall disintegration (Fig. 1) (Bhilwadikar et al., 2019).

Chlorine is broadly used in the food industry due to its cost-effectiveness, and its ability to act as a broad-spectrum antimicrobial agent (Ramos et al., 2013). But it has also been observed that chorine tends to be more corrosive and irritating than quaternary ammonium compounds or iodine compounds (Marriott and Gravani, 2006). Chlorine dioxide reacts with the cellular enzymes in the bacteria (Fig. 1). Chlorine dioxide (ClO_2) of 200 µg/mL reduces 4.42 log CFU/mL of *B. cereus* on stainless steel surfaces (Kreske et al., 2006). Poimenidou et al. (2016), observed that the *L. monocytogenes* biofilms formed on stainless steel surfaces were more resistant to disinfectants than those formed on polystyrene (Poimenidou et al., 2016). Significant quaternary ammonium tolerance was found in the persistent strain of the greatest producer of biofilm. Also, a positive correlation was found between the biofilm formation on the stainless steel and quaternary ammonium tolerance (Poimenidou et al., 2016). However, conventional solutions are only effective for a limited time and have a lot of disadvantages, motivating the development of new technology to protect food contact materials from microorganisms. Recent studies have concentrated on combining less toxic sanitizing solutions and determining the influence of surface qualities and food product components on the efficiency of mechanical–chemical procedures.

5. Emerging technology

5.1. Natural antimicrobial surface coating

Naturally derived antimicrobial agents can be obtained from various sources, such as animals, plants, bacteria, fungi, and algae. Numerous studies have confirmed the efficiency of plant-derived compounds and efficacy-influencing factors (Gyawali & Ibrahim, 2012; Hayek et al., 2013) (Table 2). Many unexplored potential sources could be used in the food industry; for example, polyphenols are the secondary metabolites of plants. They play a very important role in the defense against plant pathogens and all adverse conditions like high rainfall, UV radiation and many more. With respect to their chemical structures, a wide range of polyphenols could be divided into two subcategories: flavonoids and non-flavonoids. More than 4000 flavonoids have been derived from many plants like vegetables, fruits and beverages (Chahar et al., 2011).

Depending on the oxidation state of the central pyran ring, the flavonoids are further divided into many subcategories such as flavonols, flavones, flavanones, anthocyanidins, flavonols, and isoflavones. Non-flavonoids, depending upon the first phenolic acid, could be subdivided into derivatives of benzoic acid (gallic acid, protocatechuic acid), derivatives of cinnamic acids (ferulic, coumaric and caffeic acid), and second stilbenes (resveratrol, in both cis and trans isomeric forms) and lignans (oxidative dimerization of two phenylpropane units). Colon and Nerín (2016) summarize that the total antioxidant capacity of green tea extract was affected by synergistic, antagonistic, and additive interactions among green tea polyphenols. In addition, catechins were found to be responsible for synergism in green tea extract, with gallocatechin gallate (GCG), epigallocatechin gallate (EGCG), catechin gallate (CG), and epicatechin gallate (ECG) accounting for the majority of synergistic interactions (Colon & Nerín, 2016). Moreover, Picchio et al., (2018) observed that tannic acid was an efficient crosslinking agent for casein protein and that the resulting films, which have enhanced physicochemical properties, can be used for food packaging. Sharma et al. (2020) incorporated ferulic acid into a poly (lactide) – poly

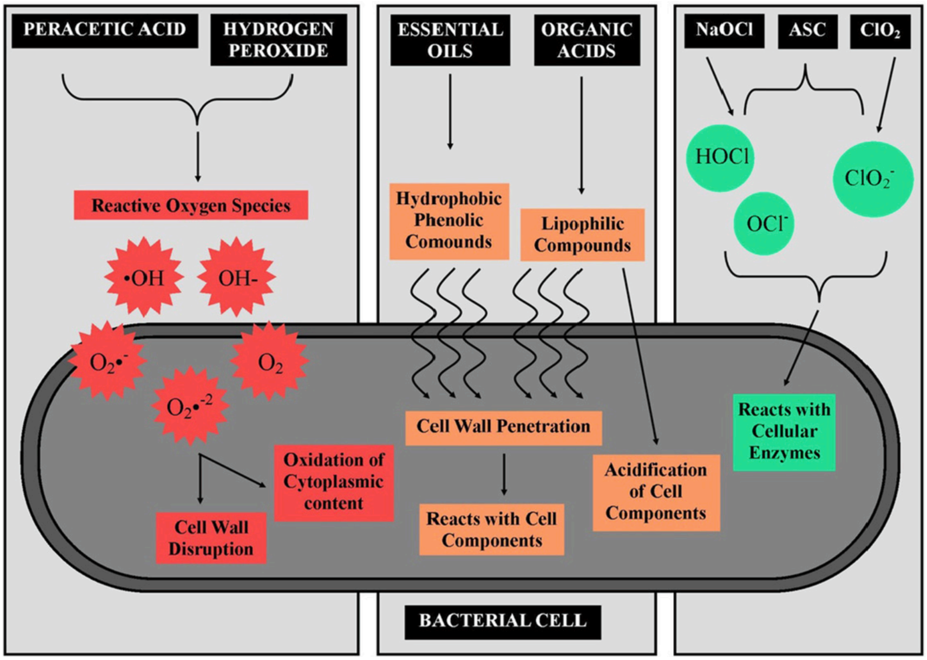

Fig. 1. Schematic representation of action on bacterial cell by the use of chemicals or natural agent (Bhilwadikar et al., 2019).

Table 2
Emerging technologies used for the decontamination of the food contact surfaces.

	Functional additives	Polymer	Result	Reference
Natural Antimicrobial				
Polyphenols	Grape stem	Stainless steel and polypropylene surfaces	Inhibited adhesion of *L. monocytogenes* on both the surfaces	(Vazquez-Armenta et al., 2018)
	Grapeseed extract	poly(lactide)/poly(butylene adipate-co-terephthalate)	Increased flexibility and antimicrobial activity	(Shankar and Rhim, 2018)
	Tannic acid	Soy Protein Isolate Matrix	Efficient barriers to water vapor and UV light	(Wang et al., 2017)
		Casein	Effective crosslinking exhibit improved physicochemical properties	(Kaczmarek et al., 2019)
		Chitin	Enhanced antibacterial and antioxidant activity	(Wang et al., 2016)
	Ferulic acid	Soy-protein based edible coatings	Potential application in extending the shelf life of fresh-cut apples.	(Li et al., 2019)
		Poly(lactide)/poly(butylene adipate-co-terephthalate)	Enhanced UV barrier property, increased flexibility and antimicrobial activity	(Sharma et al., 2020)
		Hydroxypropyl-beta-cyclodextrins	Improved UV barrier property and active packaging	(Sharif et al., 2018)
	Gallic acid	intercellular adhesion-encoded polysaccharide intercellular adhesin (PIA)	Inhibition of Biofilm formation	(Liu et al., 2017)
		Chitosan/gelatin composite films	Enhanced water vapor permeability and antimicrobial property	(Rui et al., 2017)
		Chitosan edible films	Improving the shelf stability, bacteriostatic activity against *S. aureus, E. coli, Salmonella spp*. and *C. vinaria*	(Lamarra et al., 2017)
		Stainless steel or polystyrene	Safe, easy, and cheap to use organic acids as disinfectant	(Akbas & Cag, 2016)
		Chitosan/ cassava starch	Enhanced tensile strength and water vapor barrier of films. Also showed antimicrobial activity against spoilage microbes in ham.	(Zhao et al., 2018)
	Tea Polyphenol	Polylactic Acid	Decreased mechanical property, antimicrobial activities against *E. coli* and *S. aureus* of up to 92.26% and 94.58%	(Liu et al., 2018)
		Starch	Decreased mechanical properties, significantly improved the antioxidant activity and antimicrobial activity	(Feng et al., 2018)
	Resveratrol	Polyethylene (PE) and polypropylene (PP)	Exhibit over 90% reduction of *Staphylococcus aureus* and over 77% reduction of *Escherichia coli.*	(Glaser et al., 2019)
Essential Oil	Oregano oil	Carvacrol	Effective to remove young and mature biofilms on stainless steel surfaces	(dos Santos Rodrigues et al., 2018)
	Helichrysum italicum	Along with cold nitrogen plasma	Reduced the S. aureus viable count in biofilm below 2 logs CFU per cm2 after 1-day storage	(Cui et al., 2016)
	Thymbra capitata	natural sanitizing solution	Reduced the levels of *E. coli* by > 3 log and S. enterica by 1 log under clean working	(Falcó et al., 2019)
	Clove oil and thyme oil	Poly (lactide)-Poly (butylene adipate-co-terephthalate)	*S. aureus* complete killing i.e. reduction of 6.5 log CFU/mL by clove oil composite film was observed. *E. coli* biofilm inhibited by clove oil (93.43% inhibition) and thyme oil (82.30% inhibition) composite film.	(Sharma et al., 2020a)
	Cinnamomum cassia and *Salvia officinalis* Eos	Stainless steel surface	> 3 log reductions in *S. aureus* of 24 h-old biofilms and desiccated biofilms, and up to 68% of biofilm removal after 90 min of exposure.	(Campana et al., 2017)
	Cinnamon oil, marjoram oil, and thyme oil	Polypropylene (PP) surfaces	Optimized disinfectants successfully eliminate 24, and 168 h old immature and mature biofilms formed on PP surfaces	(Vidács et al., 2018)
	ginger essential oil	Gelatin based film	Improved antioxidant activity but no antibacterial activity observed	(Alexandre et al., 2016)
	Eucalyptus oil and cinnamon oil	Poly (lactide) - Poly (butylene adipate-co-terephthalate)	Significant antimicrobial activity of approx. 3.5 to 4.5 log CFU/ml reduction was observed against *S.aureus* and *E.coli*	(Sharma et al., 2020b)
	Rosemary extracts	cassava starch films	Significant antioxidant activity, enhanced UV-properties	(Piñeros-Hernandez et al., 2017)
	Lemongrass oil	Stainless steel	Inhibited glucosyltransferase activity, glucans production, therefore, biofilm formation of *E. coli* O157:H7	(Ortega-Ramirez et al., 2020)
	Cinnamon oil	Chitosan and carboxymethyl cellulose	Cinnamon oil strongly plasticized chitosan - carboxymethyl cellulose films and showed higher antifungal activity in vitro against Aspergillus niger than ginger oil.	(Noshirvani et al., 2017)
Dual functional surface coating				
	Lysozyme protein	Aluminium surface	Antimicrobial and anticontact properties, high log reduction of 6.5 log CFU/ml for *Salmonella typhimurium* LT2 and 4 log CFU/ml for *Listeria innocua*	(Liu et al, 2020)
	Graphene oxide	Polyurethane nanocomposite (PUC) coating	Prolonged anticorrosive activity in NaCl (5%) solution Reduced bacterial surface colonization	(Ahmadi & Ahmad, 2019)
	Silver nanoparticle	Cellulose papers	Efficient killing of *E. coli* and release of over 90% of the dead bacteria with single thermo-responsive wash	(Gautam et al., 2021)
	Silica (SiO_2) aerogel	Sol gel	Bacterial anti-adhesion property, superior thermal insulation and ultra-lightweight	(Oh et al. 2015)
	Quaternized poly(2-(dimethylamino)ethyl	polymerized ethylene glycol dimethacrylate network	Dual-functional coating with antimicrobial and antifogging properties	(Zhao et al., 2016)

