Journal of Food: Microbiology, Safety & Hygiene

OPEN ACCESS Freely available online

Review Article

A Review of Common Chemical Sanitizing Agents Used in the Food Industry to Control Microbial Hazards: Current Status and Emerging Technologies

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ABSTRACT

Microbial contamination remains a persistent challenge in the food industry, driven largely by the formation of biofilms that protect microbial pathogens such as *Listeria monocytogenes*, *Salmonella spp*., pathogenic *Escherichia coli*, *Staphylococcus aureus* etc. from conventional cleaning and sanitizing practices. Effective sanitation requires thorough cleaning to remove organic residues, followed by application of chemical or physical agents to reduce microbial hazards ensuring the safety of the finished food products. Although chlorine, quaternary ammonium and *iodophors* compounds are extensively utilized for their broad-spectrum antimicrobial efficacy, their performance can be affected by organic matter, soil, pH, temperature, chemical concentration, contact time, water hardness etc. This review examines commonly used sanitizing agents in the food industry for controlling microbial hazards and evaluates their efficacy in addressing microbial biofilms. Furthermore, it also explores emerging and sustainable alternatives which offer promising solutions for enhanced microbial control with reduced environmental burden. Integrating novel technologies with established practices can enhance sanitation efficiency, reduce biofilm-related risks, advance safer and more sustainable food production, and protect consumers from foodborne illnesses.

Keywords: Chemical sanitizing agents; Microbial hazard; Biofilms; Emerging technologies; Food safety

Abbreviations: DNA; Deoxyribonucleic acid; EPS: Extracellular Polymeric Substances; CFU: Colony Forming Units; PUC: Polyurethane nanocomposite coating; PAA: Peracetic acid; ROS: Reactive Oxygen Species; GAD: Gliding Arc Discharge; APP: Atmospheric Pressure Plasma; PL: Pulsed Light; UV: Ultraviolet

INTRODUCTION

Microorganisms are ubiquitous in the environment and pose ongoing food safety challenges throughout the entire farm-to-fork supply chain. According to the World Health Organization approximately 600 million people globally suffer from foodborne illnesses annually, resulting in around 420,000 deaths [105]. In the United States alone, the Centers for Disease Control and Prevention (CDC) estimate that foodborne pathogens cause 48 million illnesses, 128,000 hospitalizations, and 3,000 deaths each year [20]. These alarming statistics highlight the critical importance of robust sanitation practices within the food industry to ensure safety and protect consumers from foodborne illnesses. Cleaning and sanitizing form the cornerstone of operations essential for maintaining the quality and safety of finished food products. Cleaning involves the physical removal of soil and food residues with water and detergents, whereas sanitizing aims to reduce or eliminate microorganisms using chemical or physical means [59]. A fundamental principle is that effective sanitization cannot be achieved on unclean surfaces, as residual organic matter and soil can protect pathogenic microorganisms from exposure to sanitizing agents [53,68]. Despite technological advancements in food processing, microbial contamination remains a persistent issue largely due to the formation of microbial biofilms. Biofilms

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Received: 18-Jan-2026, Manuscript No. JFMSH-26-40383; Editor assigned: 20-Jan-2026, PreQC No. JFMSH-26-40383 (PQ); Reviewed: 03-Feb-2026, QC No. JFMSH-26-40383; Revised: 10-Feb-2026, Manuscript No. JFMSH-26-40383 (R); Published: 17-Feb-2025, DOI: 10.35248/2476-2059.26.11.348

Citation: RameshD, Singh A, Kumar A, Channaiah LH (2026). A Review of Common Chemical Sanitizing Agents Used in the Food Industry to Control Microbial Hazards: Current Status and Emerging Technologies. J Food Microbiol Saf Hyg.11:348.

