Chapter 8
Biofilms on Food Contact Surfaces: Current Interventions and Emerging Technologies

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Introduction

Microorganisms are omnipresent. Owing to this ubiquitous nature, microorganisms are one of the most significant bumps for food processors. The prominent threats to the quality and safety of food products are the unfavourable microbial contamination of food and food contact surfaces. Apart from these two, today's food processors must overcome numerous other obstacles to ensure a steady supply of safe and healthy food.

Food contact surfaces are either "open" or "closed" type in the food industry. Pipework is a typical example of a closed surface because it contains ingredients or wet products in a flowing liquid system. Open surfaces are exposed and moist or dry food moves down conveyors, flow is absent because the liquid is not required to surround the food or cover the surface (Verran et al., 2008).

Closed systems avail solid-liquid interface for attachment and colonization of microorganisms. Such circumstances readily promote the development of biofilms in closed systems. Solid-air or a solid-liquid-air interface of open systems is comparatively less vulnerable to microbial attack as they may undergo dehydration, lack of moisture, and be subjected to routine cleaning and sanitization process. Because nutrients are concentrated more near an interface, it is metabolically advantageous for bacteria to adhere to surfaces. Once anchored, bacteria will consume and metabolize nutrients, excrete waste, and build structures or substances that promote

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adhesion and reproduction. A dynamic three-dimensional network is created as a result. The conventional and newly developed methods used currently in the removal of biofilms on food contact surfaces are discussed in the chapter. We explore both the thermal and nonthermal approaches for reducing the microbial load, highlighting the existing technologies and their drawbacks. The chapters also cover emerging technologies ranging from antimicrobial coatings to cold plasma technology.

Biofilms

Flemming and Wingender (2010) have defined biofilms as a group of microorganisms adhering to surfaces, or to one another and covered by extracellular polymeric substances (EPS). A biofilm is a stable community comprising both biotic and abiotic components and its formation in food processing environments has significant adverse effects. Hence, regular cleaning and disinfecting processes are necessary for safely operating open systems. Biofilms are formed in moist and non-sterile environments. One of the most common example is the dental plaque which leads to tooth decay and gum disease. These are caused by the metabolic by-products of the bacteria found in plaque. The human skin lining also serves as an excellent reservoir for biofilms.

Microorganisms, in the form of biofilm or otherwise, can multiply and colonize when they are transferred from an inert surface to a food milieu, which increases the risk of contamination, spoilage, and/or disruption of quality assurance operations. Development and retention of biofilms in the food industry are influenced by a variety of elements such as the topography, chemistry and configuration of the surface as well as the type, physiology, and viability of microbes, and interactions between these elements. These must be taken into account while deciding about the techniques to be used to determine the effectiveness of sanitation.

Occurrence of Biofilms and Associated Risks

The majority of the biofilm is made up of extracellular polymeric substance (EPS), which is typically made up of polysaccharides, proteins, glycolipids, enzymes, metal ions, and nucleic acids in the biological environment. Over 80% of the biofilm's volume is made up of EPS, and this component's physical and chemical makeup influences the biofilm's basic traits and features (Branda et al., 2005).

Food Industry Biofilms may form on surfaces in the food business that come into contact with or are not in contact with foods. About 60% of foodborne outbreaks are caused by biofilms (Han et al., 2017). The biofilm formation in areas where food is processed puts consumers' safety and the food business at serious risk. Contaminants in the surroundings where food is processed typically come from the air, equipment, or food surfaces. These contaminants lead to biofilm formation in food processing environments and may cause food spoilage, pose a major risk to the health of consumers, and cause a negative economic impact (Coughlan et al., 2016).

Foodborne illnesses caused by microbes are a big problem, including *Salmonella* spp., (causes Reiter's syndrome or even death); *Escherichia coli* 0157:H7 (causes hemorrhagic colitis) (Wirtanen & Salo, 2016); *Listeria monocytogenes*, (causes abortion in pregnant women and other difficulties in immunocompromised patients). This foodborne pathogen is most commonly associated with biofilm formation and also food spoilage (Galié et al., 2018); *Vibrio parahaemolyticus*, (associated with seafood infection on the consumption of undercooked seafood; *Clostridium perfringens* (a toxin-producing species); *Campylobacter jejuni* (causes human gastroenteritis); *Pseudomonas* spp., (produces proteases that leads to food spoilage); *Bacillus* spp. (responsible for diarrhea and emetic sickness); *Staphylococcus aureus* (responsible for foodborne intoxications); *Shewanella putrefaciens* (produces putrid odour due to production of volatile amine, sulphide, and trimethylamine) (Bagge et al., 2001); *Geobacillus stearothermophilus* (a typical dairy product contamination); and *Cronobacter* spp. (a species mostly responsible for infant infections and immunocompromised individuals). These organisms can even create multi-species biofilms, another significant technical issue facing the food sector, which is more persistent and challenging to regulate (Galié et al., 2018). The presence of biofilms hinders the transmission of heat through equipment, corrodes the surfaces, and also increases the resistance to fluid friction at the surfaces and thus decreases production efficiency.