(continued on next page)

Table 2 (*continued*)

	Functional additives	Polymer	Result	Reference
	methacrylate-co-methyl methacrylate)			
Surface Modification and functionalisation				
	Liquid-infused surfaces (LISs)	Grafting of a layer of polydimethylsiloxane (PDMS).	Self-cleaning surfaces	(Zhang et al., 2018)
	Dendrimers and aptamer	microfluidic channel surfaces	Capture *E. coli* O157:H7 cells to allow sensitive detection	(Hao et al., 2019)
	Silver nanoparticles	b-cyclodextrin (b-CD)	Enhancing antibiofilm activity	(Jaiswal et al., 2015)
	N-halamine-based copolymer	Stainless steel surface	Deactivated *Staphylococcus aureus* and *Escherichia coli* O157:H7 bacteria by 6 logs	(Demir et al., 2017)
	Silica nanoparticles	Aluminium	Attachment of *Salmonella typhimurium* LT2 and *Listeria innocua* was reduced>99.0%	(Oh et al., 2019)
	Sol-gel-based	Stainless Steel	Reduction in the amount of fouled layer on modified surfaces	(Liu, Jindal, et al., 2017; Liu, Wu, et al., 2017)
	ZnO, nisin	PLA on Glass	Log reduction by 3–4 CFU/mL of *Salmonella enterica*	(Jin and Gurtler, 2011)
	AgNPs, TiO_2, ZnO	Low density polyethylene	Orange juice shelf-life stable for 28 days	(Emamifar et al., 2010)
	Bacterial cellulose	Alkoxysilane polycondensation using (3-aminopropyl) triethoxysilane	Exhibited efficient antibacterial and antifungal activities against *S. aureus, E. coli, C. albicans* and *S. subtilis*	(Shao et al., 2017)
High Intensity Ultrasound				
	Ultrasonically engineered interfaces	Polymer matrix	Porous morphology, high surface area and high stability	(Kollath & Andreeva, 2017).
	High-power ultrasound	Food grade surfaces	Cleaning of biofilm	(Astráin-Redín et al., 2019; Basumatary et al., 2020)
	Ultrasound with chlorinated water and detergent	Knives used in slaughter house	Ultrasound endorsed the reduction of cleaning and decontamination temperature of knives	(Brasil et al., 2017)
	Ultrasound	Stainless steel	Use of ultrasound in moderate frequency (40 kHz) for 10 min detached the biofilms	(Webber et al., 2015)
	Ultrasound	Poly-N,N′-[(4,5-dihydroxy-1,2-phenylene)bis(methylene)] bisacrylamide	Improved antibacterial activity	(Zhang & Han, 2019)
Plasma Technology				
Non-Thermal Plasma Technology	Plasma technology	Stainless steel	• Inactivation of major foodborne viruses • Inactivation behaviour was observed for Salmonella	(Gabriel et al., 2018; Park & Ha, 2018)
	Gliding arc discharge (GAD)	stainless steel (SS), silicone (Si), and polyethylene terephthalate (PET)	Significant reductions of *S. epidermidis*, and *E. coli* was observed	(Dasan et al., 2017)
	DBD	Zein	Significant improvement in solubility and reinforcement of the tensile strength and surface hydrophilicity	(Dong et al., 2017)
	Cold nitrogen plasma with essential oil	Stainless steel, glass sheet and polystyrene plastic	*S. aureus* biofilm was approximately reduced by 2 logs after individual treatment	(Cui et al., 2016)

(butylene adipate-co-terephthalate) (PLA-PBAT) polymer blend and observed enhancement in mechanical properties, UV barrier properties, thermal degradation, and antimicrobial activity. The presence of the phenolic component in the composite film has been shown to improve antibacterial activity against *Listeria monocytogenes* and *E. coli* (Sharma et al., 2020).

Dos Santos Rodrigues et al. (2017), have studied the effects of oregano essential oil and carvacrol on biofilms of *Staphylococcus aureus* from food-contact surfaces. The results showed a significant prevalence of biofilm producers *S. aureus* isolated from food-contact surfaces, as well as the effectiveness of oregano and carvacrol in inhibiting planktonic and sessile cells. Because of the potential for inductive biofilm development, the concentrations of these antimicrobials employed to inhibit *S. aureus* biofilms should be carefully considered (Dos Santos Rodrigues et al. 2017). Soni et al. (2013) discovered that exposure to Carvacrol (0.05 to 0.1%) for 1 h on polystyrene and stainless-steel surfaces reduced *Salmonella* spp. growth by 7 log CFU/ml (Soni et al., 2013). Wang et al. (2017) demonstrated the potential of tannic acid-incorporated soy protein isolate-based nanocomposite films for food packaging applications, demonstrating effective UV barrier properties and hydrophobicity (Wang et al., 2017). Sharma et al. (2020) have also studied the incorporation of clove oil and thyme oil into poly (lactide) – poly (butylene adipate-co-terephthalate) (PLA-PBAT) for food packaging applications. The authors observed that the clove oil composite film exhibited UV blocking properties and strong antimicrobial activity (6.5 log reduction of *S. aureus*) (Sharma et al., 2020a).

5.2. Dual-functional surface coating

An ideal antimicrobial surface must prevent the initial attachment of microorganisms, kill the microbes, or remove the dead microorganisms. Various studies have resulted in the development of surfaces that combine two strategies in one system, resulting in the development of three types of dual-functional antimicrobial surfaces that can kill and resist, resist and release, and kill and release microorganisms.

Dual functional coatings are antimicrobial surfaces based on the combination of bactericidal and microorganism resistant properties. These surfaces could either have a spacer/non-biofouling agent such as hydrophilic polymer or have a deposition of an antiadhesive layer or the substantial release of an antimicrobial agent embedded in a non-fouling matrix. Ahmadi and Ahmad (2019) have developed a sustainable, active dual-functional (antimicrobial/anticorrosive) polyurethane nanocomposite (PUC) coating using the synergistic activity of π-π interaction and in situ graphene oxide integration. The coated surfaces had shown prolonged anticorrosive activity in NaCl (5%) solution and reduced bacterial surface colonization against *S. typhimurium* by 6.5 and *L. innocua* by 4.0 log-cycles as compared to planar aluminium (Ahmadi & Ahmad, 2019). Liu et al. (2020) developed a dual-functional coating with antimicrobial and anticontact properties for aluminium surfaces by immobilizing lysozyme as a superhydrophobic coating made from sintered silica nanoparticles. An exceptionally high log reduction of 6.5 log CFU/ml for *Salmonella typhimurium* LT2 and 4 log CFU/ml for *L. innocua* were observed as compared to the control (bare aluminium surface) (Liu et al., 2020). Nanoparticles appeared to give improved stability, efficacy, and cost-effectiveness.

Other kill and resist methods include layer by layer deposition of antimicrobial and non-fouling layers and release of antimicrobial agents from the non-fouling matrix. The layer by layer is the cost-effective technique in which multi-layers are utilized as a reserve for the loading and release of antimicrobial agents. Oh et al. (2015) evaluated the potential of hydrophobically enhanced, silica aerogel as anti-adhesion food contact surfaces and observed bacterial antiadhesion property. Also, the novel food contact surface showed superior thermal insulation and ultra-lightweight properties (Oh et al., 2015). In addition, Yang et al. (2012) studied a composite system of a multilayer film of PVA/PAA and chitosan/heparin. Furthermore, the controlled release of anti-microbial agents from the surface reduces microorganism colonisation and inhibits their propagation. Various zwitter-ionic hydrogels with a controlled release anti-microbial agent have been developed to attain antimicrobial property and non-fouling of the surface.