are complex microbial communities embedded in a self-produced extracellular polymeric matrix composed of polysaccharides, proteins, lipids, and extracellular DNA; the matrix typically consists of approximately 10% biomass and 90% water [10,31,100]. The extracellular polysaccharide matrix functions as a robust protective barrier, restricting the penetration of sanitizing agents such as antibiotics, chemicals, and toxic compounds, and also conferring resistance to mechanical cleaning [5,40,98]. In food processing environments, biofilms can form on a variety of surfaces, including stainless steel, plastic, wood, ceramic, glass, rubber, concrete, stainless steel, plastic etc. [40,31,44]. Pathogens such as *Listeria monocytogenes, Salmonella spp., Campylobacter jejuni, S. aureus, Pseudomonas species, Bacillus cereus*, pathogenic *Escherichia coli*, *Clostridium perfringens*, etc. can form biofilms leading to cross-contamination, reduced equipment efficiency, and compromised product safety [46,54]. The formation of biofilms is a survival strategy for microbes offering protection against unfavorable environmental conditions such as heat, desiccation, disinfectants, and other external agents. These properties make biofilms particularly challenging in food environments, where even routine sanitation procedures may fail to completely remove or inactivate embedded microorganisms [10,53]. Once formed, pathogenic microbial biofilms are challenging to eliminate and can persistently release microorganisms, causing repeated contamination events in food processing environments if not effectively controlled through proper cleaning and sanitation practices [5,67, 69].

This review examines current sanitizing practices in the food industry, with a focus on their effectiveness against microbial biofilms formed by pathogens such as *L. monocytogenes*, *Salmonella spp*., *Pseudomonas* spp., *B. cereus*, pathogenic *E. coli* and *S. aureus*. It evaluates commonly used chemical agents and identifies factors that affect their efficacy. Additionally, it explores emerging and sustainable alternatives, highlighting innovative strategies that can enhance sanitation efficiency, minimize biofilm-associated risks, and support safer, more environmentally friendly food production practices for improved consumer protection.

Role of cleaning and sanitizing in the food industry

Proper cleaning and sanitizing practices are fundamental to preventing contamination in food processing facilities, maintaining food safety, and minimizing the risk of foodborne illness outbreaks. Cleaning refers to the removal of visible residues such as food particles, oils, soils, minerals, food particles, and dirt from food contact surfaces, equipment, and utensils typically using water, detergents and mechanical actions. This is considered as a foundational step before applying sanitizing chemicals as surfaces must be visibly clean for sanitizers to work effectively and reduce microbial contamination [59]. Sanitizing follows cleaning and involves applying chemical or physical agents to reduce microbial population and eliminating foodborne pathogens on food contact surfaces ensuring compliance with regulatory standards [23,93]. Residual food materials on food and non-food contact surfaces pose a significant risk to food safety by providing essential nutrients that support harmful microbial growth and biofilm formation [10,46]. Even small traces of organic matter, such as carbohydrate, protein, fat residues, can serve as a food source for pathogenic and spoilage microorganisms, including *L. monocytogenes*, *Salmonella spp*., *E. coli*, *S. aureus* etc. to firmly adhere to stainless steel, rubber, wood, ceramic, concrete, and plastic surfaces commonly found in food processing facilities [40,10,62]. Once attached to the surface, these microorganisms produce extracellular polymeric substances, creating a biofilm that protects them from environmental stresses, sanitizers including mechanical cleaning [8,31,45]. Biofilms are highly resistant structures that enable microbes to survive on surfaces for long periods, continuously releasing newly formed bacterial cells into food contact surfaces and food products thus elevating the risk of cross-contamination and compromising food safety [31]. Furthermore, biofilms can form in areas that are difficult to clean, such as cracks, joints, and equipment crevices, making it challenging to completely remove them. In addition to supporting biofilm formation, the presence of residual food materials also interferes with the effectiveness of sanitizing agents, as organic matter can react with or shield microbes from chemical disinfecting agents [10,62,31]. Therefore, thorough cleaning to remove all food residues is a critical prerequisite for effective sanitation program [8,31,44].

Impacts of biofilms on food industry

Biofilms pose a significant challenge to the food industry globally due to their ability to harbor and protect spoilage and pathogenic microorganisms. Once established, biofilms are highly resistant to cleaning and sanitizing procedures, making them difficult to remove in a food processing operation [76,99]. This persistence allows fully established biofilms to continuously contaminate food products, increasing the risk of foodborne illnesses and outbreaks [44]. Biofilms also contribute to cross-contamination during processing, leading to widespread product recalls and reputational damage for food companies [27,31]. Apart from contaminating the finished food products, biofilms can also affect equipment efficiency by clogging pipes, conveyor belts, valves, drains, and other surfaces, which increases maintenance costs. They can also accelerate food spoilage, shortening shelf life of finished food products leading to huge economic losses [8,31,44]. Biofilm formation on food-contact surfaces is a major food safety concern, contributing to serious foodborne illness outbreaks that may result in severe illness, hospitalization, and death among consumers. Overall, microbial biofilms are a persistent microbial threat in food processing environments, requiring a robust cleaning, sanitizing, and monitoring protocols to ensure food safety.

