Chapter 16
Food Contact Surfaces, Risk of Contamination, and Solution

Barinderjit Singh, Sahil Chaudhary, Gurwinder Kaur, Vijay Kumar Juneja, and Rubrinder Singh Sandhu

Introduction

Given the growing population, the primary goal of the various food industries worldwide is to increase production and ensure food security. However, various impediments stand in the way, and the target is often compromised due to several major reasons, the most serious of which is food contamination. Microbe-contaminated food not only reduces fresh food quantitatively but also has a negative impact on humans upon consumption. Pathogens can enter food at any food processing stage. However, keeping food free of microbes and decontamination through the processing route is the best solution for avoiding the economic, environmental, and harmful effects on human health.

Limiting the survival of microorganisms on contact surfaces is one way to limit their spread. Anything that could come into touch with human food is included in the category of "food contact surfaces," as are any surfaces from where food may be contacted or drained during routine business operations (GMP, 21 CFR 110.3). The most frequent food contact surfaces in various food processing sectors include utensils, knives, workstations, cutting boards, conveyer belts, ice makers, storage containers, gloves, and aprons. Designing of equipment must take care that there is no dead area or poor drainage, but rather sufficient sloping and a proper drainage

B. Singh (✉) · S. Chaudhary · G. Kaur
Department of Food Science and Technology, I. K. Gujral Punjab Technical University, Kapurthala, Punjab, India

V. K. Juneja
USDA, Agricultural Research Service, Eastern Regional Research Center, Wyndmoor, PA, USA

R. S. Sandhu
Department of Food Technology, Ch. Devi Lal State Institute of Engineering and Technology, Sirsa, Haryana, India

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channel. Overall, equipment should be constructed using excellent design principles to facilitate easy cleaning, efficient drainage, and appropriate material compatibility with the food. Material selection for the processing machine should be selected viably, considering material compatibility with the nature of the foodstuff to be processed (Fortin et al., 2021). If equipment material remains in contact with perishable items, it can affect the property of the food. For example, pickled fish can be highly corrosive biomaterial, whereas fresh fish is comparatively weakly corrosive. In the past, wood was considered a good option for food contact materials, but with changing times and needs, new materials have been used as food contact surfaces.

When working with food products that are high in moisture, nutrients, and enzymes, it is essential to clean the surfaces frequently. The meat processing line is one such example, where biofilm formation is quite common; hence, the demand for cleaning at intervals exists. Cleaning is the first step in any procedure involving biological sound materials because previously deposited remains can harbour microbiota and introduce unwanted decontamination into the new batch. After each batch processing, thorough equipment cleaning should be ensured. Nevertheless, other factors, in addition to cleaning inspections, play a role in determining the overall effectiveness of the assurance for the sanitization of food contact surfaces (Owusu-Apenten & Vieira, 2022). Material surfaces should be manufactured with a superior smooth surface so that it can only aid in cleaning and prevent biofilm formation and harbourage niches for microbes, allergen residues, and other contaminants (Faille & Carpentier, 2009; Hasnan et al., 2022). Therefore, every sector of the food industry should adhere to a standard operating procedure that includes the oversight of cleaning tasks, verification checks, and necessary monitoring for visual inspections.

Different global markets have different regulatory requirements for food contact surfaces and materials. Therefore, many nodal agencies aim to improve food contact surface safety by developing standards, validating, and certifying the food equipment that meets the federal requirements for food processing equipment of almost any region. In the United States, National Sanitation Foundation International (NSF International), a not-for-profit-organization, provides 3-A sanitary standards dedicated to maintaining advanced food safety through sanitary equipment design. It also develops uniform, consensus-based national standards or protocols for food processing equipment and packaging that meet almost any region's material requirements. 3-A Symbol/NSF mark on any food equipment confirms that equipment is tested and audited by an independent third party and complies with the stipulations of the FDA Code of Federal Regulations or European Regulations. However, the European Hygienic and Design Group (EHEDG), a consortium of equipment manufacturers, food processing companies, educational institutions, and healthcare officials, has greatly scaled up hygienic engineering in Europe in order to promote hygiene while foods are being produced, processed, and packaged. Before the equipment can display the 3-A Symbol/NSF mark/EHEDG logo, any deficiencies discovered during an inspection must be corrected.

Important Aspects Associated with Food Contact Surfaces Decontamination

Growing concern for safety and imposing strict regulations have led manufacturers to focus more on hygiene maintenance. Substandard designed and/or maintained equipment only adds to the vulnerability of the issue. Henceforth, cross-contamination of food from a contact surface can only be stopped by paying attention to the prerequisites for the workstation including material selection, the right design, and the cleaning of the contact surface before and after use.

Prerequisite for Material Selection and Suitability

Principally, food contact surfaces should comply with regulations directed by the European Union and the Food and Drug Administration (FDA). Surfaces should be non-reactive with both food products and cleaning agents. It should be non-polluting, non-corrosive, non-toxic, non-absorbent, mechanically stable, and easily cleanable. Typically, the working surface must be free from wood and standard glass in open processing areas; however, polymer materials like polycarbonate or reinforced glass (regular glass with a protective layer) are still preferred. The most important consideration when designing any equipment that will be in direct contact with the food is that it does not introduce toxicity to the food. The designer must ensure that no harmful substances enter the food through direct or indirect contact under the intended conditions (temperature, pH, and humidity) (Moerman & Partington, 2016; Moerman, 2017). Worldwide, different federal agencies have established directives that cover material compositions. GMP (Good Manufacturing Practices) for materials and items intended to get into exposure to food throughout Europe are governed by the Food Directive 89/109/EEC, Regulation (E.C.) No. 1935/2004, and Regulation (E.C.) No. 2023/2006. Despite the fact that the member countries of the EU are free to enact their own laws, Regulation (EC) No. 764/2008 of the European Parliament and Council on July 9, 2008 stipulates that every member of the EU must concur on the principle of Cooperative Identification (Lewan & Partington, 2014). While Regulation (E.C.) No. 1935/2004 is for particular obligations on tracing and approval procedures for fresh substances, Framework Regulation (E.C.) No. 1935/2004 on materials and items destined for consumption in nearby nourishment gives general guidelines for governing any kind of food contact matter. Additional legislation involves those governing plastics and items that come into touch with food (Regulation E.U. N° 1183/2012, Regulation E.U. N° 10/2011, and Directive 2002/72/E.C.), contact between recycled plastics and food (Regulation (E.U.) No. 282/2008), elastomers and rubbers in interaction with food (Resolution A.P. (2004) 4 and Directive 93/11/EEC), certain epoxy resins in food contact (Regulation (E.C.) No 1895/2005, and Directives 2004/13/E.C. and 2002/16/E.C.), monomers of vinyl chloride in food contact plastics (Directive 78/142/EEC), and ceramic components in food contact (Directives 2005/31/E.C. and 84/500/EEC). Chemicals must be properly screened for their effects on human health and the environment under REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals), a law enacted by the European Union. In the U.S., FDA is the nodal agency that directs guidance communicated in the FDA Code of Federal Regulations (CFR), Title 21, parts 174–190 (Hennessey et al., 2011; Skjöldebrand, 2013; Moerman & Partington, 2014; Meghwal et al., 2017).

Food Contact Material

Food contact materials selection and fabrication must adhere to strict guidelines. When selecting a material, it is important to consider the working conditions, including temperature, pH, moisture, pressure, steam, porosity, corrosiveness, and non-tainting. Material suppliers are responsible for making sure that the materials they supply meet the federal requirements for evidence provision. Although there are many materials that can be used for machinery, the choice of material is crucial to the overall effectiveness of the equipment.