Medical Facility The formation of biofilms affects human health directly as well as indirectly. It is directly associated with chronic illnesses in humans such as cystic fibrosis, prostatitis, dental caries, rhinosinusitis, and otitis media. Additionally, these films cause a lot of indwelling medical devices to malfunction and raise the risk of bloodstream infections through catheters (Percival, 2007). Over 65% of infections by microorganisms are thought to be caused by the ones associated with biofilms, and these species have significant resistance to antimicrobials and elements of the host defense system (Jamal et al., 2018).

Others Human diseases and waterborne outbreaks have been linked to ingesting water polluted with bacterial biofilms. The major biofilm-producing bacteria in the drinking water system are *Pseudomonas aeruginosa, Aeromonas hydrophila, Klebsiella pneumoniae, Campylobacter jejuni, Legionella pneumophila,* and *Mycobacteria* (Chan et al., 2019). Bacterial cells may cause corrosion of water pipes, and affect water quality in terms of color, taste, turbidity, and odors, as well as its efficiency of heat exchange. This may happen when these organisms attach and form biofilms on the interior surfaces of pipes, from which cells break and enter the water supply (Prest et al., 2016). Overall, biofilms can harm water pipes and have a negative impact on the safety of drinking water.

Microbial Attachment and Development of Biofilm

Food and its contact surfaces can get contaminated with both pathogens as well as spoilage-causing microorganisms which enter through soil, water, tools, people, animals and air. For the food sector, the adhesion of microorganisms, particularly bacteria, and subsequent biomaterial accumulation has been a major source of issues. The type of microorganism responsible for developing a biofilm depends on the type of food substrate. For example, in the closed systems found in the dairy industry, thermophilic streptococci are related to product spoilage and pose a threat to the cleanability of surfaces (Flint et al., 2000). *Listeria monocytogenes* being a psychrophile pathogen is of concern in the cheese, meat and fish industries (Tresse et al., 2007). Studies have shown that biofilms containing *Listeria monocytogenes* could form on surfaces such as walls, floors, and in drains of food processing plants. A biofilm may be constituted either by only one microbial species or by a combination of a number of species belonging to different microbial groups including bacteria, yeast, fungi, algae, and protozoa. These microbes attach firmly to and have complex interactions among themselves and with the surrounding abiotic environment (Costa-Orlandi et al., 2017; Raghupathi et al., 2017). Biofilms can be formed on all food processing surfaces and equipment.

The ability of bacteria to form a particular type of biofilm will influence their persistence during manufacturing and retail. It will also influence the rate at which they cause infection. The movement of food through the processing lines or its handling in the processing, environment may cause the surface conditioning at a solid-air contact to be more generic rather than specific in nature. Food-substratum contact is another opportunity for microbial contamination and biofilm formation.

Apart from carrying pathogenic microbes, the formation of biofilm increases the frictional resistance, and thus, the cost of the process. Biofouling of heat exchangers can result in a reduction in heat transfer efficiency and an associated cost increase. Thickened biofilm may also corrode pipeline surfaces. An area beneath a microcolony becomes anodic in comparison to the rest of the metal, which is exposed to the oxygenated bulk phase. And then the associated bacteria in the biofilm deplete the oxygen near a metal surface, thus causing corrosion.

The contact surface must be inert in order to prevent the transfer of any potential contaminants to food. Stainless steel is a material of choice in the food sector as it is non-reactive, non-corrosive, and stable. It can undergo various processes such as electrolysis and mechanical transformations to form a variety of surfaces and products (Verran et al., 2004). The likelihood of contaminating germs penetrating a material increases when its flexibility is lost due to excessive wear and the ensuing breaking, which is most commonly seen in surfaces or equipment that use rubbers, plastics, epoxy resins, etc. Even cracks and slits in stainless steel and glass can serve as a reservoir for pathogens.

Additionally, temperature, chemistry, and processing of food determine the strength of attachment. All these factors drive the type of method employed to disinfect the food contact surfaces.