Kill and release is the combination of bactericidal and microorganisms release properties in a system. Accumulation of dead microorganisms on the surface effectively degrades the bactericidal property of the surface, also serving as a nutrient source for other microorganisms (Mi & Jiang, 2014). Therefore, there is a need to release or remove the debris of dead microorganisms to maintain antimicrobial properties for the longer term. Fan et al. (2014) modified the surface by attaching a cationic precursor carrying a quaternary amine group, which has the property of killing the microorganism attached to the surface initially. The cationic ester group hydrolysis in the basic or neutral aqueous environment leads to the transition of a zwitter ionic surface that releases the debris of dead microorganisms to maintain the non-fouling property (Cheng et al., 2008; Mi & Jiang, 2014). Gautam et al. (2021), modified cellulose papers to have antibacterial qualities that kill and release in a hybrid approach. Using the SI-ATRP method, cellulose papers are first grafted with the thermoresponsive copolymer poly (N-isopropylacrylamide-co-2-aminoethyl methacrylate) (p(NIPAAm-co-AEMA)). Electrostatic interactions between positively charged AEMA copolymer and negatively charged AgNPs are then used to immobilize antibacterial silver nanoparticles (AgNPs) onto the surfaces. The study validates the efficient killing of *E. coli* and the release of over 90% of the dead bacteria with a single thermo-responsive wash (Gautam et al., 2021).

5.3. *Surface functionalisation*

The development of different methods for the modification of surfaces has led to an improvement in the safety and inertness of the food contact materials. The use of wet chemicals, UV radiation, and adhesion are used to add a variety of polar groups to the surface. Therefore, these techniques must add a specific functional group to the surface. The first step for the surface modification is the selection of the polymer-based on properties like elasticity, conductivity, strength, type of material (synthetic or natural) and degradability. Immobilisation of biomolecules or the functionalisation of surfaces is considered according to the application of the surface. Therefore, the second step is to enhance the functionalisation techniques of the surface to add the desired quantity and variety of the reactive functional group. Grafting of the polyfunctional agent on the surface increases the availability of the reactive functional groups per unit area. The addition of a spacer molecule for harnessing the bioactive compound on a solid surface also increases bioactivity. It reduces the steric hindrance and covers the compound with a hydrophobic surface. The final step is the covalent attachment of the natural or synthetic bioactive compound to the functionalised polymer surface.

The surface modification is done either by atom radical transfer or by covalent bonding. Some antibacterial property was carried out on the surfaces which have chemically bonded hydrophobic polycations of a quaternary ammonium salt. The physicochemical characteristics, cytotoxicity, and antibacterial activity of quaternary ammonium amino acid-based surfactants are greatly influenced by the length of the hydrocarbon chain and are unaltered by the polar head of the amino acid (leucine or methionine) (Perinelli et al., 2019). In addition, nylon, poly (ethylene terephthalate), polyethylene, polypropylene have shown antibacterial effects. Alkylated PVP and benzyl PVP are polyvinyl pyridine-based polymers which are phosphonium or sulphonium or the polycationic quaternary ammonium salts. The antimicrobial property of these polymers depends on the length of the chain. Polymers with oxidative halogen group (Cl^+, Br^+) are the polymeric compounds with the N-halamine group which exhibit antibacterial property. The compounds having amphiphilic quaternary dimethyl ammonium compounds having oxyethylene and n-alkyl groups are synthesized and designed as surfaces that have self-decontaminating properties (Harney et al., 2008). Shao et al. (2017) produced an A-g-BC film by alkoxysilane polycondensation using (3-aminopropyl) triethoxysilane. This A-g-BC membrane exhibited efficient antibacterial and antifungal activities against *S. aureus, E. coli, C. albicans and S. subtilis* (Shao et al, 2017). Zhang and Han (2019), had immobilized poly-N,N′-[(4,5-dihydroxy-1,2-phenylene)bis(methylene)] bisacrylamide (POHABA) onto the surface of PE cling film through precipitation polymerization and UV polymerization. Because of the higher surface distribution of OHABA, antibacterial PE cling films made by precipitation polymerization were found to have better antibacterial activity than those made by UV polymerization (Zhang & Han, 2019).

In addition, the potential fast and energy-saving approach is the use of high-intensity ultrasound. An ultrasonic approach to form a hybrid functional surface is based on the cavitation effect on the solid surfaces (Kollath et al., 2017). The surfaces modified ultrasonically have microcavities in them of a nano-meter thickness in which different chemicals such as antimicrobial agents could be stored (Kollath et al., 2017). The interfaces of ultrasonically modified surfaces are very rough; therefore, they provide excellent adhesion for inorganic and organic coatings. The development of industrial applications for the modification and functionalisation of solid surfaces by ultrasonic irradiation is focused of study for many researchers.

5.4. *Modification of surface topography*

The propensity of bacteria for adhesion and colonisation on the surface of material leads to the formation of biofilm which may result in the contamination of the food and its product. However, only a few studies were carried out to find out the effect of the topography of the surface on the interaction between the material and the bacteria. Hsiao et al. (2014) had adsorbed copolymers of poly (propylene oxide) and poly (sulfobetaine methacrylate) on three kinds of surface topographies (indented, smooth and convex). They found the convex and smooth surface exhibited better resistance to the attachment of bacterial cells. The differential orientation of the copolymers resulted in the coverage of the surface by the zwitter ionic molecule more efficiently. In addition, the indented surface exhibited better anti-biofouling ability than the curved surface as the bacterial cells were unable to adhere between the indents (Hasan & Chatterjee, 2015). Awad et al. (2018), had studied food-safe oil-based slippery coatings (FOSCs) that prevent bacterial adhesion and biofilm formation by encapsulating residual oil lubricant within surface holes, preventing microbial growth. They used alkylphosphonic acid to functionalize the stainless-steel surface to get a coating of food-grade oil. Their findings suggest the potential of low-cost, sustainable techniques to improve the cleanability of SS food-processing surfaces and improve food safety by minimizing biofilm formation (Awad et al., 2018).

Rajab et al. (2017), had evaluated the impact of laser-created titanium surfaces with progressive topographical characteristics on bacterial adhesion and persistence. They observed under static inoculation settings, the combination of surface chemistry, topography, and physiochemistry resulted in a stronger anti-adhesive surface (Rajab et al., 2017). Demir et al. (2017) designed a modified stainless steel surfaces with an N-halamine-based copolymer to induce antimicrobial activity. In 15 min of contact time, the modified stainless-steel surface deactivated *S. aureus* and *E. coli* O157: H7 bacteria by 6 logs (Demir et al., 2017). The roughness of the surface determines the interaction of the surface with its environment. Generally, rough surfaces are undesirable as they are difficult to clean as compared to smooth surfaces. The R_a value is commonly used to determine the roughness of a surface. R_a can be defined as the arithmetic mean of the vertical deviation of the filtered roughness profile. A typical R_a value for a hygienic surface is 0.8 μm. As the R_a value is an arithmetical measure, it does not convey the actual attribute size or the variation in the size of the attribute along the surface. A new possibility of designing a more hygienic surface depends on the use of the intended environment by surface fabrication with nanotopographies (Kim et al., 2013; Meng et al., 2016).

An increase in the surface area of antimicrobial surfaces that release antimicrobial agents could improve their efficacy. However, the presence of previous organic substances such as food, blood or a microorganism could obstruct the antimicrobial effect. Attributes such as profile, size, and shape increase the cell contact area and enhance their ability to retain. Also, it is important to consider the issue of inactivation and cell survival. Therefore, it is necessary to consider all these subjects while developing an effective and novel hygiene surface. Studies revealed that on the titanium-coated stainless steels the removal of microorganisms was easier along with the attribute while, for the soft polymeric surface, the removal was easier by applying force across the attribute (Verran et al., 2014, 2010). This has led to surface fabrication with intended topographies which inhibit the initial microbial attachment and enhance hygiene.

5.5. *High-intensity ultrasound*

The application of ultrasound has gained significant attention in the food industry in recent years. In the food sector, ultrasound is regarded as a green and cost-effective technology (Zheng et al., 2019). Sound waves of high intensity and high frequency in a liquid are used to enhance the decontamination of the surfaces immersed in an ultrasonically activated liquid. Recently, ultrasound has become more popular and has developed numerous applications with chemical processes and conditioning of surfaces. This is non-destructive technology and has several advantages, such as uniform cleaning, microbial safety, and assurance of food quality. However, further research should be carried out to make the technology cost-effective for industrial use (Arvanitoyannis et al., 2017).

Ultrasonic cleaning is a unique and highly efficient technology. With the sound conducting liquid as the medium, it can infiltrate and clean any surface. It is also competent at cleaning complex tasks like blind holes, minute surface contours, tread roots and many more. In the compression cycle, positive pressure can bring molecules together; in the expansion cycle, a large negative pressure overcomes the liquid's tensile strength, resulting in gaps (Yu et al., 2020). Kollath and Andreeva (2017) have demonstrated that ultrasonically engineered interfaces have porous morphology, high surface area and high stability. They also suggested that the porous matrix could be loaded with antimicrobial compounds and covered by various types of coatings and could be used as a multifunctional surface due to its antimicrobial function and self-cleaning (Kollath & Andreeva, 2017).