Metals are the most important group of materials utilized in the manufacture of machinery and equipment. The metal selection depends on the stress value of the metal, apart from its corrosion resistance, workability, weldability, and cost. Metal construction equipment for wet-cleaned processing stations is logically preferred; however, alloys can also be employed, contingent on the intended working environment (Moerman & Partington, 2014). Surfaces that are bound to come into contact with food should be made of stainless steel that meets the American Iron and Steel Institute's 303, 304, or 316 Series standards or the corresponding Alloy Cast Institute kinds. The chemical compositions of these stainless steel are specified by the American Society for Testing and Materials specifications (3-A SSI 606-05, 2002). Austenite-based 18%Cr/10%Ni AISI 304 stainless steel is recommended for a variety of applications, especially in environments with lower halide ions levels. In such cases, pitting, corrosion, and stress corrosion cracking are quite prevalent. Where the environment contains elevated chloride levels (0.015–0.05%) at optimal working temperatures (<60 °C), the molybdenum comprised 17%Cr/12%Ni/2.5%Mo AISI 316 is recommended. This substance also offers improved resistivity to corrosion, which makes it perfect for drives, rotors, pump castings, and closures. However, because it is so simple to weld, its low-carbon variant, AISI 316L, is suggested for pipelines and vessels. In the case of more complex options, such as cutting blades, AISI 420 or AISI 440C may be required. For harsh working conditions, super-austenitic stainless steels, such as 254SMO offer improved chromium, nickel, molybdenum, copper, and nitrogen contents. This improves corrosion resistance. Apart from that, Incoloy 825, with integrated chromium and nickel content, or even titanium, can be appropriately selected while aiming for corrosion resistance, hardness, pliability, machinability, welding ease, and cost as well. Overall, AISI is commonly used worldwide to manufacture food-grade processing units (Lewan &

Partington, 2014). When it comes to aluminum, it is not recommended due to its insufficient corrosion resistance. However, aluminum along with its alloy can be used as contact surfaces for dry material workstations. Similarly, carbon steel can substantially be considered for dry processing chambers and dry-cleaning operations (Moerman, 2011; Moerman & Partington, 2016).

Plastics are wonderful materials that offer certain advantages over metals, including lower costs, less weight, and better chemical resistivity. However, only a few types of plastic are permitted for use in contact with food, thus when selecting a material, one must ensure that it complies with all applicable laws. Some plastics are porous; hence, there is a risk of food residues and cleaning solutions leaching into the porous materials and then back into the food. Plastics often degrade over time, and additional stress, strain, and temperature, from working conditions and cleaning solutions, hasten the degradation process. Polypropylene, polyvinylchloride, polycarbonate, and high-density polyethylene are typically as for food contact purposes in view of unambiguous cleaning. Moreover, fibre-reinforced and glass-reinforced plastics are increasingly adopted for embodying conveyor belts and for storage of raw materials (Baker, 2013; Djekic et al., 2018). Polytetrafluoroethylene, for example, is said to be porous and hard to clean. Because of this, it is rarely recommended for aseptic packaging equipment. The basic strength and other properties of polytetrafluoroethylene can be improved by the addition of composites. For example, polytetrafluoroethylene (PTFE) is allegedly porous and cumbersome to clean. Therefore, it is often not recommended for aseptic packaging equipment. Composites can be introduced to ameliorate the basic strength and other characteristics. ASTM standards can be used to check for custom-made changes to the composites.

According to the International Union of Pure and Applied Chemistry (IUPAC) definition, elastomers are genetically polymers that exhibit “rubber-like elasticity”. Elastomers have significantly impacted the field of food contact surfaces, with key applications including sealing gaskets, gloves, conveyor belts, and tubing (Kühne et al., 2021). Elastomers comprise an array of chemically different polymers. Rubber represents a group of materials that are distinguished by their elasticity (resilience). Natural rubber, isobutylene-isoprene rubber, acrylonitrile butadiene rubber, and styrene-butadiene rubber are a few examples (Lewan & Partington, 2014). Again, the selection should be made based on the test results in conformity with ASTM standards.

Besides the ones mentioned above, other types of materials are also commonly used for food contact surfaces. Ceramics are often tagged as non-metallic and inorganic materials formed by the action of heat. Clay is one of the oldest known ceramics since historic times. Ceramics are effectively used as active mechanical seal elements on rotating equipment. Adhesives are used to keep gaskets intact at a particular place. They should particularly follow the equipment guidelines, as they often incite parochial corrosion. Open adhesive areas can attract dust and dirt; therefore, no open spaces are acceptable and bonding must be continual, mechanically sturdy, and temperature resistant.

Role of Design and Construction to Minimize Food Contamination

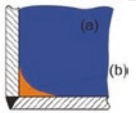
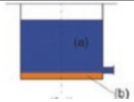
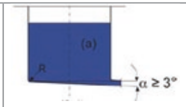
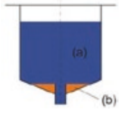
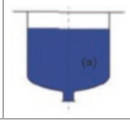
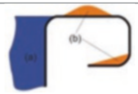
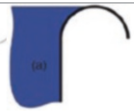
Hygienic design is an easily cleanable design. Specifically, it's not hygienic until cleaned or disinfected, so it's about the design that offers easily accessible cleaning. We find recalls and hazards that sometimes occur in the food industry and directly or indirectly are associated with improper use of equipment. It can be anything; the design of processing, storage, and packaging equipment and its use ultimately impacts. Different aspects that are important to consider while intending to frame equipment are depicted in Fig. 16.1.

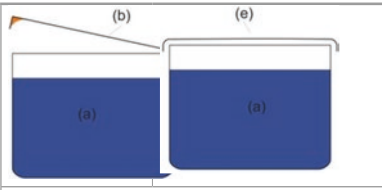
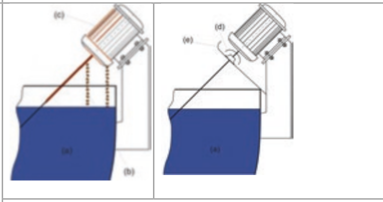
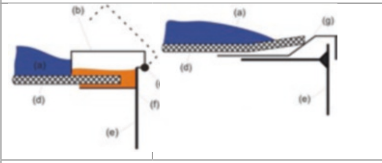
Automation systems would handle process-control activities that ensure food safety and quality. By reliably enabling more complicated activities, they would also simplify the physical design and inventory of physical equipment, reducing construction, cleaning, preventive maintenance, inventory, and dependability risks. In order to guarantee safe food, the processing and handling equipment for food items must be planned, manufactured, constructed, and installed. As a result, surfaces are protected from everyday contact with caustic food ingredients (Faillea et al., 2018). Individual equipment needs, such as joints, drainability, top rims, covers, positioning of auxiliary equipment, sides of conveyer belts and cladding, structure, and insulation, must be considered to lower the risk of food contamination. Hygiene hazards from features like protrusions, recesses, edges, and fissures may be reduced by using permanent joints instead of demountable ones. Welding is the preferred method for permanent couplings between metal parts. However, several other typical flaws may occur hitched welds, including misconfiguration, splitting, porousness, and inclusions, which could turn out out be provenance of microbial loads. Table 16.1 illustrates that welding should not be performed near equipment with sharp corners. Therefore, it is preferable to weld seams in the plane area. When the radius of a corner is limited to 3 mm or less, its cleaning capacity should be evaluated (EHEDG Doc 8, 2018; Moerman, 2011; Moerman & Lorenzen, 2017; Marriott et al., 2018; Schmidt & Piotter, 2020). Another factor that influences food safety is drainability. Equipment used to store food, such as tanks, vessels, troughs, reservoirs, hoppers, bins, and chutes, must be completely self-draining, as shown in the table. Sharp edges must be avoided for proper drainage and cleaning. The radius must be properly determined. Horizontal surfaces must have a slope of at least 3 degrees. The top rims of product-containment equipment should not have ledges where the product may collect and become difficult to clean, especially in open tanks, chutes, and boxes (EHEDG Doc 13, 2004; ISO, 2002). Open-top rims must be rounded and sloping for drainage, as shown in Table 16.1.