Mechanism of Microbial Attachment

The complicated biofilm formation process commences with the attachment of a single bacterium. The duration of this process may vary from very short to long in the food processing environment depending on the surrounding medium, the surface involved, and the type of associated microbe. The process of biofilm formation is complex, and occurs in several steps starting with the attachment of microbes reversibly to surfaces through intermolecular forces and hydrophobicity followed by the release of extracellular polymeric substances (EPS) enabling permanent adherence of the cells to a surface (Caruso et al., 2018). The process of biofilm formation usually involves five main phases that include: (i) Reversible attachment, (ii) Irreversible attachment, (iii) EPS production, (iv) Maturation of biofilm, and (v) Dispersal/detachment (Stoodley et al., 2002; Toyofuku et al., 2016).

The microbial cells, at a distance of more than 50 nm, are attracted toward the surface via hydrophobic interactions and van der Waals forces. The electrostatic force comes into play when the bacterium advances near (<20 nm) to the substratum and is the strongest force responsible for the adhesion of microbial cells. As the cells approach even closer, it marks the irreversible attachment. Studies have shown that the rate of attachment of spores is greater than vegetative cells, because of their higher hydrophobic nature and non-uniform outer surface. After the subsequent attachment, the microbial cells multiply and propagate, leading to the growth of colonies, and thus a biofilm is formed.

Factors Affecting Retention

A standard 8–12 h shift in the food sector gives bacteria plenty of time to adhere and build a biofilm on process equipment in just a few hours. Some surface characteristics are important to support bacterial colonization. These include the hydrophobic nature of the surface, its topography especially if its non-uniform, and its predisposition for protein adsorption. However, a variation has been found in the behaviour of different surfaces toward biofilm formation. It has been found that rough surfaces retain bacteria better than smooth ones while some studies have shown that there is no effect of rough surfaces (Flint et al., 2000; Medilanski et al., 2002). The retention of biofilm on the surface depends on several topographical and chemical factors.

Substratum Topography

The adherence of microorganisms on the surface increases directly in relation to the surface roughness of the surface. This can be attributed to the fact that a rougher surface has a greater surface area and low shear force. The rate and degree of adhesion may be significantly influenced by the surface's physicochemical characteristics. Most studies indicate that adherence of microorganisms is faster to nonpolar, hydrophobic surfaces(e.g., Teflon) as compared to hydrophilic surfaces(e.g., glass or metals). Glass and other hydrophilic materials are widely utilized for surfaces that will come into touch with food because they are known to prevent bacterial adhesion. Hydrophobic spores were discovered to stick to both surfaces more readily than vegetative cells did. Passive retention will be minimal if the surface irregularities are bigger than the microorganisms. The retention hence improves if the surface features are of a similar dimension or slightly smaller.

The variability of surface micro and macro-topography adds another element to be paid attention to while making surface microbes free. The rinsing process might prove to be more effective when done along with the direction, that is, parallel to the cracks or crevices rather than in a perpendicular direction.

Also, different microorganisms portray different attachment behavior toward different surfaces. *Pseudomonas spp.* gets attached to glass surfaces in the dairy industry more readily than others. The biofilms found in milk processing systems harbored *Acinetobacter spp.* even though it has a predominately gram-positive microflora.

Surface Chemistry

Due to the various chemical and physical properties of food ingredients, the contact surfaces must be non-reactive to avoid any distortion, via chemical reactions, in the final product. In the food industry, the transfer of any chemical substance from the food surface is undesirable. Various studies have shown that the chemical properties of contact surfaces and microorganisms have offered us ways, like coating surfaces with specialized substances at critical points, to ensure food safety.

Stainless steel is the most chosen metal for use as a contact surface in the food sector as it is noncorrosive, non-reactive and long lasting. Its chemical composition also allows a wider functionality, for instance, chromium increases corrosion resistance (Maller, 2007). Chromium undergoes passivation when it interacts with the atmosphere. The layer of oxide, thus formed, gives noncorrosive properties to stainless steel (Olsson & Landolt, 2003). Nickel, manganese, and molybdenum, for instance, can be included. There hasn't been much research done on how variations in stainless steel's surface chemistry affect microbial retention.

The role of surface chemistry in microbial attachment has been studied by many researchers using various surfaces having similar topography. Glass surfaces having different chemical groups with varying hydrophilicity, hydrophobicity, chain length, and chemical functionality were used to study the adhesion of *Listeria. monocytogenes, Salmonella typhimurium, Staphylococcus aureus*, and *Escherichia coli*. It was seen that the chemistry of the underlying substratum affects the adherence of *Listeria spp.* and *E. coli.* Teughels et al. (2006) have shown that the formation of biofilm is also affected by underlying surface chemistry.

