2021

Food Contact Surfaces: Challenges, Legislation and Solutions

Shubham Sharma
technological University Dublin, shubham.sharma@tudublin.ie

Amit Jaiswal
Technological University Dublin, amit.jaiswal@tudublin.ie

Brendan Duffy
Technological University Dublin, brendan.duffy@tudublin.ie

See next page for additional authors

Funder: Technological University Dublin - City Campus under the Fiosraigh Scholarship programme, 2017

Food Reviews International

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/lfri20

Food Contact Surfaces: Challenges, Legislation and Solutions

Shubham Sharma, Amit K. Jaiswal, Brendan Duffy & Swarna Jaiswal

FOOD REVIEWS INTERNATIONAL
https://doi.org/10.1080/87559129.2021.1929299

Taylor & Francis
Taylor & Francis Group

Check for updates

Food Contact Surfaces: Challenges, Legislation and Solutions

Shubham Sharma[a,b,c], Amit K. Jaiswal[a,b], Brendan Duffy[c], and Swarna Jaiswal[a,b]

[a]School of Food Science and Environmental Health, College of Sciences and Health, Technological University Dublin, Dublin, Ireland; [b]Environmental Sustainability and Health Institute, Technological University Dublin, Dublin, Ireland; [c]Centre for Research in Engineering and Surface Technology (CREST), FOCAS Institute, Technological University Dublin, Dublin, Ireland

ABSTRACT

Food contact surfaces (FCSs) include all surfaces that may come in contact with the food during production, processing, and packaging. Food processing industries encounter several challenges due to its microbial interaction with the FCSs, such as cross contamination of pathogenic microorganism or allergens in food, formation of biofilm, biodeterioration of food contact surface leads to food with reduced shelf-life and quality. A legal EU framework provides the fundamental postulates for the safety and inertness for all Food Contact Materials (FCMs). Legislations have an important role in providing regulatory guidance on the quality assurance systems and verifying their implementation as a means of regulatory compliance. This review article is focused on the challenges faced by the food processing industry with respect to food contact surfaces. Furthermore, relevant regulations provided by the European framework regarding the food contact materials are also discussed. Finally, new approaches which stand as the solutions to these challenges are discussed.

KEYWORDS

Food contact surface; food industries challenges; contamination; biofilm; eu food legislations; surface modification; natural antimicrobials

Introduction

Food processing industry comes across many challenges at every step during the whole process, from the collection of raw material till the serving of the end foodstuff. The pathogenic or deteriorative microbes could enter the food processing area through several means like the raw material, equipment, external environment, workers and the *in-situ* microbial laboratories. Microorganisms had surrounded the whole food industry with the challenges like corrosion of food contact materials (FCMs), bio deterioration of food contact surface, safety and quality of food such as cross contamination of food, formation of biofilm, and migration of toxic in the food stuff.

The demand for the antimicrobial material for the food industry application like the modified FCMs is growing exponentially. Researchers are bound to think of an innovative way to inhibit the growth of microorganism, while maintaining the freshness, safety and quality of foodstuff. The bacterial colonization on the surfaces affects the interface of materials and articles adversely. Transfer of microorganism majorly in the form of biofilms on the FCMs is a chronic source for infections. These challenges have become more troublesome for the wide range of food industries including seafood processing, brewing, poultry processing, dairy processing, and meat processing.[1] Several researches have been performed to expand the understanding of these challenges and to find a solution to avoid cross contamination of food.[1] The acidic biofilm leads to the biofouling of the equipment such as cutting tables,[2] tube system,[3] surfaces[4,5] and conveyor belts.[6] It results in the corrosion, equipment impairment and reduced heat transfer efficiency. Substantial reduction or elimination of the bacterial attachment and formation of biofilm on the surface of, rigorous strives

CONTACT Amit K. Jaiswal amit.jaiswal@TUDublin.ie School of Food Science and Environmental Health, College of Sciences and Health, Technological University Dublin–City Campus, Central Quad, Grangegorman, Dublin, D07 ADY7, Ireland

are made for the fabrication of new surfaces or in improving the potential of the existing antibacterial surfaces.[7] To substantially reduce or eliminate bacterial attachment on the aforementioned surfaces, extensive efforts have recently been made to construct an active-attack antibacterial surface by incorporating some efficient antibacterial substances, such as metals and their oxide nanoparticles, nanocomposite particles, organic quaternary ammonium salts (QAS), chitosan, and others. The use of chemicals as disinfectant may have hazardous health effects. The chlorine reaction with natural organic matter leads to the development of disinfection by products like haloacetatic acid, and trihalomethane which could be carcinogenic.[8] Ozone could be corrosive for many materials if the ozone concentration is above 4 ppm[9] and its inhalation could be toxic. Antioxidant compounds such as carotenoids, anthocyanins, polyphenols in fruits and vegetables may interact with ozone leading to the formation of reactive oxygen species such as hydrogen peroxide, superoxide in the plant cell.[9,10]

Many other disinfection techniques are used by the food industry such as heat,[11] hot water,[11] steam, and surface coatings.[3,12] Surface coating with the antibacterial agent are most widely used technique for the antibacterial surface fabrication.[13] Several shortcomings of using antibacterial surface coatings had also been noticed such as the bacteria developed resistance against the antibacterial agent.[14] Also, the antibiotics used as an antibacterial agent take a long time to release from the surface and the concentration of the antimicrobial agent is insufficient in the maintenance of the antimicrobial environment on the surface. Therefore, the research now is focused more on developing an efficient surface coating or on the modification of the surface topography which will not allow the attachment of the bacteria and formation of biofilm.[14]

Food industries around the world are progressively using standard quality assurance systems to improve and maintain the quality and safety of the food. A legal framework provides the fundamental postulates for the safety and inertness for all FCMs (Regulation (EU) No 10/2011,[15] Regulation (EC) No 282/2008,[16] Commission Directive 2007/42/EC,[17] Regulation (EC) No 450/2009[18]). To assure the quality and safety of food, the quality assurance systems enable the verification and application of control measures. To ensure safe food they are required at each step in the food production process and to show compliance with regulatory and customer requirements. Globally various authorities regulate the legislations for food, food contact materials and its potential to transfer the chemical substances from food contact material to food such as European Commission for Europe, Food and Drug Administration (FDA) for the United States of America, Canadian Food and Drug Regulations (FDR) for Canada and others. Legislations have an important role in providing regulatory guidance on the most appropriate quality assurance systems and verifying/auditing their implementation as a means of regulatory compliance.[19]

This review focusses on the major challenges faced by food industry such as microbial contamination from food contact material (FCMs), formation of biofilm on FCMs, biodeterioration of material. European legislations ensuring the inertness of FCMs like plastics, regenerative cellulose film, ceramics, active and intelligent material and nano compounds in FCMs are also considered. Also, novel approaches to prohibit the microbial growth on FCMs are discussed.

Microbial interaction with FCMs: major challenges

Microbially influenced corrosion of FCMs

Microbially influenced corrosion (MIC) is the corrosion of metal or an alloy, which is caused due to the activity of microbes. Superimposition of microbial force leads to the corrosion of the material surface. Microbes are omnipresent and can grow and reproduce at a very high rate in a suitable environment. They also exhibit high tolerance to the aggressive environment such as alkaline and acidic pH, high and low temperature and the pressure gradient. Hostile environment is caused by the microbes, stimulating direct and indirect corrosion. An association of microbes forming a biofilm may lead to the formation of a hostile substance like acids, and the variable nature of biofilm could form areas with divergent oxygen contents on the latent surface. For instance, sulphur and ferrous iron-oxidising bacteria like *Acidithiobacillus thiooxidans* and *A. ferrooxidans* are acidophilic and aerobic promoting oxidation of sulphur and sulphides.[20]

$$2H_2S + 2O_2 \rightarrow H_2S_2O_3 + H_2O$$

$$5Na_2S_2O_3 + 8O_2 + H_2O \rightarrow 5Na_2SO_4 + H_2SO_4 + 4S$$

$$4S + 6O_2 + 4H_2O \rightarrow 4H_2SO_4$$

$$Fe^{2+} \rightarrow Fe^{3+} + e$$

Acidithiobacillus bacteria can survive over a pH range from the conditions of acidic to alkaline. For the better understanding of the corrosion mechanism, it is important to understand the role of the bacteria in the process of microbial corrosion, their growth characteristics and the metabolic reactions. By hydrogenase catalyzed mechanisms, sulfate reducing bacterial strains could accelerates the corrosion by using the cathodic hydrogen and initiating the development of ferrous sulphides. Sulfate reducing bacterial strains could obtain energy by iron through electron via pathway intracellular hydrogenase-mediated electron transfer system and membrane-associated cytochrome.[21] Fig. 1 shows a tinplate oil can before and after corrosion during transportation. Dong et al.[22] had studied the stainless steel which has excellent corrosion resistance property was also prone to MIC in due to the acidic environment developed by *A. caldus* SM-1 at room temperature. The biofilm of *A. caldus* SM-1 secreted sulfuric acid and hydrogen sulfide (pH below 2) which led to the destruction of the passive film on the stainless steel.[22] Purwasena et al.[23] had observed that biosurfactant could be a good anti-corrosion agent as biosurfactant inhibited the attachment of *Pseudomonas sp. 1* and *Pseudomonas sp. 2* to carbon steel surface at room temperature and also able to eliminate biofilm on steel surface.[23]

Contamination of microorganism and allergen

Contamination could be defined as the transfer of microorganisms, allergen or any foreign substance from food, person, or object to another food product.[25] Contamination is one of the causes of food-borne illness.[26] It may occur in ready to eat products from the raw food material or between products that contain allergens (peanut butter, peanut powder, mayonnaise, whole liquid milk, wheat and cream cheese) and allergen-free products. Allergens could be transferred in the food industry by various means such as by cleaning the surface contaminated with allergen by a wipe (paper wipe, cloth or sanitizing wipe) and cleaning other surface with same wipe may lead to the transfer of allergen to multiple surfaces. The efficiency of the allergen removal treatment or the amount of the transfer of

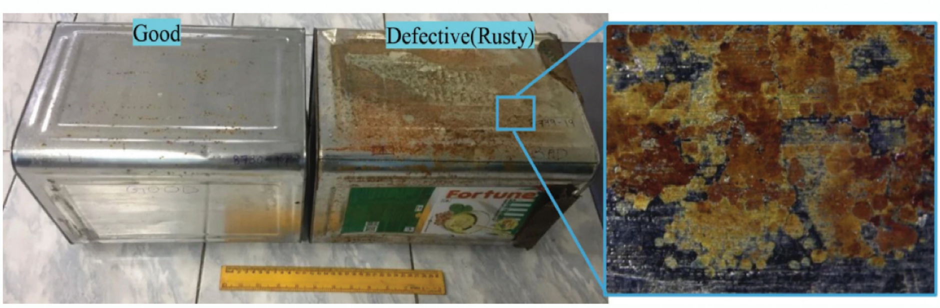

Figure 1. Good sample of tinplate oil cans and defective/corrosive sample of tinplate oil cans.[24]

allergen on the surface depends on the quantity and nature of the allergen present on the surface, texture of food contact surface, and the type of wipe cloth used.[27]

The leading cause of microbial contamination is the occurrence of contamination in the facilities of commercial processing via food contact materials such as chopping board, cutters, mixers etc. Microbial transfer could also occur through various ways such as unhygienic practices followed by food handlers, unsafe water utilization, poor sanitation and hygiene, cleaning and sterilization of equipment like conveyor belt, blanchers, wooden surfaces, presses etc.[28] The event of contamination could occur at any instance in the environment of food processing, that is, from conferring raw material to the final shipping.[29] Several means like the raw material, equipment, external environment, people and the in-situ microbial laboratories are responsible for the entrance of the pathogenic microbes and also deteriorative microorganisms in the food processing area.[29] Moreover, studies observed the survival of bacteria, its multiplication and spread through the home kitchens due to the moisture presence, contaminated dishcloth, utensils, chopping boards etc.[30]

Raw food may contain pathogenic bacteria that comes in contact with other food products directly can contaminate it. For instance, survival of the pathogens on the surface of stainless steel and their transfer on the food contaminating it.[31] The residue of food or allergens on the utensils or the equipment's due to the improper cleaning and sanitation may provide opportunity for the contamination of the food product.[32] Contaminated packaging material may also lead to the contamination of ready to eat food. The staffs that do not follow Good Manufacturing Practices (GMPs) may result in the transferring of the microorganisms and allergens to the food products. For the adequate cleaning hygiene protocols must be followed. Also, dual functional coating or multifunctional coatings on the surfaces, surface topography modification, natural antimicrobial disinfectants, active packaging, smart or intelligent packaging could be used. Sharma et al.[33] have incorporated ferulic acid in the poly (lactide)-poly (butylene adipate-co-terephthalate) composite film. Ferulic acid incorporated active packaging film had demonstrated *S. aureus* growth reduction by 3.5 log CFU/ml and *E. coli* growth reduction by 2 log CFU/ml.