Covers are also placed on tanks, transport system edges, and inspection tables to keep items clean while being processed or stored. If they are not completely removable for cleaning, they must be slanted for drainage. If hinged covers are utilized, the hinges must be made to be easily cleaned and to prevent the accumulation of item, dirt, and foreign items like bugs. Continuous-style hinges are not permitted as shown in Table 16.1. It is necessary to properly weld or seal any pipes and devices

Fig. 16.1 Key points to consider while designing or selecting a hygienic equipment design

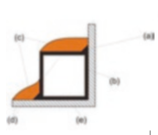
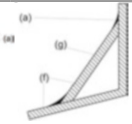
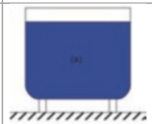
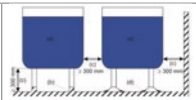
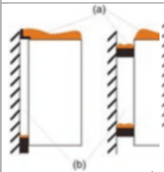
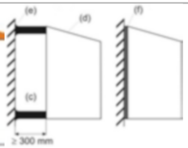
Table 16.1 Exemplification of the importance of design and construction considerations for open equipment to minimize food contamination

Component of food-containing equipment	Don'ts	Do's	Potential outcomes	References
Joints			Sharp internal angles should be avoided as mass pile-up can instigate there, contaminating the batches.	EHEDG Document No. 13 (2004). Hygienic design of equipment for open processing
	(a) Product area; (b) Sharp internal angle			
Drainability			Discharge openings must be fully self-drainable. Discharge outlets above the lowest level of equipment will prevent self-draining and cause residue silting.	
				
	(a) Product area; (b) Residue accumulation			
Top rims			Open tanks and chutes must avoid ledges where the product can become lodged and become difficult to clean. Open-top rim designs must be rounded and sloped for drainage.	
				
	(a) Product area; (b) Possible residue accretion zones			

Covers	 (a) Product area; (b) Pivoted area; (c) Hinge; (d) Dead area; (e) Not fixed	Continuous-style hinges shall not be used. Detachable, unfixed covers are preferable.	
Arrangement of ancillary equipment	 (a) Product area; (b) Contamination – condensate, lubricants; (c) Motor with fins – dead areas; (d) Thrower ring; (e) Self-draining protection sheet with "upstand"	The mounted motor drive above the product should preferably be placed beside the equipment rather than above it.	
Sides of conveyor belts	 (a) Product area; (b) Pivoted cover; (c) Hinge; (d) Belt; (e) Frame; (f) Dead area; (g) Detachable cover	Non-removable bearing surfaces for belts and covers, as well as hinges of pivoted covers, are difficult to clean.	

(continued)

Table 16.1 (continued)

Component of food-containing equipment	Don'ts	Do's	Potential outcomes	References
Cladding, framework, and insulation	 (a) Welding; (b) Frame; (c) Residues of soil; (d) Horizontal parts; (e) Cladding; (f) Slope; (g) Reinforcement		Possible soil retention in horizontal ledges, projections, and frames. Sloped surfaces avoid the accumulation of soils and assist drainage. A minimum slope of 30° is required to avoid dust accumulation and facilitate inspection. Cladding must be installed to maintain a minimum clearance of 30 cm between adjacent surfaces.	
Installation of equipment fixed to floors	 (a) Product area; (b) Rounded pedestal; (c) Clearance; (d) Sealed to the floor		Complicated cleaning underneath the equipment with a small clearance to the floor. Proper fixation of feet to rounded pedestals is ideal or sealed to the floor with sufficient clearance characterizes hygienic design.	
Installation of equipment fixed to walls	 (a) Residues of soil; (b) Small clearance; (c) Clearance; (d) Slope; (e) Radius; (f) Sealing		Horizontal surfaces or ledges retain soil and small clearances impede cleaning between walls and equipment. Horizontal equipment supports are ideal with underneath clearance; direct fixation of equipment to the wall is better if sealing materials are used.	

Adapted from DOC 13: Hygienic design of open equipment for processing of food

that are attached to or going through covers (Moerman & Kastelein, 2014; Gurnari & Gurnari, 2015). When a motor drive is installed above a product, it is preferable to install it next to the equipment rather than above the product. Drip trays and discharge rings on the drive shaft are necessary for other appliances to reduce the possibility of lubricating and dust from the electric motor or gearbox seeping onto the product and contaminating the table. The bottom of the throwing ring must be accessible for inspection. Conveyor belts may meet food when utilized for product inspection or conveyance.

Bearing surfaces that are detachable and simple to clean provides support to the belt's edges (Kold & Silverman, 2016; Rashid et al., 2023). Equipment cladding needs to be uniform, persistent, and crack-free in order to be easily cleaned. Ledges, projections, and crevices should be avoided since they pose a risk of soil retention. If feasible, tilt horizontal shelves and extensions (Table 16.1). Slopes of at least 30 degrees are recommended to discourage dust collection and make routine checks less laborious. A minimum of 30 centimeters must be left between the cladding and any adjoining walls or ceilings. If equipment support structures are connected to the floor or walls, the equipment must be adequately sealed against the mounting surface, or a minimum clearance for cleaning and inspection must be used. After cleaning, it's crucial to keep spaces, fractures, and cracks free of any places where insects or bacteria could hide or thrive. The gap depends on the equipment's bottom size, which should be 300 mm (EHEDG Doc 8, 2018; Lelieveld et al., 2014).

Traditional and Emerging Trends in Food Contact Surface Decontamination

Different factors in food processing realm may favour the formation of biofilms. Moisture and nutrients act as a nucleus to attract microbes, which not only live on them but also present a significant risk of food contamination during the processing line, which resultantly only adds to the transmission of foodborne pathogens and health implications. In reference to this, it becomes critically important to implement procedures to prevent, minimize or eliminate the cause. Conventional procedures do exist, but have few limitations that limit their use. Henceforth, associated individuals and food industrialists are constantly looking for suitable alternatives that can help with these issues while wasting as few resources as possible. An extensive summary of the various trends in the development of technology for the cleaning of food contact surfaces is shown in Table 16.2 and discussed hereunder.

Heat treatment is among the most common and traditional methods for treating food contact surfaces. Heat-based methods are still widely used in industry today. Hot water and steam have been conventionally used to eliminate formed biofilms from surfaces. To clean surfaces, a spurt of hot water is channelized to treat the processing surfaces, specifically, with water temperatures optimized to target a particular lot of microbiotas. A high-pressurized steam is splashed on surfaces,

Table 16.2 Recent approaches on technological advancements for decontaminating food contact surfaces

Approach	Treatment	Surface	Treatment specifications	Results	References
Heat	Hot water	Stainless steel	Hot deionized water 71 °C for 30 s	All biofilms were very sensitive to hot water treatment, which reduced the *S. Enteritidis* cell populations by 4.30–7.08 log CFU/cm^2	Yang et al. (2017)
	Superheated steam (SHS) and saturated steam (S.S.)	Stainless steel (type 304 with No. 4 finish (STS No. 4), stainless steel (type 304 with 2B finish (STS 2B), high-density polyethylene (HDPE), and polypropylene (P.P.)	The coupons were exposed to SHS on both sides for 2, 4, 7, 10, 15, or 20 s. The distance between the coupons and the steam generator nozzle: 7 cm Saturated steam (S.S.) treatments were performed at 100 °C, while SHS treatments were performed at 125 or 150 °C.	Amongst all coupon types, SHS was more effective than S.S. in inactivating the *S. aureus* biofilms. *S. aureus* biofilms on HDPE and P.P. coupons were reduced by 4.00 and 5.22 log CFU per coupon, respectively, after S.S. treatment (100 °C) for 20 s. S.S. treatment for 20 s reduced the amount of *S. aureus* biofilm on STS No. 4 and STS 2B coupons to below the detection limit. SHS treatment (150 °C), S. aureus biofilms on HDPE and P.P. needed 15 s to be inactivated to below the detection limit, while only 10 s for steel coupons.	Kim et al. (2019)
	Saturated steam	Stainless steel (S.S.) (AISI 316, No. 4), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polyethylene terephthalate (PET)	A stainless-steel chamber (34 cm × 57 cm × 29 cm) with three steam distribution pipes and 25 steam nozzles was used for the experiment.	Steam exposure for 30–180 s at 100 °C set off a 4.0–6.4 log10 CFU/coupon reduction of *L. innocua* biofilm on S.S., and 3.0–4.8, 2.8–4.2, 2.7–4.5 and 2.6–3.3 log10 reductions on PET, LDPE, PVC, and rubber surfaces, respectively.	Hua et al. (2021)