Availability of Organic Matter

The habitation of organic and inorganic matter on contact surfaces affects both, the formation of and its cleanability. The presence of soil hinders the action of cleaning agents physically and chemically, thus giving favorable conditions for microorganisms to flourish. The organic material might act as a nutrient medium for microorganisms to grow, thus contaminating food. The biological surface that the conditioning layer provides to microorganisms at the solid–liquid interface by means of receptors is responsible for providing a degree of specificity (Verran et al., 2001). This may occur through direct food contact in an open system (the solid-air interface), which is more common in the sector. Surface features may contain attached microorganisms mixed with organic materials like fats, carbohydrates, proteins, or detergent residue. Surface conditions, and consequently microbial attachment and retention, get affected by cumulative soiling. Verran et al. (2002) have stated that "soiling" may be used where the surface is uneven and significant exchange of organic matter occurs rather than merely "conditioning of film".

Assessment of Retention

It is generally known that bacterial cells that form a biofilm matrix and colonize surfaces possess greater resistance to toxic chemicals compared to their single-cell existence. In a biofilm, the bacterial cells receive less oxygen and nutrients. This leads them to undergo some major physiological changes, which results in their decreased growth rate. This quasi-dormant nature of bacteria in a biofilm is responsible for their resistance to a variety of antibiotics, surfactants, and sanitizers.

It may be feasible to hypothesize about the biocide resistance demonstrated by microbes attached to surfaces by examining microbial cells in terms of their structure and functions. Some species, like *Bacillus* spp., have a proteinaceous capsule that aids in adhesion, stops desiccation that blocks the action of phagocytes. Most bacteria's extracellular capsules are polysaccharides by nature. Capsular material may also make it easier for harmful substances to be absorbed, restricting their entry into the cytoplasm. Hence, a biofilm consisting of capsular material would offer protection to embedded cells against sanitizers.

Research has shown that the resistance of bacteria to disinfection depends upon their surface attachment. For example, a disinfecting agent can attack planktonic microorganisms from all sides as they are free floating. The microorganism which is attached to a surface is affected only from one side but removal from the surface increases its susceptibility to sanitizers.

Age of biofilm often improves the bacteria's resistance when present in biofilm. The older the biofilm is, the greater is the resistance to various sanitizing agents. A biofilm develops multiple layers as it ages as a result of imprisoned cells' growth and reproduction. It has been discovered that sanitizers, such as quaternary ammonium compounds (QAC), are useless against biofilm cells that are present beneath the initial layer. QAC should permeate hydrophilic and negatively charged cell surfaces since they are hydrophilic cationic molecules. However, lipophilic surfaces as in the cell wall of Gram-positive may prevent sanitizers from penetrating.

Cells in a biofilm may develop sanitizer resistance through a surface-dependent mechanism. Researchers have discovered that the type of surface to which *L. monocytogenes* had adhered was related to the bacteria's resistance, and they came to the conclusion that in comparison to surfaces made of polyester or polyester-polyurethane, stainless steel surfaces were much easier to clean and sterilize. No discernible topological changes among the surfaces were found by scanning electron microscopy to explain this variance in sanitizing resistance.

The way the bacteria in biofilms resist antibiotics appears to be comparable to how they fight sanitizers. *Staphylococcus aureus* cells from old biofilms were shown to be extremely resistant to tobramycin and cephalexin. The process underlying this resistance has been hypothesized to involve modifications of the antibiotic's ability to pass the cell membrane, the development of enzymes that break down antibiotics, alterations to the molecular targets of the antibiotics and prevent penetration by binding of bacterial exopolysaccharides to the antibiotics. Similar behavior of antibiotics like amikacin were observed when their actions were studied on the suspended and adhered *Pseudomonas aeruginosa* and *Staphylococcus epidermidis*.

Decontamination of Food Contact Surfaces

Any surface to which food substances contact during preparation, manufacturing, processing, and packing are considered as food contact surfaces. Usually, stainless steel or some other variety of plastic is used for these surfaces, but other materials, such as wood, rubber, ceramic, or glass, may also be used as contact surfaces. All these surfaces could be a great source of microbial contamination as already discussed in this chapter. Recent evolution in the food industry has paid significant attention to the methods used for decontaminating these contact surfaces.