One of the main aims of using ultrasonic cleaning is to reduce biofilm adherence. Brasil et al. (2017) evaluated the combination of ultrasound with chlorinated water and detergent (neutral) as a novel non-thermal treatment for the cleaning and sanitation of knives used in slaughter houses. They observed that ultrasound treatment leads to the reduction of cleaning and decontamination temperatures of knives, at the same time cleaning of knives was found to be more uniform, and the structure of knives was also not modified by ultrasound (Brasil et al., 2017). Yu et al. (2021) have evaluated the combined treatment of ClO_2 and high-intensity ultrasound to assess the synergistic effect on *S. aureus* biofilm detachment and biofilm cell inactivation on food contact material. Confocal laser scanning microscopy (CLSM) and SEM evaluation revealed that the combination treatment had the best bactericidal impact as well as the dispersion and detachment of *S. aureus* biofilms. With the combined treatment, the surface roughness of food contact materials was noticeable, and it was adversely linked with the biofilm clearing rate (Yu et al., 2021).

5.6. *Cold plasma technology*

A novel and versatile approach for the manufacturing of antimicrobial materials could be served by non-thermal plasma-based technology. Unlike "wet" technology, which is sensitive to the properties of the substrate, the deposition of plasma could be used as an antimicrobial coating and grafting on a wide range of materials such as polymers, metals and ceramics, including temperature-sensitive and moisture sensitive equipment. The cold plasma technique is a "rapid, waterless, zero-contact, chemical-free" tool for the removal of pathogens from food contact surfaces (Niemira et al., 2014). This approach produces a wide range of reactive oxygen species (ROS) that are sufficient for the complete bacterial load in the semi-neutral plasma system, including bacterial spores and spoilage/pathogenic microorganisms. In terms of food decontamination, this is the system's greatest advantage (Choi et al., 2017; Olatunde et al., 2021; Umair et al., 2021). Romani et al. (2020) had developed bi-layer protein solution films followed by plasma treatment (glow discharge) and coating with carnauba wax. They observed that the combination of cold plasma and carnauba wax coating improved the packaging quality in terms of tensile strength and water vapour permeability (Romani et al., 2020). Dasan et al. (2017) used a micro-plasma system with gliding arc discharge (GAD) and observed the decontamination of stainless steel, polyethylene terephthalate and silicone surfaces (Dasan et al., 2017). GAD is recommended because of its minimal equipment and operating expenses, as well as its excellent efficiency in inactivating a variety of bacteria.

Currently, the focus is on the plasma polymer film, which is deposited by plasma-enhanced chemical vapour deposition. These films have remarkable properties, such as the ability to change properties by varying a parameter or precursor, excellent adhesion, and a highly cross-linked structure. Additionally, the reduction in the use of chemical solvents by the plasma engineering of materials makes them more suitable for industrial use. The proper regulation of the parameters of the plasma source and the depositional structure arranges the chances for the synthesis of advanced composite films or complex hybrids. Kim et al. (2015) observed the bactericidal effect of an atmospheric pressure plasma (APP) jet on the biofilm formation of collagen casing (CC), polypropylene (PP) and polyethylene terephthalate (PET) against *L. monocytogenes*, *E. coli* O157: H7, and *S. typhimurium* (Kim et al., 2015). These films are most suitable for the engineering of the new class of biomaterial. Plasma treated and/or synthesised polymers serve as highly reactive surfaces as they are rich in free radicals. Therefore, these materials are engineered in such a way that free radicals lead to controllable surface functionalisation without changing the bulk properties of the material.

Plasma pre-treatment has been widely used to modify or activate the surface of the material. Plasma pre-treatment improves the surface incorporation efficacy of antimicrobial substances. In addition, grafting of chitosan onto the surface of poly (ethylene terephthalate) (PET) materials and polyethylene (PE) films with atmospheric pressure dielectric barrier discharge (DBD) plasma pre-treatment was reported (Sophonvachiraporn et al., 2011; Theapsak et al., 2012). Jacofsky and Watson (2016) used multi-frequency harmonic cold plasma treatment for the sanitisation of food transport conveyor belts and food contact surfaces for a specific period (Jacofsky & Watson, 2016).

To induce antimicrobial activity on the surface of the material, plasma polymerisation is found to be an effective approach. In some studies, nanoparticles are also incorporated into the material by the direct incorporation or on-site reduction of an attached metal cation into the zone of plasma polymerisation (Nikiforov et al., 2016). Chen et al. (2019) modified zein films by a two-step method involving compositing with chitosan followed by cold plasma treatment. They observed that after the 60-sec plasma treatment, the enhancement in the properties like thermal stability, tensile strength, and water vapor barrier (Chen et al., 2019). Katsigiannis et al. (2021) had evaluated the indirect Cold atmospheric pressure (CAP) plasma against two common foodborne pathogens (*L. monocytogenes* and *S. typhimurium*) on stainless steel surfaces. They observed, within 3 min, the system reduced *L. monocytogenes* and *S. typhimurium* to $>$ 3.55 log CFU/mL and 2.06 logCFU/mL, respectively, at a distance of 5 mm. The stainless-steel surface morphology was observed to be unaffected by the CAP exposure (Katsigiannis et al. 2021).

6. Conclusion and future perspectives

The microbial interaction leads to the deterioration of the efficiency of food contact material and has a harmful effect on health. The major challenge for the food industry is to prevent the initial microbial attachment and killing the microbes or/and removing the dead bacteria from the food contact materials. It has been observed that several new or emerging technologies could enhance the efficiency of food contact materials by reducing microbial contamination. Technologies like surface functionalisation, high-intensity ultrasound and cold plasma technologies have a high potential to decontaminate surfaces. Multifunctional surfaces are need of the food industry, which is attainable by incorporating two or more functional elements. The formation and moderation of innovative surfaces with micro or nano-sized features and the alteration in surface topography will make the food contact surface resistant to the microbial attachment. The surface coating should have more functions, but it should not be toxic to human health. Therefore, the use of natural compounds in the development of the surface would be an ideal solution to enhancing the sanitisation process and modification of physicochemical properties of the surface. Though the safety and inertness of the food contact material is a subject of future research. A multifunctional antimicrobial coating and nanoscale surface topology would have a potential application in all processing areas of the food industry to improve the safety and inertness of the food contact material while maintaining the quality of food. In addition, the combination of two techniques, such as steam followed by ultrasound, could be a cost-effective solution.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Alzubeidi, Y. S., Udompijitkul, P., Talukdar, P. K., & Sarker, M. R. (2018). Inactivation of Clostridium perfringens spores adhered onto stainless steel surface by agents used in a clean-in-place procedure. *International Journal of Food Microbiology, 277*, 26–33.

Ahmadi, Y., & Ahmad, S. (2019). Surface-active antimicrobial and anticorrosive Oleo-Polyurethane/graphene oxide nanocomposite coatings: Synergistic effects of in-situ polymerization and π-π interaction. *Progress in Organic Coatings, 127*, 168–180.

Akbas, M. Y., & Cag, S. (2016). Use of organic acids for prevention and removal of Bacillus subtilis biofilms on food contact surfaces. *Food Science and Technology International, 22*(7), 587–597.

Alexandre, E. M. C., Lourenço, R. V., Bittante, A. M. Q. B., Moraes, I. C. F., & do Amaral Sobral, P. J. (2016). Gelatin-based films reinforced with montmorillonite and activated with nanoemulsion of ginger essential oil for food packaging applications. *Food Packaging and Shelf Life, 10*, 87–96.

Arevalos-Sánchez, M., Regalado, C., Martin, S., Domínguez-Domínguez, J., & García-Almendárez, B. (2012). Effect of neutral electrolyzed water and nisin on Listeria monocytogenes biofilms, and on listeriolysin O activity. *Food Control, 24*(1–2), 116–122.

Arvanitoyannis, I. S., Kotsanopoulos, K. V., & Savva, A. G. (2017). Use of ultrasounds in the food industry–Methods and effects on quality, safety, and organoleptic characteristics of foods: A review. *Critical Reviews in Food Science and Nutrition, 57*(1), 109–128.

Astráin-Redín, L., Raso, J., Condón, S., Cebrián, G., & Álvarez, I. (2019). Application of high-power ultrasound in the food industry *Sonochemical Reactions*. IntechOpen.

Awad, T. S., Asker, D., & Hatton, B. D. (2018). Food-safe modification of stainless steel food-processing surfaces to reduce bacterial biofilms. *ACS Applied Materials & Interfaces, 10*(27), 22902–22912.

Bae, Y.-M., Heu, S.-G., & Lee, S.-Y. (2009). Inhibitory effect of dry-heat treatment and chemical sanitizers against foodborne pathogens contaminated on the surfaces of materials. *Journal of the Korean Society of Food Science and Nutrition, 38*(9), 1265–1270.

Bang, J., Hong, A., Kim, H., Beuchat, L. R., Rhee, M. S., Kim, Y., & Ryu, J.-H. (2014). Inactivation of Escherichia coli O157: H7 in biofilm on food-contact surfaces by sequential treatments of aqueous chlorine dioxide and drying. *International Journal of Food Microbiology, 191*, 129–134.

Barbut, F., Yezli, S., Mimoun, M., Pham, J., Chaouat, M., & Otter, J. A. (2013). Reducing the spread of Acinetobacter baumannii and methicillin-resistant *Staphylococcus aureus* on a burns unit through the intervention of an infection control bundle. *Burns, 39*(3), 395–403.

Bari, M., Nakauma, M., Todoriki, S., Juneja, V. K., Isshiki, K., & Kawamoto, S. (2005). Effectiveness of irradiation treatments in inactivating *Listeria monocytogenes* on fresh vegetables at refrigeration temperature. *Journal of Food Protection, 68*(2), 318–323.

Basumatary, R., Vatankhah, H., Dwivedi, M., John, D., & Ramaswamy, H. S. (2020). Ultrasound-steam combination process for microbial decontamination and heat transfer enhancement. *Journal of Food Process Engineering, 43*(4), Article e13367.