Chemical	Chlorine gas	Teflon, silicon, rubber, polyvinyl chloride (PVC), type 304 stainless steel (S.S.) with 2B or No.4 finish, and glass	ClO_2 gas was prepared using a ClO_2 gas generating system and was introduced into the polyvinyl chloride treatment chamber. Inoculated samples were placed in the treatment chamber and covered with a plastic lid. Gas concentration.: 20 ppmv ClO_2 Treatment time: 5, 10, and 15 min Treatment temp: 22 ± 2 °C. R.H. of the treatment chamber: 90%	The degree of log reduction of the three pathogens increased in the following order – silicon, Teflon, rubber, S.S. 2B, PVC, and S.S. No.4. A significantly higher ($p < 0.05$) inactivation of *E. coli* O157:H7, *S. Typhimurium*, and *L. monocytogenes,* was achieved on glass with more than 5.91 to 6.81 log reduction (detection limits <0.48 log CFU/cm^2). As treatment time increased, different levels of inactivation of the three pathogens were observed among the samples. Contact angles of food contact surfaces were highly and negatively correlated with the log reduction of all three pathogens. There were generally weaker correlations between the roughness values of sample surfaces and microbial reduction compared to those between hydrophobicity and microbial reduction	Park and Kang (2017)
	Alcohol-based sanitizer (70% v/v ethanol solution) and the chlorine-based sanitizer (200-ppm sodium hypochlorite solution)	Polypropylene (P.P.), polyethylene (P.E.), stainless steel (SUS) and glass (G.L.)	Surface coupons were immersed in 100 ml of chemical sanitizers. Immersion time: 3, 5, or 10 min Temperature: 25 °C.	Sanitization more efficiently lowered *S. aureus* counts on SUS and G.L. than on P.P. and P.E. Sanitization efficacy of ethanol was better than that of chlorine. Surfaces with scratches and biofilms were the most resistant to sanitization methods. Ethanol emerged effective bactericidal agent, regardless of the material and roughness	Kim et al. (2017)

(continued)

Table 16.2 (continued)

Approach	Treatment	Surface	Treatment specifications	Results	References
	Slightly acidic electrolyzed water (SAEW)	Stainless steel and glass	SAEW was generated by the electrolysis of sodium chloride and hydrochloric acid using a flow-type electrolysis apparatus equipped with a non-membrane electrolytic cell. SAEW was diluted to 10-, 30- and 50-fold in the sterilized water used in this study	The results showed that SAEW (pH 5.09 and available chlorine concentration (ACC) of 60.33 mg/L) could kill *L. monocytogenes* on food-contact surfaces completely in 30 s, a disinfection efficacy equal to that of NaClO solutions (pH 9.23 and ACC of 253.53 mg/L). The results showed that long exposure time and high ACC contributed to the enhancement of the disinfection efficacy of SAEW on *L. monocytogenes* on food-contact surfaces.	Hao et al. (2022)
	Slightly acid electrolyzed water (SAEW, pH = 5.0)	Stainless steel	Saturated chloride solution (25 g/L) and tap water were simultaneously pumped into the generator (18–20 °C). The amperage was fixed at 20 A. ACC: 50–200 mg/L pH = 5.93 Oxidation-reduction potential (ORP) = 948 mV Exposure time: 0–6 min	SAEW yielded higher reductions of *L. monocytogenes*, i.e., 2.30 ± 0.16 to 5.64 ± 0.11 log cfu/cm^2, in comparison with neutral electrolyzed water (NEW, pH = 7.0) (1.55 ± 0.11 to 5.22 ± 0.12 log cfu/cm^2), attributable to the synergistic bactericidal effect between the acidic pH, higher oxidation-reduction potential and the effective form of chlorine.	Possas et al. (2021)

Physical U.V.	Ultra-high irradiance (UHI) blue light	Stainless steel, glass, polypropylene, polyethylene	Light electroluminescent diode (LED)-based device was designed to generate irradiation at an ultra-high-power density (901.1 mW/cm^2).	Short-time treatments (below 10 min) at 405 nm induced a ~4.5 log reduction rate of the cultivable yeast population. The inactivation rate was positively correlated to the overall energy received by the sample and, at a similar energy, to the power density dispatched by the lamp. Within 5 min of treatment, *S. cerevisiae* disinfection was achieved for all tested surfaces. The disinfection of stainless steel was particularly effective, with a complete inactivation of the yeast after 2 min of treatment.	Lang et al. (2022)
	UV-C LED	Stainless steel (S.S.) and high-density polyethylene (H.D.)	Wavelength: 250–280 nm Power: 20 mW The lamp was operated under forward bias at a maximum 400 mA current, corresponding to 100% irradiance. The average irradiance: 2 mW/cm^2 or 4 mW/cm^2	*Salmonella* on S.S. was reduced by 1.97 and 3.48 Log CFU/cm^2 after 60 s of treatment with 50% and 100% irradiance, respectively. H.D. showed a lower decrease of *Salmonella*, but still statistically significant ($p \leq 0.05$), with 1.25 and 1.77 Log CFU/cm^2 destruction for 50 and 100% irradiance after 60 s, respectively. Longer exposure times of H.D. to UV-C yielded up to 99.999% (5.0 Log CFU/cm^2) reduction of *Salmonella* with both irradiance levels	Calle et al. (2021)
	UV-C	Polyethylene (P.E.) and stainless steel (S.S.)	Custom-made U.V. unit 95 W low-pressure mercury lamps of 50 cm length housed in an enclosed stainless-steel cabinet with internal dimensions of 790 × 390 × 345 mm. Treatment distance: 6, 16, 26 cm	When S.S. was treated with UV-C, the maximum reduction of *P. fluorescens* achieved was 2 log cycles, even at the highest dosage.	Pedrós-Garrido et al. (2018)

(continued)

Table 16.2 (continued)

Approach	Treatment	Surface	Treatment specifications	Results	References
Sound waves	Ultrasound—steam treatment	Plastic (polystyrene plates, Ø = 52 mm) and steel (Ø = 20 mm)	Ultrasound range: 20–40 kHz Nozzle delivery: 25 kg/steam per hour at 2.7 Bar(g) pressure Temperature: 85, 90 or 95 °C Treatment times: Murine norovirus (MNV) (0.8–2.0 s on plastic; 0.8–5.0 s on steel) and for hepatitis A virus (HAV) (0.8–5.0 son plastic and steel both)	For MNV on plastic and steel surfaces at temperatures 85, 90 or 95 °C, a mean genome copies (G.C.) reduction of log 0.4, 0.2 or 0.3 and 0.4, 0.4 or 0.5, respectively, were observed. For HAV on plastic and steel surfaces the mean log reduction of G.C. observed were 0.8, 0.7 or 1.5, and 0.4, 0.4 or 0.6 at temperatures of 85, 90 or 95 °C, respectively.	Rajiuddin et al. (2020)
	Ultrasound-assisted sodium hypochlorite (NaOCl) treatment	Stainless steel	Ultrasound treatment times i.e., 5, 20, 40, 60, 80, and 100 min, with NaOCl (50, 100, 150, and 200 ppm)	100 min ultrasound treatment solely reduced *L. monocytogenes* of 1.09 on stainless steel, depending on the treatment time (5–100 min). Population reduction ranged 1.48–3.79 CFU/mL, depending on the NaOCl concentration (50–200 ppm)	Lee et al. (2014)
	Ultrasound	Polyurethane conveyer belts	Ultrasound frequency: 37 kHz, 200 W Treatment time: 30 min At room temperature	Ultrasound effectively controlled the overall biomass of the biofilm inoculated from cells and spores from the surface.	Fink et al. (2017)