Formation of biofilms on FCMs

Aggregation and growth of the attached microorganism on any surface are known as the biofilm. Many factors affect the formation and spreading of the biofilms like the specific bacterial strain, properties of the material surface, and environmental parameters such as the pH, nutrient content and

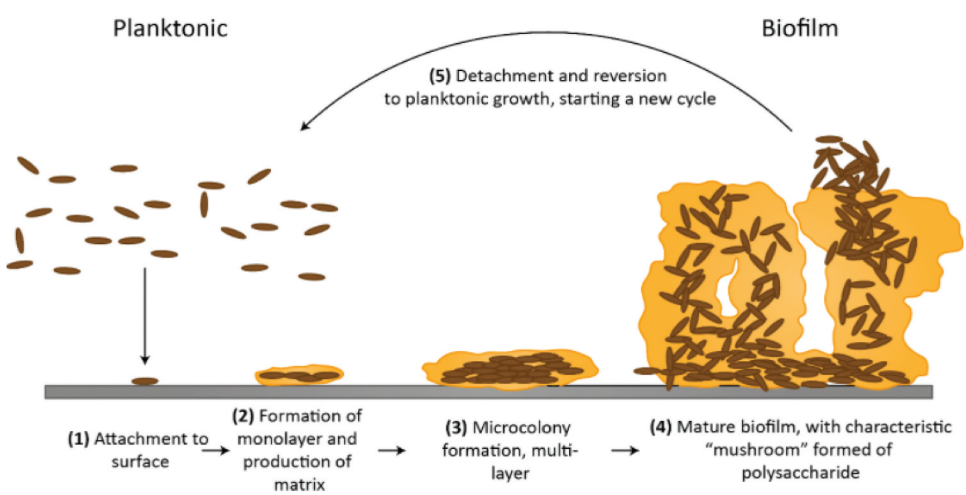

Figure 2. Biofilm development stages [34,36].

temperature.[1] The starting point of the biofilm formation is the initial interaction of the moving planktonic bacteria on the surface. This process is reversible as the cells are loosely attached to the surface. The bacteria start the formation of extracellular polymeric substances (EPS) for the protection which makes the bacterial attachment firmer and irreversible. The EPS is an extracellular matrix which consists of extracellular polysaccharides, cell debris, structural proteins and nucleic acids. Formation of matrix is initially dominated by extracellular DNA; however, at later stage, structural protein and polysaccharides take over. The microcolonies formation led to significant growth and maturation of biofilm which forms a complex three-dimensional structure. In the final stage, the biofilm disperses in the form of single planktonic cells again and possibly starts a new biofilm formation cycle (Fig. 2).[24,34,35] The cells forming the biofilm are more resistant to any antimicrobial agents as they develop a barrier which prevents or lessens the contact of the bacterial cell with antimicrobial agents.

Biofilm could be formed by microorganisms such as *S. aureus, E. coli, L. monocytogeneses* etc. which are responsible for many infections like diarrhea, nausea etc. In comparison with planktonic cells, biofilm offers higher resistance against various disinfectant; therefore, they are not detached easily by normal cleaning process. Biofilms could be a cause of contamination between the surface and the food. Shi et al.[37] had suggested that the commercial products containing alkaline detergent or acidic cleaner were not destroying biofilms formed by *S. aureus* and *P. aeruginosa* on the surface of stainless steel.[37] Quaternary-ammonium-compounds (QAC), commonly used in disinfectants is also inefficient in destroying the biofilm of *L. monocytogenes*.[38]

The initial attachment of the bacteria could be either passive or active. The adhesion of the cell depends on the physiochemical properties of the bacterial cell surface. A study by Kocot and Olszewska[39] revealed that at short contact times (1–2 hrs) *L. monocytogenes* strains at room temperature persisted and enhanced the adherence, stimulating their growth and may initiate the persistent contamination of the food processing facility.[39] A study also states that *L. monocytogenes* have high chances in the attachment and formation of biofilm in the food processing facility and can be significantly influenced by external factors like temperature, moisture etc. which may modify surface hydrophobicity of the cell.[40] It has been observed that with the increase in temperature from 4°C, 12°C, 22°C to 37°C, the cell surface hydrophobicity increases from 10.5% to 34.1%.

Numerous studies showed that the biofilm formation is independent of the type of food contact surface[41,42,43,44] as discussed in Table 1. Dourou et al.[41] had studied the adherence and formation of biofilm on and high-density polyethylene surfaces (HDPE) and stainless-steel surfaces. *E. coli* biofilm attachment was observed at the beef fabrication temperature (15°C) as well as at cold storage temperature (4°C).[41] Corcoran et al.[42] had studied early (48 h) and mature (168 h) *Salmonella* biofilm against sodium hydroxide, sodium hypochlorite and benzalkonium chloride at 37°C. In their study all disinfecting agents had demonstrated reduction in the *Salmonella* viable cell count; however, none of the tested compounds eradicated mature biofilm[42] (Table 2). Sharma et al. [45,46] have studied the Poly (lactide)-Poly (butylene adipate-co-terephthalate) composite film incorporated with essential oil (cinnamon oil, thyme oil, eucalyptus oil and clove oil) and observed high *E. coli* biofilm inhibition. Clove oil composite film had inhibited *E. coli* biofilm by 93.43%, whereas cinnamon eucalyptus and thyme oil composite film exhibited biofilm inhibition by 89.82%, 84.37%, and 82.30%, respectively.[45,46]

Deterioration of the materials and articles

Deterioration is one of the major challenges for the food industry as once the FCMs get deteriorate or corrode then they are of no use.[63] The extracellular enzymes released by the microorganism attach to the surface and start cleaving the polymer chain. This led to the surface erosion of FCM. The eroded surface becomes more vulnerable to the growth of microorganism on it. To control and maintain the safety of the food article while confirming that the food is nutritious, available, and convenient is a big challenge for the food industry. It affects the substances and the materials like wood, paper etc., which is commonly used in food industry. The deterioration of the polymer surfaces is an interfacial process

Table 1. Biofilm formation on different surfaces and some solutions for biofilm removal.

Microorganism	Surface	Treatments/Conditions	Results	Reference
E. coli	High-density polyethylene surfaces (HDPE) and stainless-steel surfaces	• Static storage conditions at 4 and 15°C for up to 168 hrs	• Biofilm attachment was observed at the beef fabrication temperature (15°C) and at cold storage temperature (4°C)	[41]
Vibrio parahaemolyticus	Stainless steel surface, shrimps, crabs	• Different temperatures of 4, 10, 15, 20, 25, 30, and 37°C	• Strong biofilm formation was observed at 25– 37°C on food and food contact surfaces	[47]
Salmonella enterica	Stainless steel, borosilicate glass, polycarbonate plastic and concrete	• Disinfectant (sodium hydroxide, sodium hypochlorite, benzalkonium chloride) was used.	• Disinfecting agents reduced the viable cell count • None of the tested compounds eradicated mature (168 h) biofilm	[42]
E. coli	Polylactic acid and polybutylene adipate-co-terephthalate	• Clove oil and thyme oil were used as active agent.	• *E. coli* biofilm was grown at 37°C for 72 hrs • Clove oil composite film had inhibited biofilm by 93.43% • Thyme oil composite film had inhibited by 82.30%	[45]
Bacillus subtilis	Stainless steel (SS)	• Efficacies of organic acid (citric, malic, and gallic acids) treatments at 1% and 2% were studied	• The biofilm was grown at 37 ° for 24, 48, or 72 hours • Concentration increase of sanitizers on 24-h biofilm with 20 min showed higher reduction	[48]
L. monocytogenes	Stainless steel and polypropylene surfaces	• Extracts of grape stems from red Globe and Carignan were studied	• Inhibited the adhesion of *L. monocytogenes* on both surfaces	[43]
E. coli	Polylactic acid and polybutylene adipate-co-terephthalate	• Cinnamon oil and eucalyptus oil were used as active antimicrobial agent	• *E. coli* biofilm was grown at 37°C for 72 hrs • Cinnamon oil composite film had shown 89.82% biofilm inhibition and eucalyptus oil film inhibited by 84.37%	[46]
Staphylococcus aureus	Stainless steel, high-density polyethylene, polypropylene	• Superheated steam was used	• High-density polyethylene and polypropylene needed 15 s of treatment for inactivation while steel requires only 10 s.	[49]
Salmonella spp.	Stainless steel, glass slides and polyurethane	• Trisodium phosphate and sodium hypochlorite	• Sodium hypochlorite treatments have resulted in countable numbers of cells. • On abiotic surfaces during the processing of poultry, trisodium phosphate has a strong potential to reduce the formation of biofilms.	[50]
Pseudomonas fragi	Polytetrafluoroethylene (PTFE), stainless steel 1.4404	• Enzymatic treatment (containing 1 < 2.5% Subtilisin, 1 < 2.5% α-amylase) and a non-foaming detergent	• Results indicate that bacterial biofilm is of concern in low temperature filling units of milk processing equipment. • For the cleaning of the PTFE-hose liner in the milk filling hose, enzymatic treatment showed good results.	[51]
Pseudomonas fluorescens	Stainless steel	• Four disinfectant (sodium hypochlorite, chlorine dioxide, acidic electrolyzed water or slightly acidic electrolyzed water) were tested	• The mature *P. fluorescens* biofilm showed certain resistance to all the disinfectants tested. • Lower dose of acidic electrolyzed water was effective and showed promising results.	[52]

(*Continued*)

Table 1. (Continued).

Microorganism	Surface	Treatments/Conditions	Results	Reference
Listeria monocytogenes	Stainless steel and propylene	• Protein solution was prepared with 5% skimmed milk and 0.5% Tween 80 in phosphate-saline buffer (PBS)	• The protein solution added to the surfaces of propylene and stainless steel is not a factor that intervenes in cell adherence.	[53]
Salmonella Enteritidis	electrolytic copper (99.9% Cu), brass (70% Cu), copper coated with tin, and stainless steel	• Benzalkonium chloride and sodium hypochlorite	• Electrolytic copper and brass have shown promising results in the prevention of *Salmonella enteritidis* biofilm formation.	[44]
Pseudomonas aeruginosa	Ion exchange membranes	• Quaternary amine groups on surfaces	• Used in desalting, concentrating and modifying products in seawater desalination, industrial wastewater treatment, and beverage and food engineering processes. • Quaternary amine groups on the surface facilitating the disruption of bacterial cell membranes. • The charged groups and the surface roughness determine the biofouling propensity of ion-exchange membranes.	[54]
Salmonella spp.	Glass with adhered cells	• Liposome-encapsulated thymol and carvacrol	• Antimicrobials were successfully encapsulated. • Short-term contact of 1 min was sufficient to inactivate glass-adhered *Salmonella spp.* and was reduced by 4 log CFU/cm^2	[55]

and depends directly on the conditions like pH, moisture, temperature existing at these surfaces. Microorganisms affect the structure and functions of the polymer surface in various different ways and make it unacceptable for use physically and chemically. Deterioration can be classified into two parts: chemical and physical.

In chemical deterioration, the material become spoilt, unsafe, or damaged due to some biochemical changes and the physical deterioration occurs when the material is physically damaged or disrupted by the growth or activities of the organisms. The FCM contains some intentionally added substances (IAS) such as additives, monomers, catalysts, and development aids are found in food contact and may contain some impurities and active compounds such as polymers, oligomers, by-products and degradation products which may be referred to as non-intentionally added substances (NIAS). Sometimes the product or the material may not necessarily be unsafe, but it is unacceptable as the appearance of the material has been compromised. Formation of biofilm on the food processing equipment's act as the source of contamination and material degradation. Tillner & Grob[64] had studied the compliance for the drinking water supply pipes and stated that the deterioration of the contact material could release substances into water which may affect human health. Moerman[65] had discussed various aspects of controlling deterioration of the food product contact surface such as silver bearing stainless steel surface, copper bearing stainless steel surface, N halamine surface functionalization (Table 3) or Titanium oxide nanoparticle coating on the surface.

European legislations: ensuring quiescence of FCMs

A legal EU Framework is provided by Regulation (EC) No 1935/2004.[59] It regularizes some fundamental postulates for the safety and inertness for all FCMs,[59] demands for the food contact material that do not change the constituent, odour, and taste of food in any unsuitable way or it should not release its components in the food to the level which harms human health. It sets out some requirements for the framework regulation. The selection of starting materials, with regards to compliance with Regulation EU 1935/2004[59] means that impurities, contaminants, and by-product in raw materials are taken into account, at least to the degree that they have the ability to migrate in the process of degradation of the food contact material. Additionally, it provides framework to set the special rule on the active and intelligent materials. It also powers to discourse EU measures for specific materials like plastics. It sets out the procedure to perform the assessments of safety according to European Food Safety Authority for the substance used to manufacture FCMs. Moreover, it also set rules for the labelling on the packaging which includes the instruction for use and the symbols for labelling FCMs.