The term decontamination refers to microbial inactivation or removal by a process of disinfection or sterilization. The reduction in the number of microorganisms usually by destructing or removing the vegetative forms of bacteria, fungi, and other microbes from inanimate objects by using a number of chemicals alone or in combination is called disinfection; the spores generally remain on using disinfectants. On the other hand, in sterilization there is complete destruction of all the microorganisms, not only the vegetative forms but their spores as well (Skåra & Rosnes, 2016). These microorganisms if not removed, particularly the pathogenic ones, develop biofilms, which are composed of single or multiple species, over and/or around these food contact surfaces. Studies have proven that these biofilm pathogens have developed resistance against many of the existing antimicrobial agents. The arising antibacterial surface designs provide the chance to lessen or eliminate microbial adherence (Sharma et al., 2022).

Types of Methods

There are numerous ways to decontaminate a food contact surface, and the ones often used employ different chemicals like chlorine and quaternary ammonium compounds. Use of chemicals directly on food-contact surfaces needs approval from FDA. The industry usually prefers to use different chemicals together or in a sequence and use multiple methods to reach /get the required level of decontamination. The most important principle when it comes to surface decontamination is the prevention of recontamination.

Broadly, decontamination methods can be divided into two classes based on the ways the exposure to heat happened. These classes are designated as "Non-Thermal'' and "Thermal" methods. It can be easily witnessed that a combination of both the aforementioned methods are used in the industry in their routine surface sanitation, both in CIP (Cleaning in plant), as well as in COP (Cleaning out plant). Each of these classes encompass several methods which are discussed here further.

Non-thermal Methods

- *Chemical Methods*

Chemical methods of decontamination require the use of a chemical agent or a mixture of multiple agents. They are popular because of their highly effective fungicidal, bactericidal, sporicidal, and antiviral effects, out of which the latter are considered among an exclusive class of disinfectants (Skåra & Rosnes, 2016). These are one such methods which are practiced by almost everyone in the business of food and related domains. But not any chemical agent can be used to meet the purpose, only the approved chemical agents which are allowed as per the regulations, which vary from country to country, can be used for food-related surfaces. When they are used excessively, there are also high chances of the residues of these chemicals being left behind and this raises a concern about whether one should continue to use these agents or not. But this can be tackled easily if the personnel in charge of the sanitation duty ensures that only the approved chemical agents are used for the decontamination, with all the instructions being followed, from concentration to rinsing and drying. The efficacy of these chemicals depends on factors like concentration, contact time, temperature, surface area and its nature, organic and inorganic content etc.

Some common agents used to decontaminate food contact surfaces include Chlorine compounds (e.g., Calcium and sodium hypochlorites), Peroxide and Peroxyacid mixtures (PAA), Quaternary Ammonium Compounds (QUATs), Iodophors, Hydrogen peroxides, and others. Many newer methods have come up to replace these agents in recent times. Some of these new technologies are described in the following sections.

- *Physical Methods*

  Physical methods of decontamination are commonly used with the thermal methods, and many times considered the same. Though physical methods are not very effective against disinfection except for food removal of soiling and some microorganisms from the surfaces, they are involved in assisting other methods of decontamination. This is because physical methods are applied prior to any other methods and thus reduces some microbial load and the number of interfering agents which could hinder the efficiency of the other methods which will be used next in the sequence. The use of both ionizing (e.g. gamma rays) and nonionizing radiations (e.g., ultraviolet rays) is also considered to be a physical method of decontamination.

Thermal Methods

Thermal methods include the application of heat energy. It is an inefficient method of decontamination as it uses up a lot of energy in its operation. Number of factors including temperature, relative humidity, duration of exposure/exposure time, etc. influences the efficacy of heat in destroying the microorganisms. It is found that the combinations of heat and other decontaminating agents are preferred as rise in temperature enhances the rate of reaction and thus efficiency of many agents. The most common agents used to provide heat energy are air, steam, and hot water, out of which, the use of steam is more common. Steam is considered to be an efficient carrier of heat energy when applied on the food contact surface, but limitation lies in difficulty in monitoring the exact contact time of steam with the surface and the temperature used and also using steam to meet this purpose is expensive.

Immersing small equipment in hot water, which is heated at or above 82 °C, is a good way of sterilizing cleaned components. The exposure time needed to remove microbes completely from any item is dependent on the water temperature used. Lower the temperature of steam, longer would be the time required to sterilize the equipment or contact surfaces. The time required would be shortened at a higher temperature.

Existing Technologies and Their Drawbacks

Since ages, many techniques have been practiced tackling the problems related to Food Contact Surfaces. Existing methods generally prove to be of little help, though some may have greater impact, but no method is perfect. CIP (Cleaning-In-Place), a very common approach to deactivate bacteria on food contact surfaces, which is still being applied by most of the food companies and uses a number of rinse cycles repeatedly, has failed to provide a clean and safe surface against planktonic cells of the bacteria.