Plasma	Cold atmospheric pressure (CAP) plasma	Stainless steel and polyvinyl chloride (PVC)	Stainless steel (S.S.) type 304 of 0.18 mm in thickness and black polyvinyl chloride (PVC) of 3.4 mm in thickness Treatment time: 120 s Treatment distance: 3 cm	A 120 s treatment time with a 3 cm treatment distance from the surface reduced both adherent cells (initial 5.6 ± 0.2 log CFU/coupon) and 24 h biofilms (initial 5.8 ± 0.4 log CFU/coupon) on stainless steel (S.S.) by >4.6 log CFU. While the same treatment reduced adherent cells (initial 5.7 ± 0.5 log CFU/coupon) and 24 h biofilms (initial 6.9 ± 0.5 log CFU/coupon) on polyvinyl chloride (PVC) by 3.8 ± 0.9 and 3.5 ± 0.5 log CFU, respectively. Mature biofilms (72 h grown) were more resistant than 24 h grown biofilms. This waterless technique induced no changes in S.S. and PVC in terms of chemical properties and visual topography.	Wang et al. (2023)
	Cold atmospheric pressure (CAP) plasma	Stainless steel, commercial poly[ether]-thermoplastic poly[urethane] (PE-TPU) conveyor belts	The plasma system was evaluated against two common food-borne pathogens (*Salmonella* Typhimurium, *Listeria monocytogenes*) on stainless steel surfaces and against *S* Typhimurium on PE-TPU conveyor belts under simulated conditions of a food-processing facility.	A significant level of microbial inactivation was achieved, up to 3.03 ± 0.18 and 2.77 ± 0.71 log CFU/mL reductions of *L. monocytogenes* and *S.* Typhimurium, respectively, within 10 s total treatment on stainless steel surfaces, and a 2.56 ± 0.37 log CFU/mL reduction of *S.* Typhimurium within 4 s total treatment on the PE-TPU material, according to a procedure based on the well-established EN 13697:2015 industrial protocol.	Katsigiannis et al. (2022a, b)

(continued)

Table 16.2 (continued)

Approach	Treatment	Surface	Treatment specifications	Results	References
	High voltage atmospheric cold plasma (HVACP)	Stainless steel, PVC, and silicone	Power supply output: 60 W Dielectric barriers: 4 pieces of plastic Electrodes: Two 15 cm diameter aluminium electrodes Coupons containing *C. sakazakii* were placed in plastic dishes inside a plastic bag (25.5 × 35.5 cm) flushed with a modified atmosphere (10% air, 90% helium) Treatment time: 0, 30, 60, and 90 s.	90 s treatment effectively reduced *C. sakazakii* by ~3 log CFU/coupon compared to untreated coupons.	Phan et al. (2023)
	Gliding arc discharge (GAD) plasma	Silicone (Si), stainless steel (S.S.), polyethylene terephthalate (PET)	GAD plasma was applied using nitrogen gas at flow rates of 0.5 and 1 m^3/h for different time intervals (5–10 min). All 3 surfaces were artificially contaminated with 8.15 ± 0.28 log cfu/mL of *E. coli* and 6.18 ± 0.21 log cfu/mL of *S. epidermidis*.	Significant reductions of 3.76 ± 0.28, 3.19 ± 0.31, and 2.95 ± 0.94 log cfu/mL in *S. epidermidis*, and 2.72 ± 0.82, 4.43 ± 0.14, and 3.18 ± 0.96 log cfu/mL in *E. coli* on S.S., Si, and PET surfaces, respectively, were achieved after 5 min of plasma treatment by using nitrogen as the plasma forming gas ($p < 0.05$).	Dasan et al. (2017)

	Cold oxygen plasma	Stainless steel	Distance b/w electrode and the sample: 10 cm Ozone production was monitored at a distance of 9.5 cm Ozone generated: 3.0 ppm Emitted U.V. light was measured by a photo-radiometer, with doses of 1210–1250 mW/cm^2 at a distance of 9.5 cm. The maximum temperature reached: 32.5 °C. Exposure time to COP: 0, 10, 30, 60, 90, 120, 180, 240, and 300 s	Decrease in the MNV-1 (a human norovirus [NoV] surrogate) and HAV (hepatitis A virus) titers resulting from 10 to 300 s of cold oxygen plasma were 0.27–3.89 and 0.77–2.02 log PFU/ml, respectively.	Park and Ha (2018)

(continued)

Table 16.2 (continued)

Approach	Treatment	Surface	Treatment specifications	Results	References
	Atmospheric pressure plasma jet	Stainless steel	Input power: 650 W	The maximum *Salmonella enterica* population reduction calculated before the inactivation tail ranged from 3.32 (316 HL) to 4.97 log CFU/in^2 (304 MR). Plasma treatment of metal surfaces resulted in an abrupt increase in surface temperature, reaching up to 180 °C within 15 s of treatment, and led to log-linear inactivation in all surfaces treated with atmospheric plasma jet.	Gabriel et al. (2018)
	Cold nitrogen plasma (CNP)	Stainless steel	CNP dose: 200, 300, 400, 500, and 600 W Exposure time: 0.5, 1, 1.5, 2, and 2.5 min.	Upon 400 W treatment for 1 min with CNP, the number of *S. aureus* biofilm was reduced by 2.02 logs. Similarly, the population of *S. aureus* biofilm on a 96-well plate was reduced from 7.30 logs to 5.61 logs. An evident decline of established *S. aureus* biofilms metabolism was seen after exposure to CNP at 400 W for more than 1 min ($P < 0.05$). The population of S. aureus biofilm was reduced by 2.03 logs after 1-min treatment. Extending the treatment time to 2.5 min, the amount of S. aureus was dropped by 3.02 logs. Correspondingly, the population value was reduced from 7.23 logs to 5.33 logs.	Cui et al. (2016)

Biological	*Cinnamomum cassia* and *Salvia officinalis* E.O. based microemulsions	Stainless steel type 304	*C. cassia* and *S. officinalis* E.O.s were selected to formulate microemulsions at relative MBEC concentration (2.5% and 5%, respectively) The two formulations were stabilized with Tween 20 as surfactant.	In reference to contact times utilized, action of E.O. microemulsions was more effective after 90 min (P b 0.05) against *S. aureus* ATCC 43387 24 h old biofilms and desiccated ones. In fact, after 90 min of contact, logarithmic reductions N3 were obtained with all the E.O. microemulsions against *S. aureus* ATCC 43387 2 biofilms in all the applied culture media, with the only exception of *C. cassia* microemulsion toward desiccated biofilms. 90 min treatment with all the formulated E.O. microemulsions ably removed up to 68% of the biofilms from stainless steel surface, in case of the microemulsion compris3ed with *C. cassia* and S. *officinalis*, but none removed biofilm completely.	Campana et al. (2017)
	Thymol, carvacrol and thymol/ carvacrol liposomes (TCL)	Stainless steel AISI 304	Sanitizing solution: 0.106 g of each compound (Carvacrol and thymol) were diluted in 10 ml of 20% (v/v) ethanol solution. Concentration: 0.5, 1.0, and 2.0 MIC Contact time: 1 and 10 min	Adhered *S. aureus* (± 6.1 log CFU/cm^2) were inhibited after 1-min and 10-min treatments using thymol or carvacrol at minimal inhibitory concentration (MIC) and 2.0 MIC. Reductions of 1.47–1.76 log CFU/cm 2 and 1.87–2.04 log CFU/cm 2 were obtained using 0.5 MIC of thymol and carvacrol, respectively. A 10-min contact with free (MIC and 2.0 MIC) and encapsulated (MIC) antimicrobials inhibited attached *Salmonella* (± 6.0 log CFU/cm^2); however, after 1-min of contact, 2.0 MIC of thymol and carvacrol were not able to inactivate adhered *Salmonella* MIC of TCL inactivated S. aureus and *Salmonella* after 10 min; however, after 1-min contact, adhered *S. aureus* and *Salmonella* populations were decreased in 1.62 log CFU/cm 2 and 2.01 log CFU/cm^2, respectively.	Engel et al. (2017)
	Red globe grape stem extracts (GSE)	Stainless steel 304 and polypropylene	Concentration: 0, 0.125, 0.25, 0.5 and 1 time the MIC	GSE reduced adhesion of *Listeria* to stainless steel (0.77–2.22 log CFU cm^{-2}) and polypropylene (0.71–2.38 log CFU cm^{-2}) and completely inhibited bacterial motility at 4.5 mg mL^{-1} of GSE.	Vazquez-Armenta et al. (2018)

however, its efficacy is conditional to direct access, as steam cannot reach hidden spots (Skåra & Rosnes, 2016). The use of steam is quite prevalent for surface decontamination as steam is a powerful energy carrier upon condensing on certain surface. However, complications are associated with contact time and temperature monitoring throughout the contact. Another issue is that, probably because of the contact surface design, the deactivation rates of interface-attached cells may be different from those of floating freely cells. Amplified temperature ranges, however, can speed up and improve the reactions, and henceforth combinations of heat and other approaches can be beneficial (Basumatary et al., 2020).