Bhilwadikar, T., Pounraj, S., Manivannan, S., Rastogi, N. K., & Negi, P. S. (2019). Decontamination of microorganisms and pesticides from fresh fruits and vegetables: A comprehensive review from common household processes to modern techniques. *Comprehensive Reviews in Food Science and Food Safety, 18*(4), 1003–1038.

Bintsis, T., Litopoulou-Tzanetaki, E., & Robinson, R. K. (2000). Existing and potential applications of ultraviolet light in the food industry–A critical review. *Journal of the Science of Food and Agriculture, 80*(6), 637–645.

Birmpa, A., Sfika, V., & Vantarakis, A. (2013). Ultraviolet light and Ultrasound as non-thermal treatments for the inactivation of microorganisms in fresh ready-to-eat foods. *International Journal of Food Microbiology, 167*(1), 96–102. https://doi.org/10.1016/j.ijfoodmicro.2013.06.005

Borucki, M. K., Peppin, J. D., White, D., Loge, F., & Call, D. R. (2003). Variation in biofilm formation among strains of *Listeria monocytogenes*. *Applied and Environmental Microbiology, 69*(12), 7336–7342.

Brasil, C. C. B., Barin, J. S., Jacob-Lopes, E., Menezes, C. R., Zepka, L. Q., Wagner, R., Campagnol, P. C. B., & Cichoski, A. J. (2017). Single step non-thermal cleaning/sanitation of knives used in meat industry with ultrasound. *Food Research International, 91*, 133–139.

Briñez, W. J., Roig-Sagués, A. X., Herrero, M. M. H., Lopez-Pedemonte, T., & Guamis, B. (2006). Bactericidal efficacy of peracetic acid in combination with hydrogen peroxide against pathogenic and non pathogenic strains of *Staphylococcus spp.*, *Listeria spp.* and *Escherichia coli*. *Food Control, 17*(7), 516–521.

Brooks, J. D., & Flint, S. H. (2008). Biofilms in the food industry: Problems and potential solutions. *International Journal of Food Science & Technology, 43*(12), 2163–2176.

Campana, R., Casettari, L., Fagioli, L., Cespi, M., Bonacucina, G., & Baffone, W. (2017). Activity of essential oil-based microemulsions against *Staphylococcus aureus* biofilms developed on stainless steel surface in different culture media and growth conditions. *International Journal of Food Microbiology, 241*, 132–140.

Cappitelli, F., Polo, A., & Villa, F. (2014). Biofilm formation in food processing environments is still poorly understood and controlled. *Food Engineering Reviews, 6*(1–2), 29–42.

Castillo, A., Lucia, L., Goodson, K., Savell, J., & Acuff, G. (1998). Use of hot water for beef carcass decontamination. *Journal of Food Protection, 61*(1), 19–25.

Castillo, A., Lucia, L., Goodson, K., Savell, J., & Acuff, G. (1999). Decontamination of beef carcass surface tissue by steam vacuuming alone and combined with hot water and lactic acid sprays. *Journal of Food Protection, 62*(2), 146–151.

Chae, M. S., & Schraft, H. (2000). Comparative evaluation of adhesion and biofilm formation of different *Listeria monocytogenes* strains. *International Journal of Food Microbiology, 62*(1–2), 103–111.

Chahar, M. K., Sharma, N., Dobhal, M. P., & Joshi, Y. C. (2011). Flavonoids: A versatile source of anticancer drugs. *Pharmacognosy Reviews, 5*(9), 1.

Chen, G., Dong, S., Zhao, S., Li, S., & Chen, Y. (2019). Improving functional properties of zein film via compositing with chitosan and cold plasma treatment. *Industrial Crops and Products, 129*, 318–326.

Cheng, G., Xue, H., Zhang, Z., Chen, S., & Jiang, S. (2008). A switchable biocompatible polymer surface with self-sterilizing and nonfouling capabilities. *Angewandte Chemie, 120*(46), 8963–8966.

Choi, S., Puligundla, P., & Mok, C. (2017). Effect of corona discharge plasma on microbial decontamination of dried squid shreds including physico-chemical and sensory evaluation. *LWT - Food Science and Technology, 75*, 323–328.

Colagiorgi, A., Bruini, I., Di Ciccio, P. A., Zanardi, E., Ghidini, S., & Ianieri, A. (2017). *Listeria monocytogenes* biofilms in the wonderland of food industry. *Pathogens, 6*(3), 41.

Colon, M., & Nerín, C. (2016). Synergistic, antagonistic and additive interactions of green tea polyphenols. *European Food Research and Technology, 242*(2), 211–220.

Cooper, R. A. (2007). Iodine revisited. *International Wound Journal, 4*(2), 124–137.

Cui, H., Li, W., Li, C., & Lin, L. (2016). Synergistic effect between Helichrysum italicum essential oil and cold nitrogen plasma against *Staphylococcus aureus* biofilms on different food-contact surfaces. *International Journal of Food Science & Technology, 51*(11), 2493–2501.

Dasan, B. G., Onal-Ulusoy, B., Pawlat, J., Diatczyk, J., Sen, Y., & Mutlu, M. (2017). A new and simple approach for decontamination of food contact surfaces with gliding arc discharge atmospheric non-thermal plasma. *Food and Bioprocess Technology, 10*(4), 650–661.

Demir, B., Broughton, R. M., Huang, T. S., Bozack, M. J., & Worley, S. D. (2017). Polymeric antimicrobial N-halamine-surface modification of stainless steel. *Industrial & Engineering Chemistry Research, 56*(41), 11773–11781.

Di Ciccio, P., Vergara, A., Festino, A., Paludi, D., Zanardi, E., Ghidini, S., & Ianieri, A. (2015). Biofilm formation by *Staphylococcus aureus* on food contact surfaces: Relationship with temperature and cell surface hydrophobicity. *Food Control, 50*, 930–936.

Dong, S., Gao, A., Xu, H., & Chen, Y. (2017). Effects of dielectric barrier discharges (DBD) cold plasma treatment on physicochemical and structural properties of zein powders. *Food and Bioprocess Technology, 10*(3), 434–444.

Donlan, R. M., & Costerton, J. W. (2002). Biofilms: Survival mechanisms of clinically relevant microorganisms. *Clinical Microbiology Reviews, 15*(2), 167–193.

dos Santos Rodrigues, J. B., de Souza, N. T., Scarano, J. O. A., de Sousa, J. M., Lira, M. C., de Figueiredo, R. C. B. Q., & Magnani, M. (2018). Efficacy of using oregano essential oil and carvacrol to remove young and mature *Staphylococcus aureus* biofilms on food-contact surfaces of stainless steel. *LWT-Food Science & Technology, 93*, 293–299.

dos Santos Rodrigues, J. B., de Carvalho, R. J., de Souza, N. T., de Sousa Oliveira, K., Franco, O. L., Schaffner, D., de Souza, E. L., & Magnani, M. (2017). Effects of oregano essential oil and carvacrol on biofilms of Staphylococcus aureus from food-contact surfaces. *Food Control, 73*, 1237–1246.

Ehuwa, O., Jaiswal, A. K., & Jaiswal, S. (2021). Salmonella, food safety and food handling practices. *Foods, 10*(5), 907.

Emamifar, A., Kadivar, M., Shahedi, M., & Soleimanian-Zad, S. (2010). Evaluation of nanocomposite packaging containing Ag and ZnO on shelf life of fresh orange juice. *Innovative Food Science & Emerging Technologies, 11*(4), 742–748.

Fagerlund, A., Møretrø, T., Heir, E., Briandet, R., & Langsrud, S. (2017). Cleaning and disinfection of biofilms composed of *Listeria monocytogenes* and background microbiota from meat processing surfaces. *Applied and Environmental Microbiology, 83*(17).

Falcó, I., Verdeguer, M., Aznar, R., Sánchez, G., & Randazzo, W. (2019). Sanitizing food contact surfaces by the use of essential oils. *Innovative Food Science & Emerging Technologies, 51*, 220–228.

Fan, X., Su, Y., Zhao, X., Li, Y., Zhang, R., Zhao, J., & Liu, Y. (2014). Fabrication of polyvinyl chloride ultrafiltration membranes with stable antifouling property by exploring the pore formation and surface modification capabilities of polyvinyl formal. *Journal of Membrane Science, 464*, 100–109.

Feng, M., Yu, L., Zhu, P., Zhou, X., Liu, H., Yang, Y., & Chen, P. (2018). Development and preparation of active starch films carrying tea polyphenol. *Carbohydrate Polymers, 196*, 162–167.

Fuchs, F. (2015). *Ultrasonic cleaning and washing of surfaces Power Ultrasonics*. 577–609: Elsevier.

Gabriel, A. A., Ballesteros, M. L. P., Rosario, L. M. D., Tumlos, R. B., & Ramos, H. J. (2018). Elimination of *Salmonella enterica* on common stainless steel food contact surfaces using UV-C and atmospheric pressure plasma jet. *Food Control, 86*, 90–100.

Galie, S., García-Gutiérrez, C., Miguélez, E. M., Villar, C. J., & Lombó, F. (2018). Biofilms in the food industry: Health aspects and control methods. *Frontiers in Microbiology, 9*, 898.

Gautam, B., Ali, S. A., Chen, J. T., & Yu, H. H. (2021). Hybrid "kill and release" antibacterial cellulose papers obtained via surface-initiated atom transfer radical polymerization. *ACS Applied Bio Materials*. https://doi.org/10.1021/acsabm.1c00817

Gião, M. S., & Keevil, C. W. (2014). *Listeria monocytogenes* can form biofilms in tap water and enter into the viable but non-cultivable state. *Microbial Ecology, 67*(3), 603–611.