The following section summarizes major pathogenic bacteria capable of forming biofilms in food production environments, posing serious risks to food safety.

Listeria monocytogenes

Listeria species, particularly *Listeria monocytogenes*, readily form resilient biofilms on stainless steel, concrete, wood, ceramic, plastic, and rubber surfaces commonly present in food processing environment causing recurrent contamination, product recalls, and serious food safety concerns [36,83]. These biofilms protect *Listeria* cells from environmental stress, routine cleaning, and chemical sanitizers, increasing the likelihood of survival and spread within facilities [6,71,77]. *Listeria* biofilm forming ability allows it to persist in the food processing environment even under adverse condition such as low temperature, high salt concentration and exposure to sanitizing agents [36,83,71,77]. The *L. monocytogenes* biofilms act as reservoirs and are particularly concerning in Ready-To-Eat foods (RTE), as they can survive typical cleaning procedures, leading to product recalls and outbreaks of listeriosis [44,46]. Effective management in a RTE food establishment requires thorough cleaning to remove organic residues, application of appropriate chemical sanitizers, and continuous environmental monitoring targeting *Listeria* spp. [71,77]. Common sanitizers effective against *L. monocytogenes* include quaternary ammonium compounds (QACs), peroxyacetic acid (PAA), sodium hypochlorite (chlorine), and chlorine dioxide [47,53]. Their efficacy improves with adequate cleaning and longer contact times, as *Listeria* biofilms are more resistant than free-floating cells. Although hydrogen peroxide, steam and blue light are also used, QACs and PAA remain industry-preferred options for controlling *Listeria* contamination on food-contact surfaces (71,77,47,89).

Salmonella spp.

Salmonella is a Gram-negative bacterium and a leading cause of foodborne illness worldwide, known for its ability to form persistent biofilms on food contact and non-food contact surfaces in food processing establishments [48,78]. *Salmonella* is responsible for an estimated 93 million illnesses and about 155,000 deaths annually in the world due to gastroenteritis, many linked to contaminated food [104,109]. *Salmonella* has the ability to form biofilms on equipment, walls, drains, and other food-contact or non-food-contact surfaces, protecting the bacteria from cleaning agents, sanitizers, and other environmental stresses [8,31,44]. Once established, *Salmonella* biofilms can serve as a continuous source of contamination, affecting a wide range of products including meat, poultry, eggs, produce, and low-moisture foods including bakery product [47,78]. *Salmonella*'s extensive presence and resilience within biofilms not only complicates cleaning and sanitation efforts but also increases the risk of outbreaks and costly product recalls, underscoring the importance of synergistic target biofilm control strategies in food processing environment [62,75,48,78]. Common sanitizers effective against *Salmonella* include sodium hypochlorite (bleach), chlorine dioxide, PAA, and 60%-90% ethanol [30,72]. Strong evidence also supports the use of formaldehyde, food-grade acidulants, and QACs. These sanitizers are most effective when applied at recommended concentrations following thorough surface cleaning, as pre-cleaning removes organic matter that can otherwise reduce antimicrobial efficacy [9,26,72].

Pseudomonas spp.

Widely distributed, *Pseudomonas* are common, yet underestimated pathogenic spoilage bacteria in the food industry, particularly in dairy, meat, seafood, and RTE food products [60,15]. *Pseudomonas* species can form biofilms on fruits, vegetables, meat, drains, floors, and low-acidity dairy products, enabling persistence and contamination in food processing environments [15,91]. Their production of Extracellular Polymeric Substances (EPS) aids biofilm formation on a wide range of surfaces, including stainless steel, plastic, and rubber, often thriving in moist areas such as cutting boards, and water lines [2,15,60]. *Pseudomonas* spp., particularly *P. aeruginosa*, is well known for its strong biofilm forming ability in food processing environments. *Pseudomonas* biofilms can also serve as reservoirs for other pathogenic microorganisms, thereby indirectly posing food safety risks [91-93].

Strong oxidizing sanitizers such as PAA, hydrogen peroxide (H_2O_2), and sodium hypochlorite (chlorine) are highly effective for controlling *Pseudomonas* in food processing environments [37]. These oxidizers often outperform traditional QACs, particularly against resilient biofilms. Conventional disinfectants, such as chlorine and quaternary ammonium compounds found less effective against *Pseudomonas* biofilms. However, novel approaches such as cold plasma, enzymes, bacteriophages, and nanomaterials demonstrate improved effectiveness, particularly when used alongside conventional disinfectants [26,92].