Chemical washing is another method to ensure microbial disinfection of food contact surfaces. It is often carried out with antimicrobial compounds such as chlorine, iodine, hydrogen peroxide, and quaternary ammonium compounds (QACs) approved chemicals for sanitation purposes. Nevertheless, antimicrobial efficacy is primarily determined by three factors: concentration, temperature, and contact duration. Traditional washing has the disadvantage of reacting with the components of the food surface, making them much more harmful (Song et al., 2019). Number of studies have been unveiled on the associated shortcoming of chemical issues. Alcohol-based disinfectants were observed to be effective for welling and hardening of rubber and certain plastic surfaces, but ineffective against some viruses (Chang et al., 2013). There have also been reports of QACs adsorbing onto cotton substrate wiping materials and ultimately limiting the disinfection procedure failure. Peroxygens have been known to cause chemical irritation and, in some cases, also turned up as corrosive for copper, brass, and bronze surfaces, particularly Peracetic acid (PAA) (Jennings et al., 2015). Prolonged chlorine application is harmful to the outer plastic coat of some insertion tubes (Song et al., 2019). Secondly, the potential reach of chemical washes is sometimes insufficient for the hidden points of apparatuses that cannot be dismantled or for unsuitable construction material used in equipment. Also, the incorrect concentration of cleaning and sanitation agents can have a significant impact on the efficiency of the cleanness and disinfection process. In order to effectively reduce harmful germs, the ratio of these chemical compounds must be tuned because a larger concentration could be damaging to human health. Chemical sanitizers are purposefully used in industries and temperature range of 13–49 °C with particular contact length is recommendable for effectiveness against microbial loads (Sharma et al., 2022). The combination of suitable chemicals at a minimum concentration can provide synergistic effects and eliminate the extreme of sole chemical application. One example is electrolyzed oxidizing water (EOW), which is formed by electrolyzing a sodium chloride solution in an electrolysis chamber with an anode and a cathode separated by a membrane. For EOW production, a salt-diluted solution and current are proceeded via chamber, parting the solution into two separate streams, i.e., acid EOW (at the anode) and alkaline EOW (at the cathode). Weak organic acids can also be used for surface decontamination (Meireles et al., 2016). Because a variety of organic acids, such as citric acid, formic acid, lactic acid, and acetic acid, are naturally present in foods, their application is consumer friendly. Many have GRAS status and have been approved by the FDA and European Commission.

Physical approaches are more popular, especially since fast, mild, and residue-free approaches have received more attention. In comparison to chemical approaches, they can be holistically applied across the processing chain and, in some cases, enables the conditioning of various surfaces (Otto et al., 2011).

Non-thermal plasma is currently being studied extensively. The final state of matter is known as plasma, and in the food sector, charged plasma is highly valued for its superior surface cleaning capabilities. Despite having a neutral net charge, plasma is often described as a "quasi-neutral" medium because it is conductive to electricity (due to the presence of free charge carriers). Its ability to produce an antimicrobial effect and its applicability for surface sanitization are both supported by the presence of electrons, atoms, ions, radical substances, and molecules in a fundamental or excited state, including reactive oxygen species, or ROS, and reactive nitrogen species (RNS), as well as electromagnetic energy (U.V. photons and visible light). These are promoted as highly effective against remnants of biofilms, which are again capable of increasing the inflammatory processes in the adjacent tissues (Mravlje et al., 2021). Plasma technology can be divided into generation, thermal, and low-temperature categories. According to many researchers, thermal plasma consists of thermodynamically balanced ions, electrons, and gas molecules at temperatures around 20,000 K. Non-equilibrium plasma is referred to by vernacular names, such as Cold Plasma, Atmospheric Cold Plasma, and Non-thermal Plasma. Cold plasma can be produced by a radiofrequency generator or by atmospheric pressure, while the dielectric barrier discharge, atmospheric plasma jets, gliding arcs, and radiofrequency-based and microwave-based discharges are the most used atmospheric Cold Plasma sources (Ansari et al., 2022; Hernández-Torres et al., 2022). In an investigation by Khan et al. (2016), a dielectric barrier discharge plasma reactor (underwater DBD) was employed for biofilm inactivation on stainless steel caused by three distinct foodborne pathogens. After 90 min of plasma treatment, results included an inactivation of 5.50 log CFU/coupon, 6.88 log CFU/coupon, and 4.20 log CFU/coupon for *Escherichia coli* O157:H7 (ATCC 438), *Cronobacter sakazakii* (ATCC 29004), and *Staphylococcus aureus* (KCCM 40050), respectively. In another study, Aboubakr et al. (2020) reported that using an air DBD against *Salmonella enterica serovar* Heidelberg on stainless steel resulted in only a 2.5 log CFU deduction on dry surfaces in 10 min. In contrast, >6.5 log CFU decrement was attained on wet surfaces in 3 min, with recommendation for apt application after cleaning to eliminate residual water molecules.

Power ultrasound, typically at a frequency of 20 kHz, is yet another technique that can aid in sanitation practices. Pulsating waves move through water because they are much stronger than regular sound waves, creating millions of tiny cavitation bubbles. These are immensely strong wave bubbles that pop and implode. During implosion, matter and energy capitulate. During an ultrasonic procedure, these imploding cavitation bubbles hit an object's surface, generating heat and even more energy. Energy bursts and rebound on the surface, removing things from the object like a high-pressure vacuum. This approach does not require scrubbing, scrapping, or chemicals, and it saves time while being eco-friendly. This ultrasound-based cleaning can be specifically tuned to ensure the sanitation of various equipment, apparatuses, and parts in the food industry. This method, when combined with heat (thermosonication) or pressure (manosonication), can effectively aid in biofilm elimination. Thermosonication is commercialized for the disinfection of conveyor belts (Musavian et al., 2015; Dallagi et al., 2023). Few studies have been conducted recently to disinfect food contact surfaces to ensure safety from microbes. Webber et al. (2015) used an ultrasound bath treatment (40 kHz frequency and 81 W potency) for 10 min to decontaminate stainless steel AISI 316 coupons (1 cm^2). The authors concluded that ultrasound effectively detached biofilms formed in vitro, highlighting the ease of use and their hydrodynamic properties responsible for destabilizing biofilm structure. In a separate study, Brasil et al. (2017) employed ultrasound (U.S.) with chlorinated water (C.W.) to decontaminate slaughtering knives and compared it to the conventional cleaning method, i.e., manual cleaning with sponges using neutral detergent and washing with chlorinated water (2.05 ± 0.8 mg/l), followed by sterilization (during 20 s at 82.0 °C). The results revealed that the conventional sanitation approach reduced ($p < 0.05$) the counts of mesophiles, *Enterobacteriaceae*, moulds and yeasts, and a similar expression was recorded for U.S. + C.W. (2.05 ± 0.08 mg/l of chlorine, and mode operation normal and sweep for 10 min) and U.S. + C.W. + ND (5 ml/l and mode operation sweep for 5 min) methods. However, increasing the detergent concentration and sonication time (20 ml/l, 15 min) resulted in a significant fall (p 0.05) for the same microbes. Ultraviolet light is another promising dry decontamination technology that is inherently non-thermal in nature. It is a U.S. Food and Drug Administration-approved intervention technique that can be potentially used for effective pathogen decontamination in food contact surfaces and food surfaces. UV gamma irradiation uses UV light technologies to disinfect environmental surfaces. These technologies are portable or stationary units that can disinfect an entire vacant room. Energy emittance from U.V. light ranges between 100 and 400 nm. They travel through waves or particles without causing radioactivity. The classification of ultraviolet light involves UV-A, with wavelengths between 315 and 400 nm, which is linked to human skin tanning; UV-B, with wavelengths between 280 and 315 nm, which is linked with cutaneous burning and cancer of the skin; and UV-C, with wavelengths between 200 and 280 nm, which is known as the germicidal differ due to its efficacy in inactivating bacteria and viruses (Monteiro et al., 2021; Byun et al., 2022). In the food industry, UV-C is used to eliminate microbes on food contact surfaces. UV-C light (200–280 nm) induces alterations in the microbial DNA structure primarily by two different mechanisms: the first is cross-linking genesis between cytosine and thymine, known as direct action, the second is free-radical generation via water radiolysis, known as indirect action. In order to combat microorganisms in the UV-C spectrum, light emittance at 253.7 nm is consistently encouraged because nucleic acids are the primary light absorbers at this particular wavelength (Monteiro et al., 2021; Monteiro et al., 2022).