In the food industry, applications of radiation, heat, and chemicals are looked for in disinfection and sanitation. The former (radiations) being expensive, heat and chemical methods are more prominently used. Chemical compounds like Iodophors and Chlorine compounds, often fail to fulfill their purpose when they interact with the food residues and dirt already present on these surfaces. Their efficiency is decreased, and they fail to disinfect the surface properly (Sharma et al., 2022). Chemical fogging is a method of decontamination that has been found to be helpful in the disinfection of water, equipment, and food surfaces (Beltrán et al., 2005; Gelman et al., 2005). It is of great interest to the food scientist and has been in focus because of its low toxicity. It is used for decontaminating whole rooms and has been very effective (Nicholas et al., 2013; Zoutman et al., 2011). But its high effectiveness comes with a cause of its high toxicity which raises a question on its use in areas inhabited by people. Because of this reason, their use is restricted to areas that can be separated during decontamination and thoroughly vented afterward, or where it is possible to give sufficient time to the gas to degrade.

Emerging Technologies

Keeping in mind the demerits associated with conventional decontamination methods, a number of advanced technologies using ultrasonication, cold plasma, and surface functionalization are emerging that hinder microbe's attachment to FCS and promote microbial killing, thus reducing contaminants and enhancing food safety and its quality (Fig. 8.1). Some of these include:

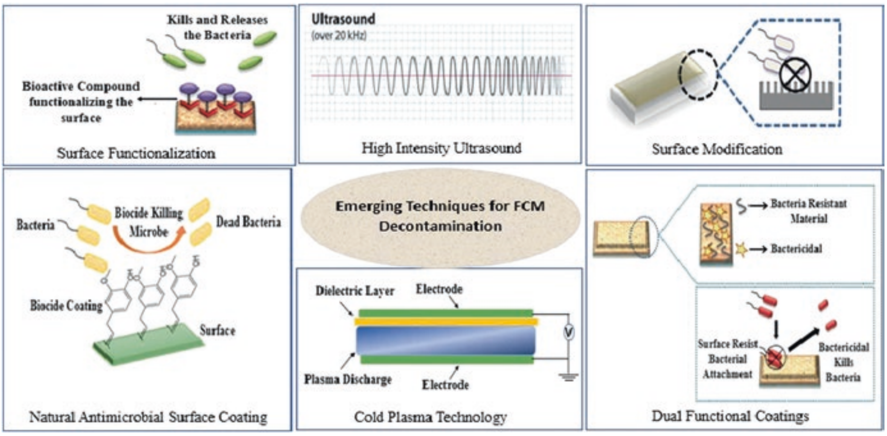

Fig. 8.1 Emerging techniques for FCM decontamination. (Source: Sharma et al., 2022)

Natural Antimicrobial Surface Coating

The term "antimicrobial coating" refers to a liquid combination, solution, or suspension that is administered to a surface with the intention of sanitizing, disinfecting, decreasing, or moderating microbial development on surfaces that come into contact with food.

Antimicrobial surface coatings are based on achieving either or both of the following motives. One that prevents the primary attack by microbes and their spores, by generating surfaces that do not permit the adherence of the microbial cells and their spores. The second one is based on the killing of approaching microbes (Tiller, 2010). The properties of an ideal antimicrobial coating as per Provider and Baghdachi (2008) are:

- It should be effective.
- It should be both mechanically as well as chemically resistant.
- The coating should be stable, non-absorbent and innocuous.
- It should be cost effective.
- Easy to clean when placed in a complex environment.

There are five guiding principles that cover all the interactions with microorganisms that result in the suppression of microbial development on food contact surfaces and may be used to categorize the possible uses of antimicrobial coatings. These include

- Anti-adhesion: Modification of surface energy to develop passive repellence.
- Antimicrobial-loaded:
  - Simple release: There is continuous release of the agent present in the matrix until depletion.
  - Controlled release: The antimicrobial located in matrix is released against a stimulus until fully consumed.
- Contact inactivation: Lysis of cell occurs when it comes in contact with active agent.
- Photocatalytic: The damage to the cell wall occurs due to the reactivity of various oxygen species which are released continuously.
- Multifunctional: Different types of action mechanisms are working together to reduce the microbial load (Torres Dominguez et al., 2019).