To ensure the compliance with the standard specification for the manufacturing process of FCMs is given by Regulation (EC) No 2023/2006.[101] It ensures the fitness of the site and the awareness of the staff for the vital production steps and set guidelines for good manufacturing practice. It also assures the quality documentation and the maintenance of the system for quality control at the premises. Moreover, it looks after the selection of the best suitable starting material for the process of manufacturing considering the safety and inertness of the final product. For the scientific advice on biological threats related to food safety and foodborne diseases such as biofilm resistance, quantitative microbiological risk assessment, food hygiene, and microbiology etc., is given by the EFSA Panel on Biological Hazards (BIOHAZ).

There are some specific EU legislations for the production of certain FCMs like plastics materials, recycled plastic materials, regenerative cellulose film, ceramics, and active and intelligent materials (Table 2).

Regulation for setting limits on plastic materials

Regulation (EU) No 10/2011[15] is the most inclusive EU law on the plastics and articles. It had established the union list of the substances, which are authorized for the use in the production of plastic FCMs. It also sets out the rules for the plastic FCMs composition and restricts the use by setting regulations.

The safety and inertness of the plastic material is assured by setting out the specific migration limits. This limit specifies the maximum amount of substance allowed to migrate to the food. European Food Safety Authority (EFSA Panel on Food Contact Materials, enzymes and processing aids (CEP)) access the risk based on the data of toxicity of each specific substance.[56]

Recital 27 of Regulation 10/2011 concerns plastic multi-layers. In order to optimize the protection provided to the food with a functional barrier separating the layers from the food, FCM may consist of several layers of different plastics. Behind the barrier, non-authorized compounds can be used, provided that their levels of migration remain within detection limits and are not mutagenic, carcinogenic or toxic. In Articles 11–12 of the law, the migration limits are laid down. Multi-layers consisting of a mixture of many components, protected by Recital 28, are subject to similar specifications.[102] As shown in Table 2, to assure the complete quality of the plastic, Regulation 10/2011, Article 3(1)(b) stated that the release of substances from food contact materials and articles should not bring unacceptable changes in the composition of the food. According to good manufacturing practice it is feasible to manufacture plastic materials in such a way that they are not releasing more than 10 mg of substances per 1 dm^2 of surface area of the plastic material. Therefore, the overall migration limit of 10 mg/dm^2 results for a cubic contact surface containing 1 kg of food to a migration of 60 mg/kg food according to Regulation 10/2011.[15] This migration test is done under standardized

Table 2. Legislations on food contact material.

Food Contact Material	Regulation	Comments	Reference
Plastics material	Regulation (EU) No 10/2011	• Sets out the Specific Migration Limits. • Overall migration limit of 60 mg/kg food • Requires Declaration of Compliance (DoC)	[15]
Recycled plastic materials	Regulation (EC) No 282/2008	• Control the process of recycling • Authorise the recycling process • Risk assessment of substance is done	[16,56]
Regenerative cellulose film	Commission Directive 2007/42/EC	• Specific provisions for the synthetic casing of regenerated cellulose • Must be among the defined three types of regenerative cellulose film	[57]
Ceramic	Directive 84/500/EEC	• Set limit for the leachable quantities of the cadmium (0.1 mg/l) and lead (1.5 mg/l) • Provision are different in all Member States • The community market which has uniform rules and harmonized limit value, tests and analysis	[58]
Active and intelligent material	Regulation (EC) No 450/2009	• Establishment of a Union list of substances permitted for the manufacture of active and intelligent materials. • Safety assessment of a substance or of a combination of substances • Rules stated in this regulation must apply without any prejudice to the provisions of the community that regulate such materials.	[18]
Glass	Regulation (EC) No 1935/2004	• The lead leaching from the glass table wares into the food stuff concerns (Council of Europe Policy Statement).	[59]
Cork	Regulation (EC) No 1935/2004	• Cork stoppers and cork materials generally used as a top cover of a drink concerns (Council of Europe Policy Statement)	[59]
Paper and board	Regulation (EC) No 1935/2004	• Paper or cardboard used as a packaging material. • It needs to meet the requirements of food contact materials legislation, including the composition of any dyes etc that may have been used in its manufacture • Council of Europe Policy Statement concerning paper and board materials	[59]
Hygiene of foodstuffs	Regulation (EC) No 852/2004	• Improving the quality of food by bringing EU standards into line with new international standards • Ensuring effective food safety controls for donations of food • Reducing food wastage • Labelling and handling of allergens	[60]
Drinking water quality	Council Directive 98/83/EC	• Concerns the water quality • Protect human health from the harmful effects of any water contamination intended for human use by making sure it is safe and clean.	[61]
Product of animal origin intended for human comsumption	Regulation (EC) No 854/2004	• Products of animal origin are regulated. • In addition to Regulation (EC) No 882/2004, it ensures verification of compliance with the requirements of feed and food law, animal health, and animal welfare.	[62]

conditions. A Declaration of Compliance (DoC) is needed to ensure the quality and safety of the plastic material (Table 2). This DoC is prepared on the basis of the supporting documents which reason the safety of plastic FCMs.

The regulation also states "Plastics can also be made by micro-organisms that create macromolecular structures out of starting substances by fermentation processes. The macromolecule is then either released to a medium or extracted. Potential health risk may occur from the migration of non- or incompletely reacted starting substances, intermediates or by-products of the fermentation process. In this case the final product should be risk assessed and authorized before its use in the manufacture of plastic materials and articles." Substances that are not included in the Union list when used as additives, natural or synthetic polymeric substances having a molecular weight of at least 1000 Da, with the exception of macromolecules obtained through microbial fermentation, comply with the specifications of this Regulation, provided that they are capable of functioning as the main structural component of the final articles.

Table 3. Recent development in the type of approaches to develop antimicrobial FCM.

Approach	Antimicrobial agent	Concentration	Comment	Reference
Surface Coating	Microparticles of $CaCO_3$	• 0.3 M • 20 mg	• Mitigate the initial burst release of antimicrobial agent. • Reduce the release rate. • Improvise the functional and • storage stabilities of immobilization	[66] [67]
	Ions (Silver, Titanium, Copper, Zinc)	• Studied different concentrations (2, 1, 0.7, 0.5, 0.3 and 0.1% (w/w))	• High antibacterial activity due to higher release of Ag+ • Promising for active food packaging applications • Exhibited high transparency, UV blocking property, particle low release and antimicrobial property.	[68,69,70]
	Zwitter ionic	• 2 mg/ml	• Simple, useful, and versatile modification • Zwitterion modifications demonstrated superior fouling resistance	[71,72]
	Quaternary ammonium compounds,	• 10 wt% of hyperbranched polyurea polyethyleneimine coating	• Reduce the incidence of biomaterial-associated infection • Inactivate microorganisms by disrupting the cell membrane and the cytoplasmic membrane through hydrophobic interactions.	[64,73,74]
	Nanoparticles (Ag, Au, Zn, ZnO, TiO_2, MgO)	• Different concentrations (1, 5, and 10 mg/mL)	• Show high-performance abilities. • Copper has been shown to be an efficient sensor for humidity • Titanium oxide has resistance to abrasion and UV-blocking performance. • TiO_2 loading on the cutting board has significant effect on the log reduction.	[68,75,76,77,78]
Surface Modification/ Functionalization	N-alkylated Poly(ethyleneimines), poly (ethylene terephthalate), polyethylene	• 0.1 mol ethylene glycol monovinyl ether	• Specific surface and bulk coating concentrations can be achieved as desired using a single class of antimicrobial additives. • greater efficacy, in particular, rather high efficacy against Gram-positive bacteria, • Improve safety and inertness of the article.	[64,79,80]
	N-halamine group	• 0.2 g of Silica-poltstyrene- 5,5-dimethylhydantoin was dispersed into 20 mL of sodium hypochlorite solution	• Barbituric acid-based N-halamine nanoparticles have higher bactericidal • Disinfection of hygienic areas, water purification, and food packaging	[81,82,83,84]
	High Intensity ultrasound	• 20 to 40 kHz for 1–2 sec	• Disinfection processes • That it can be used for continuous disinfection at fast process lines	[85]

(*Continued*)

Table 3. (Continued).

Approach	Antimicrobial agent	Concentration	Comment	Reference
Natural antimicrobial	plant essential oil	• At different concentrations according to the nature of use	• Plant essential oils are Generally Recognized as Safe (GRAS) • High efficiency and cost effective	[86,87,88]
	Polyphenols from fruit peel extract and juice	• At different concentrations according to the nature of use.	• Fruits extract and juices has many phenolics, polyphenols and flavanoids which exhibits antimicrobial activity • Less toxic chemical and physical crosslinkers • good physical properties for food applications by direct contact.	[89,90,91,92]
	Lysozymes, Lactoferrin, lactoperoxidase	• 0.1% – 0.7% (w/w)	• Strongly reduced the specific growth rate of bacteria • Enhances antibacterial efficiency against gram-negative bacteria.	[93,94,95]
	Chitosans,	• 1.5% (w/w) • 0.8% (w/v)	• Antimicrobial functionalized film • Lower oxygen and carbon dioxide permeability	[96,97,98]
Plasma Pre-treatment	Charged and neutral particles	• Usually RF discharge (13.56 MHz, 100 W); Could be adjusted according to the requirement.	• Dry chemical method • Apply immediately	[14,99,100]

The rules for the specification of any new plastic substance are set out by Regulation (EU) No 10/2011,[15] but the plastic material does not adhere to this regulation if these materials are used. To control the process of recycling a separate law exists. Regulation (EC) No 282/2008[16] regulates on the recycled plastic substances which deliberately comes in food contact. The regulation states that the recycled plastic materials and the article should be derived only from the authorized recycling process. In order to be approved, Article 4 of Regulation 282/2008[16] lays down the conditions under which a recycling process must comply, including the input of plastic materials and articles.[102] For the authorization of recycling process, it requires the details like the name of the process of recycling, short description of the process, any restriction in the input of plastic, characterization of recycled plastic, conditions on the application of recycled plastic etc. Plastic input is the plastic materials which are sorted post use in the process of recycling support sustainability. There are the loops for the products, which are in a closed and controlled chain. There is also some challenge test which shows the efficiency of the recycling process for the removal of the other chemical constituents from the plastic material or article. The person ensuring the requirements of this regulation are met is known as the converter. EFSA performs the risk assessment of the substances and provides scientific advice to the decision-makers.

The risk assessment of a substance to be performed by the EFSA should cover the substance itself, relevant impurities and foreseeable reaction and degradation products in the intended use. The risk assessment should cover the potential migration under worst foreseeable conditions of use and the toxicity.

Regulation ensuring safe use of regenerative cellulose film

Commission Directive 2007/42/EC of 29 June 2007 relates to the regenerated cellulose film materials and articles which come into contact with food (Table 2). This law had been significantly amended several times. It provides the specific provisions for the synthetic casing of regenerated cellulose. The method to determine the absence of colouring matters migration should be set at the later stage. The national provision must remain effective until the analysis method and the indicator of purity are pulled up. To fulfill the intent set out in Article 3(1) of Regulation (EC) No 1935/2004[59] provides the list of the approved substances with their limits to the usage quantity. For example, di-ethylene glycol and mono-ethylene glycol could migrate tremendously to certain food products; therefore, it is important to follow the maximum authorized quantity of such material in the food after contact with regenerative cellulose film[103,104] The direct contact between the printed surface and the food must be avoided to protect the consumer's health. The regenerative cellulose film must be among the following three types[59]:

- Uncoated regenerated cellulose film;
- Coated regenerated cellulose film with coating derived from cellulose; or
- Coated regenerated cellulose film with coating consisting of plastics.

Law directing the designing of the ceramic materials

Directive 84/500/EEC of October 15[58] was the legislation to be followed to ceramic articles intended to come into contact with food by the Member States (Table 2). Ceramic articles are those articles, which are produced by the mixture of inorganic material which is in high quantity, whereas organic material may be present in smaller quantity. These articles could be enameled, glazed, and decorated. In many Member States, there is a compulsory attention to the articles made of ceramic to secure human health. As mentioned in Table 2, there is a limit for the leachable quantities of the cadmium (0.1 mg/l) and lead (1.5 mg/l) .[58] I If these ceramic articles are placed in the community market, this has uniform rules and harmonized limit value (less than or equal to 0.01 mg/l of cadmium and 0.1 mg/l of lead), tests and analysis for ceramic articles. Article 3 of Directive 76/893/EEC; act as a suitable instrument to attain this objective. The Directive holds the possible migration of the cadmium and lead from the finished state of the ceramic article which is intended to come in contact with the food or purposefully made in contact with food.