Several studies on UV application for surface decontamination have been conducted over the last 10 years. Gabriel et al. (2018) tested the potential of UV-C (15 W UV-C light source; lamp to the metal surface distance of 9.8 cm) against stainless steel (304, and 316) with exposure times ranging from 0–180 s. An early fast, log-linear deactivation stage is followed by a gradual inactivity tail in the observed inactivation behavior. D1 and D2 values, or two decimal reduction times, were identified. The D1 values varied from 2.26 (304 MR) to 4.31 s (304 2B) during the initial quicker log-linear inactivation phase. In comparison to type 304 metals, which had D1 values of 2.26–4.31 s, type 316 metal had slightly shorter values, ranging from 2.54 to 3.51 s. In another investigation, Calle et al. (2021) employed UV-C LED light (250–280 nm wavelength, 20 mW power, 105 degrees viewing angle) at 2 mW/cm^2 (half irradiance) or 4 mW/cm^2 (full irradiance) on stainless steel (S.S.) and high-density polyethylene (H.D.), for surface decontamination targets. After 60 s of being treated with 50% or 100% irradiance, the reduction of salmonella on S.S. was 1.97 or 3.48 Log CFU/cm2, respectively. With 1.25 and 1.77 Log CFU/cm2 eradication after 60 s for 50 and 100% irradiance, respectively, H.D. demonstrated a lesser reduction of Salmonella but was still statistically significant (p 0.05). Salmonella was reduced by up to 99.999% (5.0 Log CFU/cm2) with both irradiance levels when H.D. was exposed to UV-C for longer periods of time. Aside from the associated concerns and issues with the technological application, its performance on rough surfaces is affected by certain effects. Moreover, it has been linked to eye damage, burns, and skin cancer. This reason alone is sufficient to ensure that proper protection covering is required when using it in industry. Several options are there, like adjustable portable systems to complete units for conveyor belts, small-sized equipment, and packaging materials (Bharti et al., 2022).

Cold plasma is a novel method for food contact surface decontamination. The most recognized sources are dielectric barrier discharge, atmospheric plasma jets, gliding arcs, and radiofrequency-based, and microwave-based discharges. Inherently, plasma is an ionized gas comprised of ions, free electrons, atoms, and molecules. Reactive oxygen species (ROS) and reactive nitrogen species (RNS) are the most important active plasma agents for discharge to open-air atmospheres. Different species produced during cold plasma treatment include hydrogen peroxide, singlet oxygen, superoxide anion, peroxynitrite, dinitrogen tetroxide, dinitrogen pentoxide, nitrate, nitrite, and others. These created species are highly valued for their antimicrobial effects against a variety of microbiota (Nikmaram & Keener, 2022). However, there are still impediments to the actual large-scale implementation of this technology that must be addressed. One associated issue is that it has a commensurably lower impaling depth and therefore attenuated efficiency against surface biofilms. Therefore, more studies and knowledge are required to understand the inactivation mannerisms on a cellular level using more susceptive approaches. Another issue is that there are no standardized protocols for the decontamination of particular surfaces. However, it is an environmentally sustainable technology that does not require any chemicals nor yield any residues or wastewater. Moreover, lower energy requirements validate its efficiency/suitability for food contact surface application. Furthermore, design simplicity allows for adaptability for flexible and handheld applications, as well as uses in industry (Katsigiannis et al. 2022a, b).

Antimicrobial coatings for food contact surfaces are becoming increasingly popular. Because essential oils and botanical extracts derived from flora are natural in origin, there is no concern about chemical toxicity or residues. These compounds have antimicrobial properties and have been used by mankind for centuries (Rossi et al., 2022). Extensive research on the potential applications in the food industry is currently underway. Several studies have confirmed the effective use of plant-based concoctions to food contact surfaces to ensure microbial safety. Essential oils are fancy composites which are cold pressed or distilled from botanical sources with the likes of stems, leaves, peels, etc. They are appreciably used in ancient times for numerous purposes and nowadays are popularized due to antimicrobial and antioxidant properties (Rudlong et al., 2022). Various reported action mechanisms underlying the compound's antimicrobial efficacy include microbial cell wall affecting the cytoplasmic membrane, cytoplasm congealing, membrane protein damage, and cell constituent leakage due to higher permeability (Torres Dominguez et al., 2019; Rossi et al., 2022). However, microbial inactivation and biofilm liberation depend on many factors such as the relationship between E.O.s effect and composition, concentration, involved bacteria, surface type, and surface smoothness (Nuță et al., 2021). Essential oils can be extracted from spices, herbs, fruits, vegetables, and their by-products, so this approach can alleviate consumer concerns about the green source.

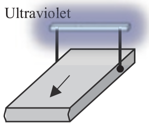
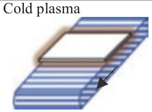
Table 16.3 provides an overview of the decontamination of food contact surfaces for the food industry, including potential benefits and associated concerns with various approaches. Growing cognizance towards incorporating the hurdle approach is high. Incorporating two or more technologies to ensure better safety and stability can be beneficial. Still, proper care must be taken to optimize the whole approach (Yuan et al., 2021). Schnabel et al. (2019) evaluated the synergic antimicrobial effect of plasma-processed air (PPA) and plasma-treated water (PTW) in a study. The plasma-on time (5–50 s) and the course of treatment length of the samples with PPA/PTW (1–5 min) were the determining factors in the unique and synergistic antibacterial capability of PPA and PTW. The only treatment with additive effects was 5 s + 1 min. Increased additive and inhibitory consequences were seen when the PPA treatment was prolonged to 50 s, followed by one, three, and 5 min. Amongst all tested combinations, inactivation was similar (additive) or enhanced (synergistic) compared to single treatments. For *B. atrophaeus* spores, single PAW and shorter CAP treatments showed <0.5 log CFU reductions, while given 3.2 log CFU reductions. The researchers promoted PTW as a potential alternative to efficient sanitation procedures in manufacturing plants by highlighting the combined advantages of PTW for washing and PPA for drying. In a recent study, Byun et al. (2022) pooled peroxyacetic acid or lactic acid with UV-C against *Salmonella* Enteritidis biofilms formed on different surfaces (stainless steel, silicone rubber, and ultra-high molecular weight polyethylene. The obtained results showed that biofilm on the contact surface significantly lowered ($P < 0.05$) by combined treatment of peroxyacetic acid or lactic acid with UV-C. In particular, PAA (50–500 μg/mL) with UV-C (5 and 10 min) reduced 3.10–6.41 log CFU/cm^2, and LA (0.5–2.0%) with UV-C (5 and 10 min) reduced 3.35–6.41 log CFU/cm^2 of *S. Enteritidis* biofilms on the surfaces.