Giaouris, E., Heir, E., Hébraud, M., Chorianopoulos, N., Langsrud, S., Møretrø, T., & Nychas, G.-J. (2014). Attachment and biofilm formation by foodborne bacteria in meat processing environments: Causes, implications, role of bacterial interactions and control by alternative novel methods. *Meat Science, 97*(3), 298–309.

Gkana, E., Chorianopoulos, N., Grounta, A., Koutsoumanis, K., & Nychas, G. J. (2017). Effect of inoculum size, bacterial species, type of surfaces and contact time to the transfer of foodborne pathogens from inoculated to non-inoculated beef fillets via food processing surfaces. *Food Microbiology, 62*, 51–57.

Gkana, E., Doulgeraki, A., & Nychas, G. E. (2017). Survival and transfer efficacy of mixed strain *Salmonella enterica ser. typhimurium* from beef burgers to abiotic surfaces and determination of individual strain contribution. *Meat Science, 130*, 58–63.

Gkana, E., Lianou, A., & Nychas, G.-J. (2016). Transfer of *Salmonella enterica serovar typhimurium* from beef to tomato through kitchen equipment and the efficacy of intermediate decontamination procedures. *Journal of Food Protection, 79*(7), 1252–1258.

Glaser, T. K., Plohl, O., Vesel, A., Ajdnik, U., Ulrih, N. P., Hrnčič, M. K., & Fras Zemljič, L. (2019). Functionalization of polyethylene (PE) and polypropylene (PP) material using chitosan nanoparticles with incorporated resveratrol as potential active packaging. *Materials, 12*(13), 2118.

Goodburn, C., & Wallace, C. A. (2013). The microbiological efficacy of decontamination methodologies for fresh produce: A review. *Food Control, 32*(2), 418–427.

Gutiérrez, D., Rodríguez-Rubio, L., Martínez, B., Rodríguez, A., & García, P. (2016). Bacteriophages as weapons against bacterial biofilms in the food industry. *Frontiers in Microbiology, 7*, 825.

Guzel-Seydim, Z. B., Greene, A. K., & Seydim, A. (2004). Use of ozone in the food industry. *LWT-Food Science and Technology, 37*(4), 453–460.

Gyawali, R., & Ibrahim, S. A. (2012). Impact of plant derivatives on the growth of foodborne pathogens and the functionality of probiotics. *Applied Microbiology and Biotechnology, 95*(1), 29–45.

Hamadi, F., Asserne, F., Elabed, S., Bensouda, S., Mabrouki, M., & Latrache, H. (2014). Adhesion of *Staphylococcus aureus* on stainless steel treated with three types of milk. *Food Control, 38*, 104–108.

Hamanaka, D., Yamada, H., Trivittayasil, V., Kadoyanagi, T., Tanaka, F., & Uchino, T. (2011). Effect of different heat treatments on *Bacillus subtilis* spores inactivated by ultraviolet irradiation. *Food Science and Technology Research, 17*(4), 289–293.

Hao, X., Yeh, P., Qin, Y., Jiang, Y., Qiu, Z., Li, S., & Cao, X. (2019). Aptamer surface functionalization of microfluidic devices using dendrimers as multi-handled templates and its application in sensitive detections of foodborne pathogenic bacteria. *Analytica Chimica Acta, 1056*, 96–107.

Harney, M. B., Pant, R. R., Fulmer, P. A., & Wynne, J. H. (2008). Surface self-concentrating amphiphilic quaternary ammonium biocides as coating additives. *ACS Applied Materials & Interfaces, 1*(1), 39–41.

Hasan, J., & Chatterjee, K. (2015). Recent advances in engineering topography mediated antibacterial surfaces. *Nanoscale, 7*(38), 15568–15575.

Havelaar, A. H., Brul, S., De Jong, A., De Jonge, R., Zwietering, M. H., & Ter Kuile, B. H. (2010). Future challenges to microbial food safety. *International Journal of Food Microbiology, 139*, S79–S94.

Hayek, S., Gyawali, R., & Ibrahim, S. (2013). Microbial Pathogens and Strategies for Combating Them: Science, Technology and Education. *Antimicrobial Natural Products. A. Méndez-Vilas Ed.*

Hosseini, S. F., Nahvi, Z., & Zandi, M. (2019). Antioxidant peptide-loaded electrospun chitosan/poly (vinyl alcohol) nanofibrous mat intended for food biopackaging purposes. *Food Hydrocolloids, 89*, 637–648.

Hsiao, S.-W., Venault, A., Yang, H.-S., & Chang, Y. (2014). Bacterial resistance of self-assembled surfaces using PPOm-b-PSBMAn zwitter ionic copolymer – Concomitant effects of surface topography and surface chemistry on attachment of live bacteria. *Colloids and Surfaces B: Biointerfaces, 118*, 254–260.

Jacofsky, M. C., & Watson, G. A. (2016). Method and apparatus for cold plasma food contact surface sanitation. Google Patents.

Jaiswal, S., Bhattacharya, K., McHale, P., & Duffy, B. (2015). Dual effects of β-cyclodextrin-stabilised silver nanoparticles: Enhanced biofilm inhibition and reduced cytotoxicity. *Journal of Materials Science: Materials in Medicine, 26*(1), 52.

Jin, T., & Gurtler, J. B. (2011). Inactivation of *Salmonella* in liquid egg albumen by antimicrobial bottle coatings infused with allyl isothiocyanate, nisin and zinc oxide nanoparticles. *Journal of Applied Microbiology, 110*(3), 704–712.

Kaczmarek, B., Owczarek, A., Nadolna, K., & Sionkowska, A. (2019). The film-forming properties of chitosan with tannic acid addition. *Materials Letters, 245*, 22–24.

Katara, G., Hemvani, N., Chitnis, S., Chitnis, V., & Chitnis, D. (2008). Surface disinfection by exposure to germicidal UV light. *Indian Journal of Medical Microbiology, 26*(3), 241.

Katsigiannis, A. S., Bayliss, D. L., & Walsh, J. L. (2021). Cold plasma decontamination of stainless steel food processing surfaces assessed using an industrial disinfection protocol. *Food Control, 121*, 107543. https://doi.org/10.1016/j.foodcont.2020.107543

Khadre, M., & Yousef, A. (2001). Sporicidal action of ozone and hydrogen peroxide: A comparative study. *International Journal of Food Microbiology, 71*(2–3), 131–138.

Khamisse, E., Firmesse, O., Christieans, S., Chassaing, D., & Carpentier, B. (2012). Impact of cleaning and disinfection on the non-culturable and culturable bacterial loads of food-contact surfaces at a beef processing plant. *International Journal of Food Microbiology, 158*(2), 163–168.

Kim, C. Y., Ryu, G. J., Park, H. Y., & Ryu, K. (2017). Resistance of Staphylococcus aureus on food contact surfaces with different surface characteristics to chemical sanitizers. *Journal of Food Safety, 37*(4), Article e12354.

Kim, H.-J., Jayasena, D. D., Yong, H. I., Alahakoon, A. U., Park, S., Park, J., & Jo, C. (2015). Effect of atmospheric pressure plasma jet on the foodborne pathogens attached to commercial food containers. *Journal of Food Science And Technology, 52*(12), 8410–8415.

Kim, P., Kreder, M. J., Alvarenga, J., & Aizenberg, J. (2013). Hierarchical or not? Effect of the length scale and hierarchy of the surface roughness on omniphobicity of lubricant-infused substrates. *Nano Letters, 13*(4), 1793–1799.

Kollath, A., & Andreeva, D. V. (2017). *Use of high-intensity ultrasound for production of antimicrobial and self-cleaning surfaces. Food Preservation* (pp. 229–264). Elsevier.

Kollath, A., Brezhneva, N., Skorb, E. V., & Andreeva, D. V. (2017). Microbubbles trigger oscillation of crystal size in solids. *Physical Chemistry Chemical Physics, 19*(8), 6286–6291.

Kreske, A. C., Ryu, J.-H., Pettigrew, C. A., & Beuchat, L. R. (2006). Lethality of chlorine, chlorine dioxide, and a commercial produce sanitizer to *Bacillus cereus* and *Pseudomonas* in a liquid detergent, on stainless steel, and in biofilm. *Journal of Food Protection, 69*(11), 2621–2634.

Lamarra, J., Giannuzzi, L., Rivero, S., & Pinotti, A. (2017). Assembly of chitosan support matrix with gallic acid-functionalized nanoparticles. *Materials Science and Engineering: C, 79*, 848–859.

Li, K., Zhu, J., Guan, G., & Wu, H. (2019). Preparation of chitosan-sodium alginate films through layer-by-layer assembly and ferulic acid crosslinking: Film properties, characterization, and formation mechanism. *International Journal of Biological Macromolecules, 122*, 485–492.

Liu, D. Z., Jindal, S., Amamcharla, J., Anand, S., & Metzger, L. (2017). Evaluation of a sol-gel–based stainless steel surface modification to reduce fouling and biofilm formation during pasteurization of milk. *Journal of Dairy Science, 100*(4), 2577–2581.

Liu, M., Wu, X., Li, J., Liu, L., Zhang, R., Shao, D., & Du, X. (2017). The specific anti-biofilm effect of gallic acid on *Staphylococcus aureus* by regulating the expression of the ica operon. *Food Control, 73*, 613–618.

Liu, S., Zheng, J., Hao, L., Yegin, Y., Bae, M., Ulugun, B., Taylor, T. M., Scholar, E. A., Cisneros-Zevallos, L., Oh, J. K., & Akbulut, M. (2020). Dual-functional, superhydrophobic coatings with bacterial anticontact and antimicrobial characteristics. *ACS Applied Materials & Interfaces, 19*, 21311–21321.