Legislation on the active and intelligent material

Active and intelligent materials extend the shelf-life by maintaining or improving the condition, by releasing or absorbing substances to or from the food or its surrounding environment.[59] As a result, they are exempted from the general inertness rule in Regulation (EC) No 1935/2004.[59] Regulation (EC) No 450/2009[18] specific rules for their specific purposes like the absorption of substances such as oxygen and liquid from the interior of the food packaging, indication of the expiry of food through the colour changing labelling which changes colour when the storage temperature is exceeded, or the shelf life is maximum or the substance like preservatives are released in the substances. An active material does not include any system that absorbs the substances entering from the atmosphere like the active oxygen barriers.

Regulation (EC) No 450/2009[18] envisions the establishment of a union list of substances permitted for the manufacture of active and intelligent materials (Table 2). There are varieties of active and intelligent materials and articles exist.[18] The substances that are responsible for the active or intelligent function could be contained in a separate container, for example, the substances can be directly incorporated in the packaging material or inclusion in a small paper sachet.[104] Those substances which are responsible for the active and intelligent functioning should be evaluated in accordance with this regulation. The packaging material and the packaging in which the container is placed and packaging in which the substance is incorporated are covered by the specific community. These materials may be composed of one or more layers, or parts of different types of materials, such as plastics, paper and cardboard or coatings and varnishes. The rules stated in this regulation must apply without any prejudice to the provisions of the Community that regulate such materials.

Regulation (EC) No 1935/2004 provides[59] that those substances must undergo the safety assessment prior to their authorization, if the substances in the list authorized within the community for use in the manufacture of materials and articles intended to come into contact with food. In accordance with Articles 9 and 10 of Regulation (EC) No 1935/2004[59], the safety assessment of a substance or of a combination of substances, which is comprised of the active and intelligent components should be carried out by the EFSA(Table 2).

They are intentionally designed to incorporate active and intelligent components that would absorb or release the substances into or from the surrounding environment to food. They also monitor the packaged food condition. 'Component' is an individual substance or a combination of individual substances, which are responsible for the active and intelligent material or article function. 'Functional barrier' is a barrier comprising of one or more layers of food contact materials which assure that the product complies with Article 3 of Regulation (EC) No 1935/2004.[59] Those active materials and articles which are designed to purposefully incorporate components by the release of substances into or onto the packaged food or the environment surrounding the food are known as the 'releasing active materials and articles'.

Legislation on the use of nanomaterial

Recent research development led to the increase in use of nanoparticles in the food contact surface which are subject to authorize before being permitted for use. The EU Commission Recommendation 2011/696/EU introduces nano materials in the area of FCM and defines it as "a natural or manufactured material having particles for 50% or more in the size range of 1 nm-100 nm and its distribution in unbound/aggregated/agglomerated state".[15] The smaller size of several nanomaterials shows different physical and chemical properties from the larger or macro-size material. European Framework[59] lays the general ethics for the food contact materials, doesn't address the use of nanoparticle directly. Although Article 3 states the general requirements for the use of "nanoform elements" in the FCM.

European Regulation (EU) No 10/2011[15] particularly discuss about the use of nanomaterials in the plastic materials or the articles that may come in contact with food.[15] Annex I of the Plastics

Regulation (Article 9) specifies that as the element changes its size from macro to nanoform, it could have different physico-chemical properties and toxicity; therefore, the authorization of the material will depend on its risk assessment.[105] European Regulation (EC) No 450/2009[18] on active n active and intelligent materials and articles[18] defines the use of elements in nanoform if the substance is not listed in the Union list and if it is present in the layer of the multilayer material and not in direct contact with food. However, the legal evaluation of the nanosubstance which are not included in the Union list like catalyst or colorant is still unclear.[105]

Table 2 also shows that Regulation (EC) No 1935/2004[59] states about other materials such as glass[59], cork, paper and board.[59] The lead leaching from the glass table wares into the food stuff concerns Council of Europe Policy Statement. Also, interaction of cork with wine and the transfer of elements from cork stopper to wine when cork was used to seal the bottles. A particular regulations for cork are listed in Resolution ResAP(2004)2, which has been adopted by the Committee of Ministers, for the agreement in the social and public health.[106] Paper or cardboard are also used as a packaging material. Paper or cardboard legislation also includes the composition of any dyes used for printing on it (Table 2).

Legislation on hygiene of food and food contact materials

As a general principle, legislation conceptualizing the culture of food safety was adopted. The EU introduced three basic acts in April 2004, which form the center of the 'Food Hygiene Package' that are: Regulation (EC) 852/2004[60] on the hygiene of foodstuffs[60] Regulation (EC) 853/2004[107] laying down specific hygiene rules for food of animal origin,[107] and Regulation (EC) 854/2004 laying down specific rules for the organization of official controls on products of animal origin intended for human consumption.[62]

Regulation (EC) No. 852/2004[60] allows food business operators in Europe, to develop, incorporate and manage ongoing procedures based on the concepts of Hazard Analysis and Critical Control Point (HACCP). Furthermore, through its incorporation into company policy, the food hygiene culture should be integrated in the perception of employees in such a way that food safety effects almost naturally from the actions of each employee. This is important for organizational hygiene at all levels to be implemented efficiently.[108] The scope of this regulation focuses on the following principles: (i) The operator of the food business is primarily responsible for food safety; (ii) The food safety must be ensured throughout the process; (iii) For food that cannot be safely stored at ambient temperatures, particularly frozen food, it is essential to maintain the cold chain; (iv) In relation to the development of good hygiene practices, general implementation of strategies focused on the HACCP principles should enhance the responsibility of food business operators; (v) Guides to good practice are a valuable tool to assist food business operators at all stages of the food chain to comply with food hygiene rules and to enforce the HACCP concept; (vi) Microbiological standards and temperature control specifications need to be defined based on a scientific risk assessment; (vii) It is important to ensure that the food imported has at least the same hygiene quality as the food produced in the Community, or that it is equal to that of the food produced in the Community.[60]

The Regulation (EC) 853/2004[107] sets down basic guidelines for food business operators on the hygiene of food of animal origin[107]. These rules are analogous to those defined by Regulation (EC) No 852/2004[60] Unprocessed and manufactured items of animal origin are subject to these provisions. However, this regulation shall not extend to foods containing both products of plant origin and processed products of animal origin. Processed animal products used for the preparation of such food mean to be obtained and processed in compliance with the requirements of this Regulation. Moreover, to ensure the compliance with microbiological standards implemented in accordance with Regulation (EC) No 852/2004[60]. Regulation (EC) No 854/2004 lays down specific guidelines for the organization of official evaluations of products of animal origin consumed by humans[62] Animal products need to be check on the chemical, physical, organoleptic and microbiological criteria to be in compliance with the relevant Community legislation.

Approaches used to inhibit microbial growth on FCMs

Several approaches are used to prohibit the growth of microorganism (Table 3) on the FCMs. Approaches such as the incorporation of the antimicrobial agent in the surface materials,[109] by coating surfaces with antimicrobials agent or by modifying the physiochemical property of the surfaces,[110] active packages with the incorporation of new and natural compounds are used. Recent research is focused on the use of innovative and effective technologies like use of nanoparticle[111,112] or by the pre-treatment by plasma.[111,113]

Design of hygiene surface coating

Designing a hygiene surface coating had been focused by the researchers since a decade considering the challenges faced by the food industry.[32] The antibacterial surfaces were categorized according to the physical and chemical changes made on the surface. Antimicrobial coatings resist the initial attachment of the microorganism on the surface by inactivating the cell and exhibiting cell death. In the fabrication of the antibacterial surfaces the application of surface coatings is frequently applied. These coatings include ions silver, titanium,[114] copper and zinc,[68] nanoparticles,[115] zeolites[116] and zwitter ions.[117]

In a study on control for biofilm, microparticles of $CaCO_3$ coated with benzyl-dimethyl-dodecyl-ammonium chloride were found to inactivate the formation of biofilm effectively.[118] Silver surface coating was reported by many other researchers for the inhibition of biofilm formation.[109,119] Prevention of bacterial adhesion has also been reported by the pre-conditioning of the surface.[120] Zeraik and Nitschke (2010)[121] demonstrated in their research that the surface became more hydrophilic after conditioning with surfactant. The data illustrated the treated surfaces decrease in hydrophobicity and had shown a significant decrease in the attachment of bacteria had developed surface which has coating with zwitter ionic polymer like poly (sulfobetaine methacrylate) and poly(carboxybetaine methacrylate) which showed resistant effectively and prevented the biofilm formation.[122]

Immobilization technology has been developed extensively in the past two decades.[123] Now the technology is advancing for the use of organo-silanes to improve mechanical, chemical and physical properties of the material. The carbon silicon bond is a non-polar stable bond. In the presence of an alkyl group it gives rise to hydrophobicity and low surface energy.[124] Organo-silane are environment friendly, improve cell adhesion and provide better protection against corrosion.[124]

Silver-based antimicrobial coatings releases silver ions from the surface and show bactericidal effect against both gram-positive and gram-negative bacteria.[68,125] Hydroxyapatite (HA) and Quaternary ammonium compounds were also reported to exhibit antimicrobial properties. However, HA coatings were not found to be long lasting, whereas microorganism were observed to develop resistance on QAC coatings.[126] The combinational compounds like silver doped silica film,[127] silver doped titanium,[128] titanium doped iron and silver doped HA coatings[14] were reported to have potential resistant against microorganisms.

Coating of a nanostructured material on the FCMs is the emerging technology through a wide range of exploration in the research. Design and development of the nanoparticles coating, which could be used in the variety of industrial application is the main focus of the researchers. These nanostructure materials could be released on the surface for a longer duration of time which could prevent the growth of pathogenic bacteria and avoid food spoilage had coated TiO_2 nanoparticle on the chopping board surface and found a significant log reduction on bacterial growth.[77,78] Although several shortcomings were also reported for the use of antimicrobial surface coatings. The antimicrobial agent takes time to release from the surface and the optimized concentration must be effectively maintained. The microorganisms were also reported to develop resistance against the antimicrobial coating.[65,114]

Surface modification and functionalization

Development of different methods for the modification of surfaces had led to the improvement in the safety and inertness of the article. Use of wet chemicals, UV radiations and adhesion are used to add a variety of polar group to the surface. Modification of the surfaces necessarily require the attachment of bioactive compound; therefore, these techniques must add a specific functional group the surface.[129] The first step for the surface modification is the selection of the polymer considering the properties like elasticity, conductivity, strength, type of material (synthetic or natural) and degradability. Immobilization of biomolecule or the functionalization of surfaces is considered according to the application of the surface. Therefore, the second step is to enhance the functionalization 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.[129] Addition of a spacer molecule for harnessing the bioactive compound on a solid surface also increases the bioactivity. It reduces the steric hinderance and covers the compound from hydrophobic surface. The final step is the covalent attachment of the natural or the synthetic bioactive compound to the functionalized polymer surface.[129]

The surface modification is done either by atom radical transfer or by covalent bonding. Some antibacterial properties are studied on the surfaces, which is chemically bounded (hydrophobic polycations of quaternary ammonium salt). Studies exhibit that higher the molecular weight of the chain (N-alkylated Poly(ethyleneimines)) more is the antibacterial property.[14] Alkylated PVP and benzyl PVP are the polyvinyl pyridine-based polymers which are the phosphonium or the sulphonium or the polycationic quaternary ammonium salts. The antimicrobial property of these polymers depends on the length of the chain. Dimethyl-diocta-decyl-ammonium (DDA) bromide-based polymers have DDA as the end group. The presence of satellite group (methyl, hexadecyl, decyl) are the deciding factors of the antibacterial activity. Polymers with oxidative halogen group (Cl^+, Br^+) are the polymeric compounds with the N-halamine group which exhibits antibacterial properties. The compounds having amphiphilic quaternary dimethyl ammonium compounds having oxyethylene and n-alkyl groups are synthesized and designed as the surfaces which has self-decontaminating properties.[130] Immobilization of the antibacterial agent on the FCM by of physicochemical adsorption method is also surface modification approach. These antibacterial agents could be antibacterial polymer, enzymes and peptides immobilized on a polymeric surface like poly(methacrylate) and poly (hexamethylene bi-guanidinium hydrochloride).[131]

Another one of 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.[132] The surfaces modified ultrasonically have the microcavities in which different chemicals such as antimicrobial agents could be stored.[132] The interfaces of ultrasonically modified surfaces are very rough; therefore, they provide excellent adhesion for the inorganic and the organic coatings. The development of the industrial application for the modification and functionalization of the solid surface by the ultrasonic irradiation is focused by the researchers.