Animals, plants, bacteria, fungi, and algae are just a few examples of the many sources from which antimicrobial agents can be derived. Plants are found to have polyphenols as their secondary metabolites. These polyphenols are generally subcategorized as flavonoids and non-flavonoids. There are numerous studies that support the efficiency of these polyphenols and essential oils when incorporated in antimicrobial coatings in food contact surfaces. Vazquez-Armenta et al. (2018) studied the effect of extracts obtained from the grape stem on *Listeria monocytogenes* attached to stainless steel and polypropylene surfaces. They studied the factors like motility, surface energy and adhesion. The essential oil from *Origanum* *vulgare L.* (oregano; OVEO) and carvacrol (CAR) was used for the removal of biofilms formed on stainless steel surfaces by Dos Santos Rodrigues et al. (2018).

Dual Functional Coatings

In recent times, a number of antibacterial surfaces have been formulated. These surfaces or coatings have been classified on the basis of their mode of action by Yu et al. (2015). They are classified are:

(i) Surfaces which are bactericidal in nature
(ii) Surfaces resistant to bacteria
(iii) Surfaces which do not permit the attachment of bacteria

Surfaces with dual functional coatings combine both bactericidal and microorganism-resistant qualities. Ahmadi and Ahmad (2019) created a polyurethane nanocomposite (PUC) covering that is durable, active, and dual-functional (antimicrobial/anticorrosive) by combining the synergistic activity of graphene oxide incorporation and π-π interaction. This covering reduced the bacterial colonization against *Salmonella typhimurium* and *Listeria innocua* as compared to planar aluminium and also had anticorrosive action. A large number of studies have been done to develop a surface coating having dual functionality.

Surface Functionalization

Research in the area of surface modification has led to many techniques which have improved both the inertness and safety of the materials commonly used in making of food contact surfaces. Different agents such as UV rays, wet chemicals, and adhesion techniques can be used to add various polar groups to the surface and create different functional surfaces. Different factors such nature of material, and its properities including conductivity, strength etc., have to be considered while selecting the polymer. This is the initial stage in the surface modification process which is followed by the addition of appropriate quantity and type of the reactive functional group. This second stage helps in increasing the surface functionality. The use of the surface decides which type of biomolecules to be immobilized or its functionalization. The availability of the reactive functional groups per unit area is increased by grafting the polyfunctional agent onto the surface. The bioactivity is also increased by adding spacer molecules to utilize the bioactive compounds on a solid surface. Hence, the steric hindrance is decreased and the compound is coated with a hydrophobic substance. The last step is the covalent bonding of the natural or synthetic bioactive compound to the functionalized polymer surface.

Atom radical transfer or covalent bonding are the two techniques of achieving surface modification. In a study, antibacterial property was achieved by using hydrophobic polycations of quaternary ammonium salt which were chemically bound on surfaces (Sharma et al., 2022). Perinelli et al. (2019) showed that the specific properties such as cytotoxicity, and antibacterial activity of surfactants having quaternary ammonium amino acids are affected by the length of the hydrocarbon chain. On the other hand, they are unaltered by the polar head of the amino acid-leucine or methionine.

Surface Modification

Biofilms contaminate food and its product because the bacterial population has a tendency to adhere and colonize material surfaces, thus forming a biofilm. Few studies have been conducted to determine the effect of surface topography of the material on the bacterial adhesion. Hsiao et al. (2014) showed that the surfaces which are smooth and convex are more resistant to the bacterial cell attachment. The indented surfaces have better anti-biofouling properties as compared to the curved surfaces as the bacterial cells cannot adhere in between the indents (Hasan & Chatterjee, 2015). The role of food-safe oil-based anti-friction coatings (FOSCs) was studied by Awad et al. (2018) in preventing biofilm formation, this was attributed to the fact that the residual oil formed a coating on the surface holes thereby stopping the microbial growth as no anchorage was available. Their findings indicated that the film formation on stainless-steel food contact surfaces can be reduced by employing cheap yet sustainable approaches which in turn do not allow the biofilm formation and enhance the safety of food.

High-Intensity Ultrasound

In recent years, the food sector has paid a lot of attention to the use of ultrasound. Ultrasound is considered a green and cost-effective technology (Zheng et al., 2019). The decontamination of surfaces submerged in an ultrasonically activated liquid is easily achieved by the application of high-intensity, high-frequency sound waves. The ultrasound has become more popular as a technique due to better understanding of chemical reactions and surface conditioning in recent times. This technique is non-destructive and offers many benefits such as uniform cleaning, microbiological safety, and maintains quality of food (Sharma et al., 2022).