Liu, Y., Liang, X., Wang, S., Qin, W., & Zhang, Q. (2018). Electrospun antimicrobial polylactic acid/tea polyphenol nanofibers for food-packaging applications. *Polymers, 10*(5), 561.

Lo, M. Y., Ngan, W. Y., Tsun, S. M., Hsing, H.-L., Lau, K. T., Hung, H. P., & Pu, Y. (2019). A field study into Hong Kong's wet markets: Raised questions into the hygienic maintenance of meat contact surfaces and the dissemination of microorganisms associated with nosocomial infections. *Frontiers in Microbiology, 10*, 2618.

Marquenie, D., Lammertyn, J., Geeraerd, A., Soontjens, C., Van Impe, J., Nicolaı, B., & Michiels, C. (2002). Inactivation of conidia of *Botrytis cinerea* and *Monilinia fructigena* using UV-C and heat treatment. *International Journal of Food Microbiology, 74*(1–2), 27–35.

Marriott, N. G., & Gravani, R. B. (2006). Sanitizers. *Principles of Food Sanitation*, 165–189.

Meireles, A., Giaouris, E., & Simões, M. (2016). Alternative disinfection methods to chlorine for use in the fresh-cut industry. *Food Research International, 82*, 71–85.

Meng, Q., Wang, Z., Chai, X., Weng, Z., Ding, R., & Dong, L. (2016). Fabrication of hematite (α-Fe2O3) nanoparticles using electrochemical deposition. *Applied Surface Science, 368*, 303–308.

Mi, L., & Jiang, S. (2014). Integrated antimicrobial and nonfouling zwitterionic polymers. *Angewandte Chemie International Edition, 53*(7), 1746–1754.

Møretrø, T., & Langsrud, S. (2017). Residential bacteria on surfaces in the food industry and their implications for food safety and quality. *Comprehensive Reviews in Food Science and Food Safety, 16*(5), 1022–1041.

Møretrø, T., Heir, E., Nesse, L. L., Vestby, L. K., & Langsrud, S. (2012). Control of *Salmonella* in food related environments by chemical disinfection. *Food Research International, 45*(2), 532–544.

Myintzaw, P., Jaiswal, A. K., & Jaiswal, S. (2021). A review on campylobacteriosis associated with poultry meat consumption. *Food Reviews International*, 1–15.

Niemira, B. A., Boyd, G., & Sites, J. (2014). Cold plasma rapid decontamination of food contact surfaces contaminated with *Salmonella* biofilms. *Journal of Food Science, 79* (5), M917–M922.

Nikiforov, A., Deng, X., Xiong, Q., Cvelbar, U., DeGeyter, N., Morent, R., & Leys, C. (2016). Non-thermal plasma technology for the development of antimicrobial surfaces: A review. *Journal of Physics D: Applied Physics, 49*(20), Article 204002.

Noshirvani, N., Ghanbarzadeh, B., Gardrat, C., Rezaei, M. R., Hashemi, M., Le Coz, C., & Coma, V. (2017). Cinnamon and ginger essential oils to improve antifungal, physical and mechanical properties of chitosan-carboxymethyl cellulose films. *Food Hydrocolloids, 70*, 36–45.

Oh, J. K., Liu, S., Jones, M., Yegin, Y., Hao, L., Tolen, T. N., & Taylor, T. M. (2019). Modification of aluminum surfaces with superhydrophobic nanotextures for enhanced food safety and hygiene. *Food Control, 96*, 463–469.

Oh, J. K., Perez, K., Kohli, N., Kara, V., Li, J., Min, Y., & Cisneros-Zevallos, L. (2015). Hydrophobically-modified silica aerogels: Novel food-contact surfaces with bacterial anti-adhesion properties. *Food Control, 52*, 132–141.

Olatunde, O. O., Shiekh, K. A., & Benjakul, S. (2021). Pros and cons of cold plasma technology as an alternative non-thermal processing technology in seafood industry. *Trends in Food Science & Technology, 111*, 617–627. https://doi.org/10.1016/j.tifs.2021.03.026

Ortega-Ramirez, L. A., Gutiérrez-Pacheco, M. M., Vargas-Arispuro, I., González-Aguilar, G. A., Martínez-Téllez, M. A., & Ayala-Zavala, J. F. (2020). Inhibition of glucosyltransferase activity and glucan production as an antibiofilm mechanism of lemongrass essential oil against *Escherichia coli* O157: H7. *Antibiotics, 9*(3), 102.

Overney, A., Jacques-André-Coquin, J., Ng, P., Carpentier, B., Guillier, L., & Firmesse, O. (2017). Impact of environmental factors on the culturability and viability of *Listeria monocytogenes* under conditions encountered in food processing plants. *International Journal of Food Microbiology, 244*, 74–81.

Pagán, R., & García-Gonzalo, D. (2015). Influence of environmental factors on bacterial biofilm formation in the food industry: A review. *Journal of Postdoctoral Research.* ART-2015-95845.

Park, S. Y., & Ha, S.-D. (2018). Assessment of cold oxygen plasma technology for the inactivation of major foodborne viruses on stainless steel. *Journal of Food Engineering, 223*, 42–45.

Park, S.-H., & Kang, D.-H. (2017). Influence of surface properties of produce and food contact surfaces on the efficacy of chlorine dioxide gas for the inactivation of foodborne pathogens. *Food Control, 81*, 88–95.

Perera, K. Y., Sharma, S., Pradhan, D., Jaiswal, A. K., & Jaiswal, S. (2021). Seaweed polysaccharide in food contact materials (active packaging, intelligent packaging, edible films, and coatings). *Foods, 10*(9), 2088.

Perinelli, D. R., Petrelli, D., Vitali, L. A., Vllasaliu, D., Cespi, M., Giorgioni, G., … Palmieri, G. F. (2019). Quaternary ammonium surfactants derived from leucine and methionine: Novel challenging surface active molecules with antimicrobial activity. *Journal of Molecular Liquids, 283*, 249–256.

Petersson, L. P., Albrecht, U.-V., Sedlacek, L., Gemein, S., Gebel, J., & Vonberg, R.-P. (2014). Portable UV light as an alternative for decontamination. *American Journal of Infection Control, 42*(12), 1334–1336.

Picchio, M. L., Linck, Y. G., Monti, G. A., Gugliotta, L. M., Minari, R. J., & Igarzabal, C. I. A. (2018). Casein films crosslinked by tannic acid for food packaging applications. *Food Hydrocolloids, 84*, 424–434.

Piñeros-Hernandez, D., Medina-Jaramillo, C., López-Córdoba, A., & Goyanes, S. (2017). Edible cassava starch films carrying rosemary antioxidant extracts for potential use as active food packaging. *Food Hydrocolloids, 63*, 488–495.

Poimenidou, S. V., Chrysadakou, M., Tzakoniati, A., Bikouli, V. C., Nychas, G.-J., & Skandamis, P. N. (2016). Variability of *Listeria monocytogenes* strains in biofilm formation on stainless steel and polystyrene materials and resistance to peracetic acid and quaternary ammonium compounds. *International Journal of Food Microbiology, 237*, 164–171.

Rajab, F. H., Liauw, C. M., Benson, P. S., Li, L., & Whitehead, K. A. (2017). Production of hybrid macro/micro/nano surface structures on Ti6Al4V surfaces by picosecond laser surface texturing and their antifouling characteristics. *Colloids and Surfaces B: Biointerfaces, 160*, 688–696.

Ramos, B., Miller, F. A., Brandão, T. R. S., Teixeira, P., & Silva, C. L. M. (2013). Fresh fruits and vegetables – An overview on applied methodologies to improve its quality and safety. *Innovative Food Science & Emerging Technologies, 20*, 1–15. https://doi.org/10.1016/j.ifset.2013.07.002

Refaat, A. (2011). Biodiesel production using solid metal oxide catalysts. *International Journal of Environmental Science & Technology, 8*(1), 203–221.

Rico-Munoz, E. (2017). Heat resistant molds in foods and beverages: Recent advances on assessment and prevention. *Current Opinion in Food Science, 17*, 75–83.

Ríos-Castillo, A. G., González-Rivas, F., & Rodríguez-Jerez, J. J. (2017). Bactericidal efficacy of hydrogen peroxide-based disinfectants against gram-positive and gram-negative bacteria on stainless steel surfaces. *Journal of Food Science, 82*(10), 2351–2356.

Ripolles-Avila, C., Hascoët, A., Martínez-Suárez, J., Capita, R., & Rodríguez-Jerez, J. (2019). Evaluation of the microbiological contamination of food processing environments through implementing surface sensors in an iberian pork processing plant: An approach towards the control of *Listeria monocytogenes*. *Food Control, 99*, 40–47.

Romani, V. P., Olsen, B., Collares, M. P., Oliveira, J. R. M., Prentice, C., & Martins, V. G. (2020). Cold plasma and carnauba wax as strategies to produce improved bi-layer films for sustainable food packaging. *Food Hydrocolloids, 108*, 106087. https://doi.org/10.1016/j.foodhyd.2020.106087

Rossi, C., Chaves-López, C., Serio, A., Casaccia, M., Maggio, F., & Paparella, A. (2020). Effectiveness and mechanisms of essential oils for biofilm control on food-contact surfaces: An updated review. *Critical Reviews in Food Science and Nutrition*, 1–20.