Naturally inspired antimicrobial agent

The natural compounds studied as an antimicrobial agent are derived from plant, animal, microorganisms. The essential oils derived from different plants like basil, oregano, thyme, clove, rosemary and cinnamon. The plant essential oils are Generally Recognized as Safe (GRAS). Gutierrez, Barry-Ryan, and Bourke[133] studied that the plant essential oil fractions are commonly found with the active components which are effective against a wide range of spoilage bacteria and foodborne pathogens. The presence of hydrophilic functional group like the lipophilicity of some essential oil components and the hydroxyl group of phenolic components are responsible for the antimicrobial activity of the plant essential oils. Soni et al.[134] studied the antimicrobial activity of carvacrol on the polystyrene and stainless-steel surfaces. They had used carvacrol of 0.05% – 0.1% for an hour which lead to the reduction of *Salmonella spp* by 7 log CFU.[134] Campana et al.[135] had formulated three micro-emulsion with essential oils (*C. cassia, S. officinalis* or both) and tested against the biofilm of *S. aureus* with 90 minutes of exposure time and observed more than 3 log reductions and 68% biofilm removal.[135]

Defensins are cationic peptide which exhibits antimicrobial activity against Gram positive and Gram-negative bacteria, fungi and viruses. Lysozymes are antimicrobial against *C. tyrobulyricum, B. micrococcus* and *L. monocytogenes*.[136] Bacteriocin are obtained from microbial sources. Few examples of bacteriocin are nisin, caseicin, alveicin, lactocin etc. Bacteriocin are the small peptides which are produced in bacteria and exhibits a strong antimicrobial activity against closely related bacteria. Arevalos-Sánchez et al.[137] had used nisin of 6.75×10^{-3} ppm for 5 min at 20°C on the stainless-steel surface. They observed a reduction of *Listeria monocytogenes* by 2.58 log CFU/cm^2.[137] In addition to this study, they had used nisin on the glass surface at 6.75×10^{-3} ppm for 20 min at 20°C and observed the reduction of *Listeria monocytogenes* by 1.92 log CFU/cm^2.[137]

Surface pre-treatment with plasma

Plasma technology is new upcoming technology, which is highly effective and environment-friendly. Plasma could be defined as the mixture of charged and the neutral particles. It consists of positively and negatively charged ions, charged and neutral atoms and molecules and electrons. The plasma has the illumination characteristics which are due to the emission of radiation by the excited species. In the plasma, the reactive species forms the radical site throughout the molecular chain where the polar groups could attach. Primarily the oxygenated groups like carbonyl (-CO), carboxylic (-COOH) and hydroxyl (-OH) are bonded to the upper molecular layer and therefore, changes the polarity of the surface by transforming it to polar from a non-polar surface. The change in polarity results in enhanced bonding strength as the interaction between the functional groups and the active surface is firm. Moreover, the energy input and surface functionalization results in the roughening of the surfaces at the μm range which results in the firm coating. Conte et al.[138] had tested the antimicrobial activity of the plasma processed polyethylene film followed by the immobilization of lysozyme. In their study, they found that the plasma treated film with immobilization of lysozyme exhibit more active antimicrobial property.[138]

To be pre-treated with plasma, the surface must be compatible for the process. The surface needs to be very clean, and it must be proactive to form the adhesive bond with the coating. During the ultra-fine cleaning, the reactive species present in the plasma converts the organic layer to the gas phase and with the polymer the functional group will attach and transform its polarity which was required for the adhesive bonding with the surface. The plasma has the reactive species enables the polymer surfaces to be finely cleaned without any use of chemicals, therefore, its environment friendly. Plasma coating process is the dry chemical method which helps in the applying the coating immediately. The coating applied by plasma is anti-corrosive, anti-microbial, scratch-resistant and adhesive. Theapsak, Watthanaphanit, and Rujiravanit[139] reported that chitosan films along with dielectric barrier discharge (DBD) plasma treatment shows good potential abilities for use.[139] Concentration of higher functional group is linked to the antibacterial behavior; therefore, more work is needed to determine the density of the functional group and optimize antimicrobial behavior. Karam et al.[140] had conducted a study to investigate the absorption of nisin on the plasma treated polymer surface and observe its antimicrobial property. They had modified low density polyethylene (LDPE) with argon/oxygen plasma, nitrogen plasma and plasma-induced grafting of acrylic acid. They found that the highest antibacterial activity was exhibited by the argon/oxygen plasma treated LDPE followed by acrylic acid plasma grafted, and nitrogen plasma treated film and lowest antimicrobial activity was found on the non-treated native native surface.[140] Rtimi et al.[100] had stated stated that on TiO_2 coated chopping board, plasma treatment enhanced the bactericidal property without affecting the physical stability.[100]

Conclusion

Food industries faces major challenges in the form of contamination of allergen and microorganism from surface to food, formation of biofilm on food contact material, microbially influenced corrosion of FCMs and biodeterioration of materials. The adhesion of the bacterial cell depends on the physiochemical properties of the surface. Contaminated packaging material may also lead to the contamination of ready to eat food. Legal EU Framework is provided by Regulation (EC) No 1935/2004[59] and it regularizes some fundamental postulates for the safety and inertness for all FCMs. EU standard quality assurance systems develops the framework to improve and maintain the quality and safety of the food in food industry. There are some specific EU legislations for the production of certain FCMs like plastics materials, recycled plastic materials, regenerative cellulose film, ceramics and active and intelligent materials. To ensure safe food they are required at each step in the food production process and to show compliance with regulatory and customer requirements. However, there is a need of developing the novel coating technology which would have dual function such as prevention of the initial attachment of bacteria and debarment of formation of biofilm, or a multi-functionality will be attained by two or more functional element. Greater considerations are also given in modifying the surface topography in order to make the antibacterial or anti-biofouling FCM surface. A dual functionality antimicrobials coating and nanoscale surface topology will have a potential application in all processing areas of the food industry to improve safety and inertness of the FCM while maintaining the quality of food and also compile with European legislation.

Acknowledgments

Authors would like to acknowledge the funding from Technological University Dublin - City Campus under the Fiosraigh Scholarship programme, 2017.

ORCID

Shubham Sharma http://orcid.org/0000-0003-4098-6313
Amit K. Jaiswal http://orcid.org/0000-0002-4551-4182
Brendan Duffy http://orcid.org/0000-0003-2471-9063
Swarna Jaiswal http://orcid.org/0000-0003-1414-9052

Conflicts of interest

The authors declare no conflict of interest.

References

[1] Srey, S.; Jahid, I. K.; Ha, S. D. Biofilm Formation in Food Industries: A Food Safety Concern. *Food Control*. 2013, 31(2), 572– 585. DOI: 10.1016/j.foodcont.2012.12.001.

[2] Yang, H.; Kendall, P. A.; Medeiros, L. C.; Sofos, J. N. Efficacy of Sanitizing Agents against *Listeria Monocytogenes* Biofilms on High-density Polyethylene Cutting Board Surfaces. *J. Food Prot*. 2009, 72(5),990– 998. DOI: 10.4315/0362-028X-72.5.990.

[3] Brooks, J. D.; Flint, S. H. Biofilms in the Food Industry: Problems and Potential Solutions. *Int. J. Food Sci. Technol*. 2008, 43(12), 2163– 2176. DOI: 10.1111/j.1365-2621.2008.01839.x.

[4] Galie, S.; García-Gutiérrez, C.; Miguélez, E. M.; Villar, C. J.; Lombó, F. Biofilms in the Food Industry: Health Aspects and Control Methods. *Front. Microbiol*. 2018, 9, 898. DOI: 10.3389/fmicb.2018.00898.

[5] Nahar, S.; Mizan, M. F. R.; Ha, A. J. W.; Ha, S. D. Advances and Future Prospects of Enzyme-Based Biofilm Prevention Approaches in the Food Industry. *Compr. Rev. Food Sci. Food Saf*. 2018, 17(6), 1484– 1502. DOI: 10.1111/1541-4337.12382.

[6] Chaturongkasumrit, Y.; Takahashi, H.; Keeratipibul, S.; Kuda, T.; Kimura, B. The Effect of Polyesterurethane Belt Surface Roughness on *Listeria Monocytogenes* Biofilm Formation and Its Cleaning Efficiency. *Food Control*. 2011, 22(12),1893– 1899. DOI: 10.1016/j.foodcont.2011.04.032.

[7] Hu, J.; Lin, J.; Zhang, Y.; Lin, Z.; Qiao, Z.; Liu, Z.; Yang, W.; Liu, X.; Dong, M.; Guo, Z. A New Anti-Biofilm Strategy of Enabling Arbitrary Surfaces of Materials and Devices with Robust Bacterial Anti-Adhesion via A Spraying Modified Microsphere Method. *J. Mater. Chem. A*. 2019, 7(45), 26039– 26052. DOI: 10.1039/C9TA07236E.
[8] Hua, G.; Reckhow, D. A. Comparison of Disinfection Byproduct Formation from Chlorine and Alternative Disinfectants. *Water Res*. 2007, 41(8),1667–1678. DOI: 10.1016/j.watres.2007.01.032.
[9] Brodowska, A. J.; Nowak, A.; Śmigielski, K. Ozone in the Food Industry: Principles of Ozone Treatment, Mechanisms of Action, and Applications: An Overview. *Crit. Rev. Food Sci. Nutr*. 2018, 58(13), 2176– 2201. DOI: 10.1080/10408398.2017.1308313.
[10] Miller, F. A.; Silva, C. L.; Brandão, T. R. A Review on Ozone-based Treatments for Fruit and Vegetables Preservation. *Food Eng. Rev*. 2013, 5(2),77–106. DOI: 10.1007/s12393-013-9064-5.
[11] Pereira, R.; Vicente, A. Environmental Impact of Novel Thermal and Non-Thermal Technologies in Food Processing. *Food Res. Int*. 2010, 43(7),1936–1943. DOI: 10.1016/j.foodres.2009.09.013.
[12] Casariego, A.; Souza, B.; Vicente, A.; Teixeira, J.; Cruz, L.; Díaz, R. Chitosan Coating Surface Properties as Affected by Plasticizer, Surfactant and Polymer Concentrations in Relation to the Surface Properties of Tomato and Carrot. *Food Hydrocoll*. 2008, 22(8), 1452– 1459. DOI: 10.1016/j.foodhyd.2007.09.010.
[13] Yu, Q.; Wu, Z.; Chen, H. Dual-Function Antibacterial Surfaces for Biomedical Applications. *Acta Biomater*. 2015, 16, 1–13. DOI: 10.1016/j.actbio.2015.01.018.
[14] Hasan, J.; Crawford, R. J.; Ivanova, E. P. Antibacterial Surfaces: The Quest for a New Generation of Biomaterials. *Trends Biotechnol*. 2013, 31(5),295–304. DOI: 10.1016/j.tibtech.2013.01.017.
[15] Commission, E. Commission Regulation (EU) No 10/2011 of 14 January 2011 on Plastic Materials and Articles Intended to Come into Contact with Food. *Off. J. Eur. Union*. 2011, 12(1), 1– 89.
[16] EC, Commission regulation (EC) No 282/2008 of 27 March 2008 on Recycled Plastic Materials and Articles Intended to Come into Contact with Foods and Amending Regulation (EC) No 2023/2006. *Off. J. Eur. Union L*. 2008, OJ L86, 9 – 18.
[17] Commission Directive 2007/42/EC of 29 June 2007 Relating to Materials and Articles Made of Regenerated Cellulose Film Intended to Come into Contact with Foodstuffs. *Off. J. Eur. Union L*., 22, 120–131.
[18] Commission, E. Commission Regulation (EC) No 450/2009 of 29 May 2009 on Active and Intelligent Materials and Articles Intended to Come into Contact with Food. *Off. J. Eur. Union*. 2009, 135, 3– 11.
[19] Trienekens, J.; Zuurbier, P. Quality and Safety Standards in the Food Industry, Developments and Challenges. *Int. J. Prod. Econ*. 2008, 113, 107–122.
[20] Watling, H.; Watkin, E.; Ralph, D. The Resilience and Versatility of Acidophiles that Contribute to the Bio-assisted Extraction of Metals from Mineral Sulphides. *Environ. Technol*. 2010, 31(8–9), 915–933. DOI: 10.1080/09593331003646646.
[21] Duan, J.; Wu, S.; Zhang, X.; Huang, G.; Du, M.; Hou, B. Corrosion of Carbon Steel Influenced by Anaerobic Biofilm in Natural Seawater. *Electrochim. Acta*. 2008, 54(1), 22– 28. DOI: 10.1016/j.electacta.2008.04.085.
[22] Dong, Y.; Jiang, B.; Xu, D.; Jiang, C.; Li, Q.; Gu, T. Severe Microbiologically Influenced Corrosion of S32654 Super Austenitic Stainless Steel by Acid Producing Bacterium *Acidithiobacillus caldus* SM-1. *Bioelectrochemistry*, 2018, 123, 34–44.
[23] Purwasena, I. A.; Astuti, D. I.; Fauziyyah, N. A.; Putri, D. A. S.; Sugai, Y. Inhibition of Microbial Influenced Corrosion on Carbon Steel ST37 Using Biosurfactant Produced by *Bacillus Sp. Mater. Res. Express*. 2019, 6 (11),115405. DOI: 10.1088/2053-1591/ab4948.
[24] Stoodley, P.; Sauer, K.; Davies, D. G.; Costerton, J. W. Biofilms as Complex Differentiated Communities. *Ann. Rev. Microbiol*. 2002, 56(1),187–209. DOI: 10.1146/annurev.micro.56.012302.160705.
[25] Addis, M.; Sisay, D. A Review on Major-Food Borne Bacterial Illnesses. *J. Trop. Dis*. 2015, 3(4), 176– 183.
[26] Scott, E. Relationship Between Cross-Contamination and the Transmission of Foodborne Pathogens in the Home. *Pediatr. Infect. Dis. J*. 2000, 19(10), S111– S113. DOI: 10.1097/00006454-200010001-00005.
[27] Bedford, B.; Liggans, G.; Williams, L.; Jackson, L. Allergen Removal and Transfer with Wiping and Cleaning Methods Used in Retail and Food Service Establishments. *J. Food Prot*. 2020, 83(7), 1248– 1260. DOI: 10.4315/JFP-20-025.
[28] Chatterjee, A.; Abraham, J. Microbial Contamination, Prevention, and Early Detection in Food Industry. In *Microbial Contamination and Food Degradation*; Academic Press University of Bucharest, Bucharest, Romania, 2018, 21– 47.
[29] Nerin, C.; Aznar, M.; Carrizo, D. Food Contamination During Food Process. *Trends Food Sci. Technol*. 2016, 48, 63– 68. DOI: 10.1016/j.tifs.2015.12.004.
[30] Medrano-Félix, A.; Martínez, C.; Castro-del Campo, N.; León-Félix, J.; Peraza-Garay, F.; Gerba, C. P.; Chaidez, C. Impact of Prescribed Cleaning and Disinfectant Use on Microbial Contamination in the Home. *J. Appl. Microbiol*. 2011, 110(2), 463– 471. DOI: 10.1111/j.1365-2672.2010.04901.x.
[31] Lim, S. M.; Lim, E. S.; Kim, J. S.; Paik, H. D.; Koo, O. K. Survival of Foodborne Pathogens on Stainless Steel Soiled with Different Food Residues, *Food Sci. Biotechnol*. 2020, 29, 729–737. DOI: 10.1007/s10068-019-00705-6