The ultrasonic waves are made up of compression and expansion cycles. They have the ability to penetrate and disinfect any surface which is submerged in a liquid medium that conducts sound. These waves can reach difficult areas and expertly clean tread roots, blind holes, and even the smallest surface shapes. Yu et al. (2020) stated that positive pressure pushes all the molecules together during compression whereas expansion cycle creates voids due to the created negative pressure which overcomes the tensile strength of the fluids. This makes ultrasonic cleaning a very effective and distinctive method.

Reduction in the attachment of biofilms is one of the main features of ultrasonic cleaning. Brasil et al. (2017) evaluated a non-thermal method of cleaning and disinfecting knives used in slaughterhouses in combination with ultrasound using chlorinated water and a neutral detergent. The temperature required to clean and decontaminate cutlery was reduced after the ultrasonic treatment. The cleaning process of the knives was more effective and ultrasound had no effect on the structural integrity of cutlery tested.

Cold Plasma Technology

Plasma-based technology is a unique and non-thermal method used for the production of antimicrobial materials and can be used as an antimicrobial coating. These coatings can be used on different types of metallic, polymeric and ceramic surfaces also. These can be applied even on temperature and moisture reliant devices. This is not doable using wet technology. Niemira and Gutsol (2011) have stated that terms like cold, cool, and non-thermal plasmas are applicable to the procedures operating at or near room temperature whereas thermal plasmas are associated with arc welders, combustion tools, or other high-temperature methods. Cold plasma is a non-contact, waterless technology and does not employ any antiseptic substances but an effective decontamination technique. Therefore, food contact surfaces that are prone to contamination with human pathogens can be treated with cold plasma. Romani et al. (2020) found that the treatment with plasma and carnauba wax coating on bi-layered myofibrillar protein film improved its tensile strength and water vapor permeability for its use as packaging material.

The current focus is on the plasma polymer film, which is made by plasma-enhanced chemical vapor deposition. These films exhibit exceptional adhesion, a highly crosslinked structure, and the capacity to change attributes by varying a parameter or precursor. Additionally, they are suitable for industrial use, due to the reduction in the use of chemical solvents. Advanced composite films or complex hybrids can be synthesized when plasma source parameters and deposition structure are properly controlled. Due to their abundance of free radicals, polymers that have been plasma-treated or created serve as highly reactive surfaces.

Prevention

When a food contact surface is decontaminated, the following core task is to prevent any recontamination from occurring, either on the same surface or on the finished product. This can be achieved by the complete removal of the source or potential source of recontamination from the whole processing line. Altering the environment in which the processing is done can also help in the prevention of recontamination. Microbes generally grow in places of high moisture so removal of moisture becomes a key point in preventing recontamination. All the places, where there are chances of water being found stagnant, must be identified and must be taken care of. Similarly, some dead ends are not properly cleaned or are left unintentionally, as a result, these places start harboring microbes that can eventually cause failure in the decontamination systems. Changing the materials of the equipment could be really helpful as well, for example, replacing conveyor belts with stainless steel would prevent microorganisms from attaching to the surface, hence lowering the chances of contamination during the process.

Conclusion

The microbial contamination in the form of biofilm formation on the food contact surfaces is detrimental to the efficacy of the contact surface in terms of both high or low temperature exchange as well as poses health hazards to the end consumers. Food scientists and technologists have worked for years on developing methods that may reduce the microbial attachment or create an antimicrobial environment using layers which are both functional as well as safe. The research has resulted in generating a number of solutions and technologies to resolve the problem of biofilms. Cold Plasma technology, High Intensity Ultrasound, and Surface functionalization are some technologies that are revolutionizing nature and usher in the change in tackling this issue. Their efficiency can be increased further by incorporating two or three technologies together to generate better results. Multifunctionality is the need of the hour. The surface coating should be multifunctional yet safe for human health. Therefore, incorporating natural compounds into the surface's growth is and would be the best way to enhance the sanitization process and change the physicochemical characteristics of the surface. However, more research is needed in the field of safety and inertness of the food contact material. The quality of the food must be retained along with increasing the safety and inertness of the food contact material. There is an urgent need for a multifunctional antimicrobial coating having a nanoscale surface topology may find use in all aspects of food processing. Additionally, combining two treatments, such as using steam followed by ultrasound, could be a practical choice. A significant focus should be placed on using more natural agents or their extracts for decontamination purposes as consumers are looking for natural or organic solutions. There is an increased awareness and consumers nowadays are familiar with the toxic effects as well as carcinogenicity of some detergents and cleaning materials which might find entry into the food indirectly and make food unsafe for consumption.

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