Rui, L., Xie, M., Hu, B., Zhou, L., Yin, D., & Zeng, X. (2017). A comparative study on chitosan/gelatin composite films with conjugated or incorporated gallic acid. *Carbohydrate Polymers, 173*, 473–481.

Schaer, T. P., Stewart, S., Hsu, B. B., & Klibanov, A. M. (2012). Hydrophobic polycationic coatings that inhibit biofilms and support bone healing during infection. *Biomaterials, 33*(5), 1245–1254.

Schmidt, R. H. (1997). *Basic elements of equipment cleaning and sanitizing in food processing and handling operations: University of Florida Cooperative Extension Service*. Institute of Food and Agriculture Sciences, EDIS.

Shankar, S., & Rhim, J.-W. (2018). Preparation of antibacterial poly (lactide)/poly (butylene adipate-co-terephthalate) composite films incorporated with grapefruit seed extract. *International Journal of Biological Macromolecules, 120*, 846–852.

Shao, W., Wu, J., Liu, H., Ye, S., Jiang, L., & Liu, X. (2017). Novel bioactive surface functionalization of bacterial cellulose membrane. *Carbohydrate Polymers, 178*, 270–276.

Sharif, N., Golmakani, M.-T., Niakousari, M., Hosseini, S. M. H., Ghorani, B., & Lopez-Rubio, A. (2018). Active food packaging coatings based on hybrid electrospun gliadin nanofibers containing ferulic acid/hydroxypropyl-beta-cyclodextrin inclusion complexes. *Nanomaterials, 8*(11), 919.

Sharma, S., Barkauskaite, S., Duffy, B., Jaiswal, A. K., & Jaiswal, S. (2020a). Characterization and antimicrobial activity of biodegradable active packaging enriched with clove and thyme essential oil for food packaging application. *Foods, 9* (8), 1117.

Sharma, S., Barkauskaite, S., Jaiswal, A. K., & Jaiswal, S. (2021). Essential oils as additives in active food packaging. *Food Chemistry, 343*, Article 128403.

Sharma, S., Barkauskaite, S., Jaiswal, S., Duffy, B., & Jaiswal, A. K. (2020b). Development of essential oil incorporated active film based on biodegradable blends of Poly (Lactide)/Poly (Butylene Adipate-co-Terephthalate) for food packaging application. *Journal of Packaging Technology and Research*, 1–11.

Sharma, S., Jaiswal, A. K., Duffy, B., & Jaiswal, S. (2020). Ferulic acid incorporated active films based on poly (lactide)/poly (butylene adipate-co-terephthalate) blend for food packaging. *Food Packaging and Shelf Life, 24*, Article 100491.

Soni, K. A., Oladunjoye, A., Nannapaneni, R., Schilling, M. W., Silva, J. L., Mikel, B., & Bailey, R. H. (2013). Inhibition and inactivation of *Salmonella typhimurium* biofilms from polystyrene and stainless steel surfaces by essential oils and phenolic constituent carvacrol. *Journal of Food Protection, 76*(2), 205–212.

Sophonvachiraporn, P., Rujiravanit, R., Sreethawong, T., Tokura, S., & Chavadej, S. (2011). Surface characterization and antimicrobial activity of chitosan-deposited DBD plasma-modified woven PET surface. *Plasma Chemistry and Plasma Processing, 31*(1), 233–249.

Srivastava, S., & Kotov, N. A. (2008). Composite layer-by-layer (LBL) assembly with inorganic nanoparticles and nanowires. *Accounts of Chemical Research, 41*(12), 1831–1841.

Theapsak, S., Watthanaphanit, A., & Rujiravanit, R. (2012). Preparation of chitosan-coated polyethylene packaging films by DBD plasma treatment. *ACS Applied Materials & Interfaces, 4*(5), 2474–2482.

Torres Dominguez, E., Nguyen, P. H., Hunt, H. K., & Mustapha, A. (2019). Antimicrobial coatings for food contact surfaces: Legal framework, mechanical properties, and potential applications. *Comprehensive Reviews in Food Science and Food Safety, 18*(6), 1825–1858.

Umair, M., Jabbar, S., Ayub, Z., Muhammad Aadil, R., Abid, M., Zhang, J., & Liqing, Z. (2021). Recent advances in plasma technology: Influence of atmospheric cold plasma on spore inactivation. *Food Reviews International*, 1–23. https://doi.org/10.1080/87559129.2021.1888972

Valdramidis, V., Belaubre, N., Zuniga, R., Foster, A., Havet, M., Geeraerd, A., & Kondjoyan, A. (2005). Development of predictive modelling approaches for surface temperature and associated microbiological inactivation during hot dry air decontamination. *International Journal of Food Microbiology, 100*(1–3), 261–274.

Vazquez-Armenta, F., Bernal-Mercado, A., Lizardi-Mendoza, J., Silva-Espinoza, B., Cruz-Valenzuela, M., Gonzalez-Aguilar, G., & Ayala-Zavala, J. (2018). Phenolic extracts from grape stems inhibit *Listeria monocytogenes* motility and adhesion to food contact surfaces. *Journal of Adhesion Science and Technology, 32*(8), 889–907.

Verran, J., Jackson, S., Coulthwaite, L., Scallan, A., Loewy, Z., & Whitehead, K. (2014). The effect of dentifrice abrasion on denture topography and the subsequent retention of microorganisms on abraded surfaces. *The Journal of Prosthetic Dentistry, 112*(6), 1513–1522.

Verran, J., Packer, A., Kelly, P., & Whitehead, K. (2010). Use of the atomic force microscope to determine the strength of bacterial attachment to grooved surface features. *Journal of Adhesion Science and Technology, 24*(13–14), 2271–2285.

Vidács, A., Kerekes, E., Rajkó, R., Petkovits, T., Alharbi, N. S., Khaled, J. M., & Krisch, J. (2018). Optimization of essential oil-based natural disinfectants against *Listeria monocytogenes* and *Escherichia coli* biofilms formed on polypropylene surfaces. *Journal of Molecular Liquids, 255*, 257–262.

Wang, Y., Li, J., & Li, B. (2016). Nature-inspired one-step green procedure for enhancing the antibacterial and antioxidant behavior of a chitin film: Controlled interfacial assembly of tannic acid onto a chitin film. *Journal of Agricultural and Food Chemistry, 64*(28), 5736–5741.

Wang, Z., Kang, H., Zhang, W., Zhang, S., & Li, J. (2017). Improvement of interfacial interactions using natural polyphenol-inspired tannic acid-coated nanoclay enhancement of soy protein isolate biofilms. *Applied Surface Science, 401*, 271–282.

Webber, B., Canova, R., Esper, L. M., Perdoncini, G., Nascimento, V. P. D., Pilotto, F., Santos, L. R. D., & Rodrigues, L. (2015). The use of vortex and ultrasound techniques for the in vitro removal of Salmonella spp. biofilms. *Acta Scientiae Veterinariae, 43*(1), 1–5.

Weber, D. J., & Rutala, W. A. (2013). Self-disinfecting surfaces: Review of current methodologies and future prospects. *American Journal of Infection Control, 41*(5), S31–S35.

Weerarathne, P., Kountoupis, T., & Jaroni, D. (2020). Efficacy of Bacteriophage and Its Depolymerase Enzyme against *Escherichia coli* O45 Biofilms on Food Contact Surfaces. IAFP 2020.

Yang, W. J., Pranantyo, D., Neoh, K.-G., Kang, E.-T., Teo, S.-L.-M., & Rittschof, D. (2012). Layer-by-layer click deposition of functional polymer coatings for combating marine biofouling. *Biomacromolecules, 13*(9), 2769–2780.

Yang, Y., Hoe, Y. W., Zheng, Q., Chung, H.-J., & Yuk, H.-G. (2017). Biofilm formation by *Salmonella enteritidis* in a simulated liquid egg processing environment and its sensitivity to chlorine and hot water treatment. *Food Control, 73*, 595–600.

Yu, H., Liu, Y., Li, L., Guo, Y., Xie, Y., Cheng, Y., & Yao, W. (2020). Ultrasound-involved emerging strategies for controlling foodborne microbial biofilms. *Trends in Food Science & Technology, 96*, 91–101.

Yu, H., Liu, Y., Yang, F., Xie, Y., Guo, Y., Cheng, Y., & Yao, W. (2021). Synergistic efficacy of high-intensity ultrasound and chlorine dioxide combination for Staphylococcus aureus biofilm control. *Food Control, 122*, Article 107822.

Zhang, C., Xia, Y., Zhang, H., & Zacharia, N. S. (2018). Surface functionalization for a nontextured liquid-infused surface with enhanced lifetime. *ACS Applied Materials & Interfaces, 10*(6), 5892–5901.

Zhang, Z., & Han, X. (2019). Polymer antibacterial agent immobilized polyethylene films as efficient antibacterial cling films. *Materials Science and Engineering: C, 105*, Article 110088.

Zheng, T., Li, X., Taha, A., Wei, Y., Hu, T., Fatamorgana, P. B., & Hu, H. (2019). Effect of high intensity ultrasound on the structure and physicochemical properties of soy protein isolates produced by different denaturation methods. *Food Hydrocolloids, 97*, Article 105216.

Zhao, J., Ma, L., Millians, W., Wu, T., & Ming, W. (2016). Dual-functional antifogging/antimicrobial polymer coating. *ACS Applied Materials & Interfaces, 8*(13), 8737–8742.

Zhao, Y., Teixeira, J. S., Gänzle, M. M., & Saldaña, M. D. (2018). Development of antimicrobial films based on cassava starch, chitosan and gallic acid using subcritical water technology. *The Journal of Supercritical Fluids, 137*, 101–110.