[32] Lelieveld, H. L.; Holah, J.; Gabric, D. Handbook of Hygiene Control in the Food Industry; Second edition, Woodhead Publishing, UK, 2016.
[33] Sharma, S.; Jaiswal, A. K.; Duffy, B.; Jaiswal, S. Ferulic Acid Incorporated Active Films Based on Poly (Lactide)/ poly (Butylene Adipate-co-terephthalate) Blend for Food Packaging. *Food Pack. Shelf Life*. 2020a, 24, 100491. DOI: 10.1016/j.fpsl.2020.100491.
[34] Hollmann, B.; Perkins, M.; Walsh, D. Biofilms and Their Role in Pathogenesis. *British Society for Immunology*, 2014. https://www.immunology.org/public-information/bitesized-immunology/pathogens-anddisease/biofilms-and-their-role-in (accessed on 20 February 2021)
[35] Sauer, K. The Genomics and Proteomics of Biofilm Formation. *Genome Biol*. 2003, 4(6), 1– 5. DOI: 10.1186/gb-2003-4-6-219.
[36] Vasudevan, R. Biofilms: Microbial Cities of Scientific Significance. *J. Microbiol Exp*. 2014, 1(3), 00014. DOI: 10.15406/jmen.2014.01.00014.
[37] Shi, X.; Zhu, X. Biofilm Formation and Food Safety in Food Industries. *Trends Food Sci. Technol*. 2009, 20(9), 407– 413. DOI: 10.1016/j.tifs.2009.01.054.
[38] Barroso, I. L. *Listeria Monocytogenes* Biofilms Produced under Nutrient Scarcity and Cold Stress: Disinfectant Susceptibility of Persistent Strains Collected from the Meat Industry in Spain, 2007.
[39] Kocot, A. M.; Olszewska, M. A. Biofilm Formation and Microscopic Analysis of Biofilms Formed by *Listeria Monocytogenes* in a Food Processing Context.*LWT- Food Sci. Technol*. 2017, 84, 47– 57. DOI: 10.1016/j.lwt.2017.05.042.
[40] Di Bonaventura, G.; Piccolomini, R.; Paludi, D.; D'orio, V.; Vergara, A.; Conter, M.; Ianieri, A. Influence of Temperature on Biofilm Formation by *Listeria Monocytogenes* on Various Food-Contact Surfaces: Relationship with Motility and Cell Surface Hydrophobicity. *J. Appl. Microbiol*. 2008, 104(6),1552– 1561. DOI: 10.1111/j.1365-2672.2007.03688.x.
[41] Dourou, D.; Beauchamp, C. S.; Yoon, Y.; Geornaras, I.; Belk, K. E.; Smith, G. C.; Nychas, G.J.E.; Sofos, J. N. Attachment and Biofilm Formation by *Escherichia Coli* O157: H7 at Different Temperatures, on Various Food-Contact Surfaces Encountered in Beef Processing. *Int. J. Food Microbiol*. 2011, 149(3),262– 268. DOI: 10.1016/j.ijfoodmicro.2011.07.004.
[42] Corcoran, M.; Morris, D.; De Lappe, N.; O'Connor, J.; Lalor, P.; Dockery, P.; Cormican, M. Commonly Used Disinfectants Fail to Eradicate *Salmonella Enterica* Biofilms from Food Contact Surface Materials. *Appl. Environ. Microbiol*. 2014, 80(4),1507– 1514. DOI: 10.1128/AEM.03109-13.
[43] Vazquez-Armenta, F. J.; Bernal-Mercado, A. T.; Lizardi-Mendoza, J.; Silva-Espinoza, B. A.; Cruz-Valenzuela, M. R.; Gonzalez-Aguilar, G. A.; Nazzaro, F.; Fratianni, F.; Ayala-Zavala, J. F. Phenolic Extracts from Grape Stems Inhibit *Listeria Monocytogenes* Motility and Adhesion to Food Contact Surfaces. *J. Adhes. Sci. Technol*. 2018, 32 (8),889– 907. DOI: 10.1080/01694243.2017.1387093.
[44] Pontin, K. P.; Borges, K. A.; Furian, T. Q.; Carvalho, D.; Wilsmann, D. E.; Cardoso, H.R.P.; Alves, A.K.; Chitolina, G.Z.; Salle, C.T.P.; de Souza Moraes, H.L.; do Nascimento, V.P. Antimicrobial Activity of Copper Surfaces against Biofilm Formation by *Salmonella enteritidis* and Its Potential Application in the Poultry Industry. *Food Microbiol*. 2021, 94, 103645. DOI: 10.1016/j.fm.2020.103645
[45] Sharma, S.; Barkauskaite, S.; Duffy, B.; Jaiswal, A. K.; Jaiswal, S. Characterization and Antimicrobial Activity of Biodegradable Active Packaging Enriched with Clove and Thyme Essential Oil for Food Packaging Application. *Foods*. 2020b, 9(8), 1117. DOI: 10.3390/foods9081117.
[46] Sharma, S.; Barkauskaite, S.; Jaiswal, A. K.; Jaiswal, A. K.; Jaiswal, S. Development of Essential Oil Incorporated Active Film Based on Biodegradable Blends of Poly (Lactide)/poly (Butylene Adipate co terephthalate) for Food Packaging Application. *J. Packag. Technol. Res*. 2020c, 4(3), 235– 245. DOI: 10.1007/s41783-020-00099-5
[47] Han, N.; Mizan, M. F. R.; Jahid, I. K.; Ha, S. D. Biofilm Formation by *Vibrio parahaemolyticus* on Food and Food Contact Surfaces Increases with Rise in Temperature. *Food Control*. 2016, 70, 161– 166. DOI: 10.1016/j.foodcont.2016.05.054.
[48] Akbas, M. Y.; Cag, S. Use of Organic Acids for Prevention and Removal of *Bacillus subtilis* Biofilms on Food Contact Surfaces. *Food Sci. Technol. Int*. 2016, 22(7),587–597. DOI: 10.1177/1082013216633545.
[49] Kim, S. H.; Park, S. H.; Kim, S. S.; Kang, D. H. Inactivation of *Staphylococcus aureus* Biofilms on Food Contact Surfaces by Superheated Steam Treatment. *J. Food Prot*. 2019, 82(9),1496– 1500. DOI: 10.4315/0362-028X.JFP-18-572.
[50] Sarjit, A.; Dykes, G. A. Antimicrobial Activity of Trisodium Phosphate and Sodium Hypochlorite against *Salmonella* Biofilms on Abiotic Surfaces with and without Soiling with Chicken Juice. *Food Control*. 2017, 73, 1016– 1022. DOI: 10.1016/j.foodcont.2016.10.003.
[51] Fysun, O.; Kern, H.; Wilke, B.; Langowski, H. C. Evaluation of Factors Influencing Dairy Biofilm Formation in Filling Hoses of Food-Processing Equipment. *Food Bioprod. Process*. 2019, 113, 39– 48. DOI: 10.1016/j.fbp.2018.10.009.
[52] Wang, H.; Cai, L.; Li, Y.; Xu, X.; Zhou, G. Biofilm Formation by Meat-borne *Pseudomonas fluorescens* on Stainless Steel and Its Resistance to Disinfectants. *Food Control*. 2018, 91, 397– 403. DOI: 10.1016/j.foodcont.2018.04.035.