Table 16.3 An overview on technologies for decontamination of food contact surfaces

Technology	Exemplification	Treatment/type description	Advantages	Concerns	References
Thermal		Hot air Hot water	Cheap, environmentally friendly	The conventional method has limited efficacy, higher water consumption, and is unsuitable with heat and moisture-sensitive gadgetry.	Skåra and Rosnes (2016)
Chemical		Chlorine compounds such as hypochlorite, inorganic and organic chloramines, liquid chlorine, and chlorine dioxide can be used as a sanitizer to reduce and eliminate microbiota harbouring on food contact surfaces. Iodine compounds - Iodophors, alcohol-iodine solutions, and aqueous iodine solutions are commonly used to decontaminate surfaces. Ozone is composed of 3 O_2 atoms, is an oxidative agent that has the potential to inactivate microbes due to its oxidizing properties.	Represents a less expensive option than mechanical cleaning, effective as a process since all parts will be reached, resulting in more uniform cleaning.	Practically impossible with fully plugged equipment, severe damage can occur if improper procedures are applied, or unskilled personnel are employed in the application process.	Gallandat et al. (2021); Visconti et al. (2021)

(continued)

Table 16.3 (continued)

Technology	Exemplification	Treatment/type description	Advantages	Concerns	References
Physical		U.V. radiation is specified as the portion of the electromagnetic spectrum between X-rays and visible light. U.V. light ranges from 100–400 nm, further subdividing into UVA (315–400 nm), UVB (280–315), and UVC (200–280), which is called as the germicidal range. Sources – Mercury lamps, excimer (E.L.), pulsed light (P.L.) and LEDs The use of U.V. radiation adds a variety of polar groups to the surface. Hence, this technique must add a specific functional group to the surface.	The process is very fast – with typical exposure times lasting only a few seconds. U.V. light is environmentally friendly.	U.V. light is known to be carcinogenic and causes a mutation in the body, and persistent exposure can lead to cancer.	Calle et al. (2021)
		This generates a wide range of reactive oxygen species (ROS) that are sufficient for the complete bacterial load in the semi-neutral plasma system, including bacterial spores and spoilage/pathogenic microorganisms. Sources – Dielectric barrier discharge (DBD), atmospheric plasma jets (APJs), gliding arcs (G.A.s), radiofrequency-based (R.F.), and microwave-based (M.W.) discharges	Rapid, waterless, zero contact, chemical-free	It cannot be used for the complete inactivation of endogenous enzymes that might be typically adherent to perishable processing units. Secondly, technology is limited to lab-scale only. Commercial-level coverage is still trivial.	Katsigiannis et al. (2022a, b)

	Ultrasound 	This process uses 'ultrasound' to safely enhance and intensify the cleaning process. This refers to sound waves with a frequency above the upper limits of human hearing. Regarding food contact surfaces, ultrasound is most often seen as an expedient for cleaning and removing biofilm.	Irregularities and pores at solid surfaces limit the effectivity; however, ultrasounds ably access and instigate deeper cleaning. Ultrasound also enhances the efficacy of chemical cleaning by favoring the release of contaminants such as oils, proteins, and even microbial biofilms, making them more accessible to chemicals	The ultrasonic field is variable and non-uniform throughout the treatment medium. The same levels of decontamination may not be achieved throughout the whole surface or material.	Astráin-Redín et al. (2019), Yu et al. (2020), Khaire et al. (2022), Dallagi et al. (2023)
Biological	Essential oils, extracts 	Eos, enzymes, biosurfactants, and extract formulations can be used as natural disinfectants to decontaminate food contact surfaces, thus lowering the risk of the indirect transfer of bacterial pathogens to food or persons.	The natural way is energy efficient, has no chemical involvement, antimicrobial activity, or insecticidal activity, and curbs down foul smells.	Accumulation of dead microorganisms on the surface effectively degrades the bactericidal property of the surface, also serving as a nutrient source for other microorganisms. Therefore, there is a need to release or remove the debris of dead microorganisms to maintain antimicrobial properties for the longer term.	Falcó et al. (2019), Rossi et al. (2022)

Validation of Contact Surface Cleanability and Disinfection as an Essential Component

Validation of the cleaning and disinfection process is an important step that can be added to the cleaning and production process. All of the determined prospects and applied regimes can only benefit if their proper application is made. To validate and authenticate the cleaning process, proper validation is necessary. Industries also manufacture foods for different community target groups, such as infants, pregnant women, people suffering from allergies, immunocompromised people, etc., which incites the need to validate the process properly. Moreover, proper cleaning inspection is required to maintain the brand image, particularly for products that are sensitive to people's religious sentiments (Schmitt & Moerman, 2016; Voss, 2018). ISO 22000 defines monitoring as "conducting a planned sequence of observations or measurements to assess whether control measures are operating as intended" and verification as "confirmation, through the provision of objective evidence, that specified requirements have been fulfilled" (ISO, 2005). Various steps are involved in the overall process, which emerges as an important part of the validation process regime. It includes everything from scope determination of cleaning validation to validation reports. The foremost step is to establish a validation objective, which can range from a proper cleaning check of the equipment to a particular microbial strain for a specific industry in order to substantiate the manufacturing authenticity. A qualified and experienced individual should be able to determine the objective and perform validatory checks (Schmitt & Moerman, 2016; Agüeria et al., 2021). When working on a decided objective, the first step is equipment qualification which requires proper certifiable proof of suitability for the intended application. Only properly serviced and operational devices should be marked for use Next is hazard evaluation, which is one the most important and critical steps in the procedure. HACCP is the foundation of the food safety management system that involves proper evaluation of risk factors that can compromise product safety. The evaluation consists of enumerating assessment factors that may have an impact on the cleaning results. Acceptance criteria should be determined on this basis. Therefore, if microorganisms or chemicals are present, whether the limit falls below the levels permitted by the legislative authorities for the particular industry must be determined. As an example, $\mu g/cm^2$ for organic matter or chemicals; while CFU (colony forming units)/cm^2 for microorganisms (Schmitt & Moerman, 2016).

This can only be accomplished through sampling followed by the proper procedures that will guide the success of the cleaning regimen. Both direct and indirect samplings are ideal, however, combined methods are most effective. The direct sampling technique involves collecting samples using swabs, wipes, sponges, or scraping devices (Agüeria et al., 2021). ISO 18593 provides detailed information about the procedure for sampling with swabs and contact plates (ISO, 2004). For an established amount of water from the rinse that can be captured and its leftover constituents identified, secondary sampling is more frequently performed. This technique is commonly used to sample inaccessible areas that cannot be easily dismantled. Followed by analytical methods, which are important for detecting residuals and contaminants. Allergens, chemicals, and DNA can be found using techniques like serological and molecular biology tests, whereas product residues can be found using fast laboratory tests for ATP, which is proteins, or sugars. Besides chemical options, HPLCs are also available, but they are more costly alternatives. Any method can be used as long as it is validated, has a known limit of detection and quantification, and is sensitive enough to detect the established acceptable levels.

A suitable cleaning and/or disinfecting procedure should be selected and marked as an SOP (standard operating procedure). It must address the target microorganisms, cleaning frequency, equipment type, design, and anticipated food materials. A cleaning validation protocol must be established as a step. It is an imperative step as it outlines the entire process in detail, including the worst-case scenarios and corrective actions. There is also the report development, which summarizes the objective, course, evaluations, and results with specific commentary on the particulars (Holah et al., 2016; Ryther, 2014).

Additionally, maintaining a validated state is important and contributes to do the success of the process. This ensures the longevity of the validated conditions, though, necessary changes can be induced when required. Validation should be properly documented by qualified personnel and include the process for revalidation requirements. Overall, a food contact surface cleanliness and decontamination play a crucial part in ensuring safe, secure, and sound food manufacturing conditions.

Conclusion

Food safety is a grave concern for the food industries, customers, and federal agencies which are significantly affected by cross contamination of food products due to microbial contamination from the equipment surfaces. The primary cause of food product cross-contamination from contact surfaces is poor material selection and design for equipment construction, as well as ineffective cleaning procedures for installed equipment. Considering this, the major approaches that can be accustomed to minimize the microbial load from food contact materials are discussed in the chapter. The standards and guidelines on sanitary aspects of food contact materials are provided by different federal agencies, which helps to minimize food safety hazards that occur from contact surfaces. Future research should consider whether new approaches to ensuring food contact safety introduce any toxicological aspects to human health. Before moving forward, it is necessary to focus on the optimization of existing techniques to make them more effective. Additionally, combining a few techniques can have a positive impact on microbial safety and yield proficient results, with special consideration given to the economic feasibility of the approach. Finally, in light of the Covid-19 outbreak, future *in-vitro* studies should also look for the antiviral efficacies of the different technologies.

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