[53] Ripolles-Avila, C.; Hascoët, A. S.; Guerrero-Navarro, A. E.; Rodríguez-Jerez, J. J. Establishment of Incubation Conditions to Optimize the in Vitro Formation of Mature *Listeria monocytogenes* Biofilms on Food-Contact Surfaces. *Food Control*. 2018, 92, 240– 248. DOI: 10.1016/j.foodcont.2018.04.054.
[54] Herzberg, M.; Pandit, S.; Mauter, M. S.; Oren, Y. Bacterial Biofilm Formation on Ion Exchange Membranes. *J. Membr. Sci*. 2020, 596, 117564. DOI: 10.1016/j.memsci.2019.117564.
[55] Heckler, C.; Silva, C. M. M.; Cacciatore, F. A.; Daroit, D. J.; Da Silva Malheiros, P. Thymol and Carvacrol in Nanoliposomes: Characterization and a Comparison with Free Counterparts Against Planktonic and Glass-Adhered *Salmonella*. *LWT-Food Sci. Tech*. 2020, 127, 109382. DOI: 10.1016/j.lwt.2020.109382.
[56] EFSA Panel on Food Contact Materials, Flavourings and Processing Aids. Scientific Opinion on the Criteria to be Used for Safety Evaluation of a Mechanical Recycling Process to Produce Recycled PET Intended to be used for Manufacture of Materials and Articles in Contact with Food. *EFSA Journal*, 2011, 9, 2184. DOI:10.2903/j.efsa.2011.2184.
[57] Ariosti, A. Global Legislation for Regenerated Cellulose Materials in Contact with Food. In *Global Legislation for Food Contact Materials*; Joan Sylvain Baughan (ed,) Woodhead Publishing, Elsevier, 2015, 109– 139.
[58] Directive, C. 84/500/EEC of 15 October 1984 on the Approximation of the Laws of the Member States Relating to Ceramic Articles Intended to Come into Contact with Foodstuffs. *OJ L*. 277, 1984, 12– 16.
[59] Commission, E., Regulation (EC) No 1935/2004 of the European Parliament and of the Council of 27 October 2004 on Materials and Articles Intended to Come into Contact with Food and Repealing Directives 80/590/EEC and 89/109/EEC. EEC. *Off. J. Eur. Communities*., 2004, OJ L338, 4 – 17.
[60] Commission, E. Regulation (EC) No 852/2004 of the European Parliament and of the Council of 29 April 2004 on the Hygiene of Foodstuffs. *Off. J. Eur. Union*, 2004, 50.
[61] Directive, C. On the Quality of Water Intended for Human Consumption. *Off. J. Eur. Communities*.1998, 330, 32–54.
[62] Commission, E., "Regulation (EC) No 854/2004 of the European Parliament and of the Council of 29 April 2004 Laying Down Specific Rules for the Organisation of Official Controls on Products of Animal Origin Intended for Human Consumption," *Off. J. Eur. Union L*., 2004, 139, 206.
[63] Hueck, H. J., The Biodeterioration of Materials - an Appraisal. *Int. Biodeterior. Biodegrad*. 2001, 48(1–4), 5– 11. DOI:10.1016/S0964-8305(01)00061-0.
[64] Tillner, J.; Grob, K. Compliance Work for Food Contact Materials: Feasibility of the Legally Required Safety Assessment of an Epoxy/amine-based Coating for Domestic Water Pipe Restoration. *Food Addit. Contam*. 2014, 31(7), 1310– 1323. DOI: 10.1080/19440049.2014.916421
[65] Moerman, F. Antimicrobial Materials, Coatings and Biomimetic Surfaces with Modified Microtography to Control Microbial Fouling of Product Contact Surfaces within Food Processing Equipment: Legislation, Requirements, Effectiveness and Challenges. *J. Hygienic Eng. Des*. 2014, 7, 8– 29.
[66] Karimi, M.; Habibi-Rezaei, M.; Safari, M.; Moosavi-Movahedi, A. A.; Sayyah, M.; Sadeghi, R.; Kokini, J. Immobilization of Endo-inulinase on Poly-d-lysine Coated $CaCO_3$ Micro-particles. *Food Res. Int*. 2014, 66, 485– 492. DOI: 10.1016/j.foodres.2014.08.041.
[67] Peng, C.; Zhao, Q.; Gao, C. Sustained Delivery of Doxorubicin by Porous $CaCO_3$ and Chitosan/Alginate Multilayers-Coated $CaCO_3$ Microparticles. *Colloids Surf. A*. 2010, 353(2–3),132– 139. DOI: 10.1016/j.colsurfa.2009.11.004.
[68] Jaiswal, S.; McHale, P.; Duffy, B. Preparation and Rapid Analysis of Antibacterial Silver, Copper and Zinc Doped Sol–gel Surfaces. *Colloids Surf. B*. 2012, 94, 170– 176. DOI: 10.1016/j.colsurfb.2012.01.035.
[69] Valerini, D.; Tammaro, L.; Di Benedetto, F.; Vigliotta, G.; Capodieci, L.; Terzi, R.; Rizzo, A. Aluminum-Doped Zinc Oxide Coatings on Polylactic Acid Films for Antimicrobial Food Packaging. *Thin Solid Films*. 2018, 645, 187– 192. DOI: 10.1016/j.tsf.2017.10.038.
[70] Von Goetz, N.; Fabricius, L.; Glaus, R.; Weitbrecht, V.; Günther, D.; Hungerbühler, K. Migration of Silver from Commercial Plastic Food Containers and Implications for Consumer Exposure Assessment. *Food Addit. Contam*. 2013, 30(3), 612– 620. DOI: 10.1080/19440049.2012.762693.
[71] Kolewe, K. W.; Dobosz, K. M.; Rieger, K. A.; Chang, C. C.; Emrick, T.; Schiffman, J. D. Antifouling Electrospun Nanofiber Mats Functionalized with Polymer Zwitterions. *ACS Appl. Mater. Interfaces*. 2016, 8(41), 27585–27593. DOI: 10.1021/acsami.6b09839.
[72] Li, Q.; Imbrogno, J.; Belfort, G.; Wang, X. L. Making Polymeric Membranes Antifouling via "Grafting From" Polymerization of Zwitterions. *J. Appl. Polym. Sci*. 2015, 132(21), 1–12. DOI: 10.1002/app.41781
[73] Asri, L. A.; Crismaru, M.; Roest, S.; Chen, Y.; Ivashenko, O.; Rudolf, P.; Tiller, J. C.; Van Der Mei, H. C.; Loontjens, T. J.; Busscher, H. J. A Shape-Adaptive, Antibacterial-Coating of Immobilized Quaternary-Ammonium Compounds Tethered on Hyperbranched Polyurea and Its Mechanism of Action. *Adv. Funct. Mater*. 2014, 24(3), 346– 355. DOI: 10.1002/adfm.201301686.
[74] Bastarrachea, L. J.; Denis-Rohr, A.; Goddard, J. M. Antimicrobial Food Equipment Coatings: Applications and Challenges. *Ann. Rev. Food Sci. Technol*. 2015, 6, 97– 118. DOI: 10.1146/annurev-food-022814-015453.
[75] Dizaj, S. M.; Lotfipour, F.; Barzegar-Jalali, M.; Zarrintan, M. H.; Adibkia, K. Antimicrobial Activity of the Metals and Metal Oxide Nanoparticles. *Mater. Sci. Eng C*. 2014, 44, 278– 284. DOI: 10.1016/j.msec.2014.08.031.

[76] Llorens, A.; Lloret, E.; Picouet, P. A.; Trbojevich, R.; Fernandez, A. Metallic-based Micro and Nanocomposites in Food Contact Materials and Active Food Packaging. *Trends Food Sci. Technol.* 2012, 24(1), 19–29. DOI: 10.1016/j.tifs.2011.10.001.

[77] Smolander, M.; Chaudhry, Q. Nanotechnologies in Food Packaging. *Nanotechnol Food*. 2010, 14(2010), 86e–101e.

[78] Yemmireddy, V. K.; Hung, Y. C. Photocatalytic TiO_2 Coating of Plastic Cutting Board to Prevent Microbial Cross-Contamination. *Food Control*. 2017, 77, 88– 95. DOI: 10.1016/j.foodcont.2017.01.025.

[79] Nekmard, F.; Komesvarakul, N.; Varga-Baragh, O.; Sun, G. Polymer-containing Cleaning Compositions and Methods of Production and Use Thereof: Google Patents. *U.S. Patent No. 9,464,261*. 2016 Oct 11.

[80] Pei, D. F.; Chen, S.; Li, S. Q.; Shi, H. F.; Li, W.; Li, X.; Zhang, X. Fabrication and Properties of Poly (Polyethylene Glycol N-alkyl Ether Vinyl Ether) S as Polymeric Phase Change Materials. *Thermochim. Acta*. 2016, 633, 161–169. DOI: 10.1016/j.tca.2016.04.007.

[81] Dong, A.; Xue, M.; Lan, S.; Wang, Q.; Zhao, Y.; Wang, Y.; Harnoode, C.; Gao, G.; Liu, F.; Harnoode, C. Bactericidal Evaluation of N-Halamine-Functionalized Silica Nanoparticles Based on Barbituric Acid. *Colloids Surf. B*. 2014, 113, 450– 457. DOI: 10.1016/j.colsurfb.2013.09.048.

[82] Dong, A.; Zhang, Q.; Wang, T.; Wang, W.; Liu, F.; Gao, G. Immobilization of Cyclic N-Halamine on Polystyrene-Functionalized Silica Nanoparticles: Synthesis, Characterization, and Biocidal Activity. *J. Phys. Chem. C*. 2010, 114(41), 17298– 17303. DOI: 10.1021/jp104083h.

[83] Li, L.; Ma, W.; Cheng, X.; Ren, X.; Xie, Z.; Liang, J. Synthesis and Characterization of Biocompatible Antimicrobial N-Halamine-Functionalized Titanium Dioxide Core-shell Nanoparticles. *Colloids Surf. B*. 2016, 148, 511–517. DOI: 10.1016/j.colsurfb.2016.09.030.

[84] Qiao, M.; Ren, T.; Huang, T.-S.; Weese, J.; Liu, Y.; Ren, X.; Farag, R. N-Halamine Modified Thermoplastic Polyurethane with Rechargeable Antimicrobial Function for Food Contact Surface. *RSC Adv*. 2017, 7(3),1233–1240. DOI: 10.1039/C6RA25502G.

[85] Musavian, H. S.; Butt, T. M.; Larsen, A. B.; Krebs, N. Combined Steam-Ultrasound Treatment of 2 Seconds Achieves Significant High Aerobic Count and *Enterobacteriaceae* Reduction on Naturally Contaminated Food Boxes, Crates, Conveyor Belts, and Meat Knives. *J. Food Prot*. 2015, 78(2), 430– 435. DOI: 10.4315/0362-028X.JFP-14-155.

[86] Falcó, I.; Verdeguer, M.; Aznar, R.; Sánchez, G.; Randazzo, W. Sanitizing Food Contact Surfaces by the Use of Essential Oils. *Innovative Food Sci. Emerg. Technol*. 2019, 51, 220– 228. DOI: 10.1016/j.ifset.2018.02.013.

[87] Lin, C. M.; Sheu, S. R.; Hsu, S. C.; Tsai, Y. H. Determination of Bactericidal Efficacy of Essential Oil Extracted from Orange Peel on the Food Contact Surfaces. *Food Control*. 2010, 21(12), 1710– 1715. DOI: 10.1016/j.foodcont.2010.06.008.

[88] Rodrigues, F. F.; Costa, J. G.; Coutinho, H. D. Synergy Effects of the Antibiotics Gentamicin and the Essential Oil of *Croton Zehntneri. Phytomedicine*. 2009, 16(11),1052– 1055. DOI: 10.1016/j.phymed.2009.04.004.

[89] Abeysundara, P. D. A.; Dhowlaghar, N.; Nannapaneni, R.; Schilling, M. W.; Chang, S.; Mahmoud, B.; Sharma, C. S.; Ma, D. P. Growth and Biofilm Formation by *Listeria Monocytogenes* in Cantaloupe Flesh and Peel Extracts on Four Food-Contact Surfaces at 22° C and 10° C. *Food Control*. 2017, 80, 131– 142. DOI: 10.1016/j.foodcont.2017.04.043.

[90] Azeredo, H. M.; Waldron, K. W. Crosslinking in Polysaccharide and Protein Films and Coatings for Food Contact – A Review. *Trends Food Sci. Technol*. 2016, 52, 109– 122. DOI: 10.1016/j.tifs.2016.04.008.

[91] Corrales, M.; Fernández, A.; Han, J. H. Antimicrobial Packaging Systems. *Innovations in Food Packaging*, Jung H. Han (ed.), PepsiCo Corporate R&D/PepsiCo Advanced Research, USA, Elsevier, 2014, 133– 170.

[92] Du, W. X.; Olsen, C.; Avena-Bustillos, R.; Friedman, M.; McHugh, T. Physical and Antibacterial Properties of Edible Films Formulated with Apple Skin Polyphenols. *J. Food Sci*. 2011, 76(2), M149– M155. DOI: 10.1111/j.1750-3841.2010.02012.x.

[93] Lee, H.; Min, S. C. Development of Antimicrobial Defatted Soybean Meal-Based Edible Films Incorporating the Lactoperoxidase System by Heat Pressing. *J. Food Eng*. 2014, 120, 183– 190. DOI: 10.1016/j.jfoodeng.2013.07.035.

[94] Mousavi Khaneghah, A.; Hashemi, S. M. B.; Eş, I.; Fracassetti, D.; Limbo, S. Efficacy of Antimicrobial Agents for Food Contact Applications: Biological Activity, Incorporation into Packaging, and Assessment Methods: A Review. *J. Food Prot*. 2018, 81(7), 1142– 1156. DOI: 10.4315/0362-028X.JFP-17-509.

[95] Padrão, J.; Gonçalves, S.; Silva, J. P.; Sencadas, V.; Lanceros-Méndez, S.; Pinheiro, A. C.; Vincente, A. A.; Rodrigues, L. R.; Dourado, F. Bacterial Cellulose-Lactoferrin as an Antimicrobial Edible Packaging. *Food Hydrocolloids*. 2016, 58, 126– 140. DOI: 10.1016/j.foodhyd.2016.02.019.

[96] Khwaldia, K.; Arab-Tehrany, E.; Desobry, S. Biopolymer Coatings on Paper Packaging Materials. *Compr. Rev. Food Sci. Food Saf.* 2010, 9(1), 82– 91. DOI: 10.1111/j.1541-4337.2009.00095.x.

[97] Zemljič, L. F.; Tkavc, T.; Vesel, A.; Šauperl, O. Chitosan Coatings onto Polyethylene Terephthalate for the Development of Potential Active Packaging Material. *Appl. Surf. Sci*. 2013, 265, 697– 703. DOI: 10.1016/j.apsusc.2012.11.086.

[98] Di Pierro, P.; Sorrentino, A.; Mariniello, L.; Giosafatto, C. V. L.; Porta, R. Chitosan/Whey Protein Film as Active Coating to Extend Ricotta Cheese Shelf-life. *LWT Food Sci. Technol.* 2011, 44(10), 2324– 2327. DOI: 10.1016/j.lwt.2010.11.031.
[99] Pankaj, S. K.; Bueno-Ferrer, C.; Misra, N.; Milosavljević, V.; O'donnell, C. P.; Bourke, P.; Keener, K.M.; Cullen, P. J. Applications of Cold Plasma Technology in Food Packaging. *Trends Food Sci. Technol.* 2014, 35(1), 5– 17. DOI: 10.1016/j.tifs.2013.10.009.
[100] Rtimi, S.; Nesic, J.; Pulgarin, C.; Sanjines, R.; Bensimon, M.; Kiwi, J. Effect of Surface Pretreatment of TiO_2 Films on Interfacial Processes Leading to Bacterial Inactivation in the Dark and Under Light Irradiation. *Interface Focus*. 2015, 5(1),20140046. DOI: 10.1098/rsfs.2014.0046.
[101] Commission, E. "Commission Regulation (EC) No 2023/2006 of 22 December 2006 on Good Manufacturing Practice for Materials and Articles Intended to Come into Contact with Food," *Off J Eur Union*., 2006, 50, 75–78.
[102] Matthews, C.; Moran, F.; Jaiswal, A. K. A Review on European Union's Strategy for Plastics in A Circular Economy and Its Impact on Food Safety. *J. Cleaner Prod.* 2021, 125263, 1– 13. DOI: 10.1016/j.jclepro.2020.125263.
[103] Simoneau, C. Guidelines on Testing Conditions for Articles in Contact with Foodstuffs. *Eur. Commun. (JRC Scientific and Technical Reports)*. Retrieved January. 2009, 14, 2016.
[104] Day, B. P. F.; Potter, L., Active Packaging. *Food and Beverage Packaging Technology*, Second Edition, Blackwell Publishing Ltd., London, 2011, 251–262. doi:10.1002/9781444392180.ch9
[105] Störmer, A.; Bott, J.; Kemmer, D.; Franz, R. Critical Review of the Migration Potential of Nanoparticles in Food Contact Plastics, *Trends in* Food Sci Tech.y, 2017, 63, 39–50. DOI: 10.1016/j.tifs.2017.01.011
[106] Corona, T.; Iglesias, M.; Anticó, E. Migration of Components from Cork Stoppers to Food: Challenges in Determining Inorganic Elements in Food Simulants. *J. Agric. Food Chem.* 2014, 62(24), 5690– 5698. DOI: 10.1021/jf500170w.
[107] Commission, E., Regulation (EC) No 853/2004 of the European Parliament and of the Council of 29 April 2004 Laying Down Specific Hygiene Rules for Food of Animal Origin, *J. Eur. Union L*., 2004, 139, 55–205.
[108] Lopp, S.; Goebelbecker, J. M.; Ruff, P. C. The Draft of the Regulation (EC) No 852/2004: Food Safety Culture Under New Administration. *J. Consumer Protect Food Safety*. 2021, 1 – 4. doi:10.1007/s00003-020-01306-w.
[109] Knetsch, M. L.; Koole, L. H. New Strategies in the Development of Antimicrobial Coatings: The Example of Increasing Usage of Silver and Silver Nanoparticles. *Polymers*. 2011, 3(1), 340– 366. DOI: 10.3390/polym3010340.
[110] Rosmaninho, R.; Santos, O.; Nylander, T.; Paulsson, M.; Beuf, M.; Benezech, T.; Yiantsios, S.; Andritsos, N.; Karabelas, A.; Rizzo, G. Modified Stainless Steel Surfaces Targeted to Reduce Fouling – Evaluation of Fouling by Milk Components. *J. Food Eng.* 2007, 80(4), 1176– 1187. DOI: 10.1016/j.jfoodeng.2006.09.008.
[111] Calzolai, L.; Gilliland, D.; Rossi, F. Measuring Nanoparticles Size Distribution in Food and Consumer Products: A Review. *Food Addit. Contam.* 2012, 29(8), 1183– 1193. DOI: 10.1080/19440049.2012.689777.
[112] Cushen, M.; Kerry, J.; Morris, M.; Cruz-Romero, M.; Cummins, E. Evaluation and Simulation of Silver and Copper Nanoparticle Migration from Polyethylene Nanocomposites to Food and an Associated Exposure Assessment. *J. Agric. Food Chem.* 2014, 62(6), 1403– 1411. DOI: 10.1021/jf404038y.
[113] Niemira, B. A.; Boyd, G.; Sites, J. Cold Plasma Rapid Decontamination of Food Contact Surfaces Contaminated with *Salmonella* Biofilms. *J. Food Sci.* 2014, 79(5),M917 – M922. DOI: 10.1111/1750-3841.12379.
[114] Yemmireddy, V. K.; Hung, Y. C. Using Photocatalyst Metal Oxides as Antimicrobial Surface Coatings to Ensure Food Safety - Opportunities and Challenges. *Compr. Rev. Food Sci. Food Saf.* 2017, 16(4), 617– 631. DOI: 10.1111/1541-4337.12267.
[115] Borrelli, N. F.; Morse, D. L.; Senaratne, W.; Verrier, F. C. M.; Wei, Y. Coated, Antimicrobial, Chemically Strengthened Glass and Method of Making: Google Patents. *U.S. Patent No. 9,609,873*, 2017 Apr 4.
[116] Griffith, A.; Neethirajan, S.; Warriner, K. Development and Evaluation of Silver Zeolite Antifouling Coatings on Stainless Steel for Food Contact Surfaces. *J. Food Saf.* 2015, 35(3), 345– 354. DOI: 10.1111/jfs.12181.
[117] Mérian, T.; Goddard, J. M. Advances in Nonfouling Materials: Perspectives for the Food Industry. *J. Agric. Food Chem.* 2012, 60(12), 2943– 2957. DOI: 10.1021/jf204741p.
[118] Makwana, M. R. Characterization of Biofilm Forming Microbes and Their Control; *NDRI*: Karnal, 2015.
[119] Jaiswal, S.; Bhattacharya, K.; McHale, P.; Duffy, B. Dual Effects of β-Cyclodextrin-Stabilised Silver Nanoparticles: Enhanced Biofilm Inhibition and Reduced Cytotoxicity. *J. Mater. Sci.: Mater. Med.* 2015, 26(1), 52. DOI: 10.1007/s10856-014-5367-1.
[120] Choi, N. C.; Park, S. J.; Lee, C. G.; Park, J. A.; Kim, S. B. Influence of Surfactants on Bacterial Adhesion to Metal Oxide-Coated Surfaces. *Environ. Eng. Res.* 2011, 16(4), 219– 225. DOI: 10.4491/eer.2011.16.4.219.
[121] Zeraik, A. E.; Nitschke, M. Biosurfactants as Agents to Reduce Adhesion of Pathogenic Bacteria to Polystyrene Surfaces: Effect of Temperature and Hydrophobicity. *Curr. Microbiol.* 2010, 61(6), 554– 559. DOI: 10.1007/s00284-010-9652-z.
[122] Cheng, G.; Li, G.; Xue, H.; Chen, S.; Bryers, J. D.; Jiang, S. Zwitterionic Carboxybetaine Polymer Surfaces and Their Resistance to Long-Term Biofilm Formation. *Biomaterials*. 2009, 30(28), 5234– 5240. DOI: 10.1016/j.biomaterials.2009.05.058.

[123] Ravindran, R.; Jaiswal, A. K. Current Advances in Immobilization Techniques of Enzymes. *Enzym Fuel Cells*. 2019, 44, 51–72.

[124] Kregiel, D., Advances in Biofilm Control for Food and Beverage Industry Using Organo-Silane Technology: A Review. *Food Control*. 2014, 40, 32–40. DOI: 10.1016/j.foodcont.2013.11.014.

[125] Ivanova, E. P.; Hasan, J.; Truong, V. K.; Wang, J. Y.; Raveggi, M.; Fluke, C.; Crawford, R. J. The Influence of Nanoscopically Thin Silver Films on Bacterial Viability and Attachment. *Appl. Microbiol. Biotechnol*. 2011, 91(4), 1149– 1157. DOI: 10.1007/s00253-011-3195-5.

[126] Swartjes, J.; Sharma, P.; Kooten, T.; Van Der Mei, H.; Mahmoudi, M.; Busscher, H.; Rochford, E. Current Developments in Antimicrobial Surface Coatings for Biomedical Applications. *Curr. Med. Chem*. 2015, 22(18), 2116– 2129. DOI: 10.2174/0929867321666140916121355.

[127] Marini, M.; De Niederhausern, S.; Iseppi, R.; Bondi, M.; Sabia, C.; Toselli, M. Antibacterial Activity of Plastics Coated with Silver-Doped Organic- Inorganic Hybrid Coatings Prepared by Sol– gel Processes, *Biomacromolecules*, 2007, 8, 1246–1254.

[128] Yin, Y.; Wang, C. Multifunctional Performances of Nanocomposite SiO_2/TiO_2 Doped Cationic EBODAC Film Coated on Natural Cellulose Matrix. *J. Sol-Gel Sci. Technol*. 2011, 59(1),36– 42. DOI: 10.1007/s10971-011-2458-z.

[129] Goddard, J. M.; Hotchkiss, J. Polymer Surface Modification for the Attachment of Bioactive Compounds. *Prog. Polym. Sci*. 2007, 32(7), 698– 725. DOI: 10.1016/j.progpolymsci.2007.04.002.

[130] Harney, M. B.; Pant, R. R.; Fulmer, P. A.; Wynne, J. H. Surface Self-Concentrating Amphiphilic Quaternary Ammonium Biocides as Coating Additives. *ACS Appl. Mater. Interfaces*. 2008, 1(1), 39– 41. DOI: 10.1021/am800046r.

[131] Siedenbiedel, F.; Tiller, J. C. Antimicrobial Polymers in Solution and on Surfaces: Overview and Functional Principles. *Polymers*. 2012, 4(1), 46– 71. DOI: 10.3390/polym4010046.

[132] Kollath, A.; Brezhneva, N.; Skorb, E. V.; Andreeva, D. V. Microbubbles Trigger Oscillation of Crystal Size in Solids. *Phys. Chem. Chem. Phys*. 2017, 19(8), 6286–6291. DOI: 10.1039/C6CP07456A.

[133] Gutierrez, J.; Barry-Ryan, C.; Bourke, P. Antimicrobial Activity of Plant Essential Oils Using Food Model Media: Efficacy, Synergistic Potential and Interactions with Food Components. *Food Microbiol*. 2009, 26(2), 142– 150. DOI: 10.1016/j.fm.2008.10.008.

[134] Soni, K. A.; Oladunjoye, A.; Nannapaneni, R.; Schilling, M. W.; Silva, J. L.; Mikel, B.; Bailey, R. H. Inhibition and Inactivation of *Salmonella typhimurium* Biofilms from Polystyrene and Stainless Steel Surfaces by Essential Oils and Phenolic Constituent Carvacrol. *J. Food Prot*. 2013, 76(2), 205– 212. DOI: 10.4315/0362-028X.JFP-12-196.

[135] Campana, R.; Casettari, L.; Fagioli, L.; Cespi, M.; Bonacucina, G.; Baffone, W. Activity of Essential Oil-Based Microemulsions Against *Staphylococcus aureus* Biofilms Developed on Stainless Steel Surface in Different Culture Media and Growth Conditions," *Int. J. of Food Micro*., 2017, 241, 132–140. DOI: 10.1016/j.ijfoodmicro.2016.10.021

[136] Juneja, V. K.; Dwivedi, H. P.; Yan, X. Novel Natural Food Antimicrobials. *Ann. Rev. Food Sci. Technol*. 2012, 3, 381– 403. DOI: 10.1146/annurev-food-022811-101241.

[137] Arevalos-Sánchez, M.; Regalado, C.; Martin, S. E.; Domínguez-Domínguez, J.; García-Almendárez, B. E. Effect of Neutral Electrolyzed Water and Nisin on *Listeria Monocytogenes* Biofilms, and on Listeriolysin O Activity. *Food Control*. 2012, 24(1–2),116– 119. DOI: 10.1016/j.foodcont.2011.09.012.

[138] Conte, A.; Buonocore, G. G.; Sinigaglia, M.; Lopez, L. C.; Favia, P.; d'Agostino, R.; Del Nobile, M. A. Antimicrobial Activity of Immobilized Lysozyme on Plasma-treated Polyethylene Films. *J. Food Prot*. 2008, 71 (1),119 – 125. DOI:10.4315/0362-028X-71.1.119.

[139] Theapsak, S.; Watthanaphanit, A.; Rujiravanit, R. Preparation of Chitosan-Coated Polyethylene Packaging Films by DBD Plasma Treatment. *ACS Appl. Mater. Interfaces*. 2012, 4(5),2474–2482. DOI: 10.1021/am300168a

[140] Karam, L.; Jama, C.; Mamede, A. S.; Fahs, A.; Louarn, G.; Dhulster, P.; Chihib, N.-E. Study of Nisin Adsorption on Plasma-Treated Polymer Surfaces for Setting Up Materials with Antibacterial Properties. *React. Funct. Polym*. 2013, 73(11),1473–1479. DOI: 10.1016/j.reactfunctpolym.2013.07.017.