Bacillus spp.

Bacillus species are Gram-positive, spore-forming bacteria capable of forming biofilms in food processing environment. Particularly, the *Bacillus cereus* biofilms can adhere strongly to stainless steel, glass, and plastic surfaces, making them difficult to remove through conventional cleaning and sanitizing procedures [12,42]. *Bacillus biofilms* protect both vegetative cells and spores, allowing the bacteria to persist under harsh conditions such as heat, desiccation, and exposure to chemical disinfectants. Prevalent in dairy processing, *Bacillus* species can withstand heat treatments due to their spore-forming ability and are known to accumulate on joints, pipelines, storage tanks, and stainless steel in dairy processing plant [55]. The persistence of *Bacillus* biofilms in food plants poses significant challenges for maintaining hygiene and ensuring food safety. Effective chemical sanitizers used to control *Bacillus* spp. in food processing environments include chlorine/ hypochlorite, PAA, chlorine dioxide, and hydrogen peroxide [50]. QACs are also widely applied, although their effectiveness against highly resistant spores varies. Sanitizing chemicals such as PAA, chlorine dioxide, and hydrogen peroxide demonstrate strong sporicidal activity by disrupting spore structures, while chlorine remains a preferred sanitizer for routine use, especially against *B. cereus* biofilms [1].

Pathogenic *Escherichia coli*

E. coli particularly Shiga toxin-producing strains (STEC) such as *E. coli* O157:H7, is a Gram-negative bacterium capable of forming biofilms on surfaces in food processing facilities, including stainless steel, plastic, and rubber [113]. Within these biofilms, *E. coli* cells gain enhanced protection against cleaning and sanitizing agents and environmental stresses, enabling them to persist in hard-to-reach areas like drains, conveyor belts, and processing equipment. Biofilm formed by pathogenic *E. coli* poses a serious food safety risk due to its potential to cause severe illnesses, including hemorrhagic colitis and hemolytic uremic syndrome [114,2]. Its persistence in the processing environment increases the likelihood of cross-contamination, making stringent sanitation and biofilm control measures critical for preventing foodborne illness outbreaks [62,75]. Effective agents for controlling *E. coli* biofilms include conventional sanitizers such as chlorine, QACs, and oxidizing agents like peracetic acid [8,31,44]. Natural antibiofilm compounds, including flavonoids, caffeine, and phenolic acids, have also shown inhibitory activity. In addition, emerging approaches utilize metal oxide nanoparticles such as MgO nanoparticles and enzyme combinations including DNase and papain with suitable carrier. These strategies primarily target quorum sensing mechanisms or disrupt the extracellular biofilm matrix, although potential toxicity and safety concerns must be considered [114,2,51].

Staphylococcus aureus

S. aureus is a major foodborne pathogen that readily forms biofilms on food-contact surfaces in the dairy industry and has been frequently associated with outbreaks linked to milk and dairy products, posing persistent contamination and public health risks [61,56,82]. *S. aureus* is particularly concerning because it produces heat-stable enterotoxins that can cause food poisoning, even when the bacteria are destroyed during cooking or thermal processing [56,82,95]. *S. aureus* presence in biofilms increases the risk of cross-contamination, product recalls, and outbreaks, making effective biofilm control strategies critical to maintain food safety in processing facilities [31,32,82]. Effective chemical agents against *S. aureus* biofilms in food processing plants include conventional sanitizers such as QACs, PAA, sodium hypochlorite, as well as natural alternatives including essential oils (thymol, carvacrol), organic acids (citric, acetic, lactic), and gallic acid [43,110]. These agents are often combined with physical methods such as ultrasound to enhance biofilm disruption by damaging cell membranes, altering pH, interfering with the extracellular matrix, and inhibiting biofilm-related gene expression.

Chemical sanitizers commonly used in food processing environment

Chlorine compounds

Chlorine is one of the most widely used chemical sanitizers in the food industry due to its broad-spectrum antimicrobial activity, cost-effectiveness, and ease of application [74]. Available in various forms, such as sodium hypochlorite, calcium hypochlorite, and chlorine gas, it is effective against a wide range of microorganisms, including bacteria, viruses, and fungi [68,73]. In food processing environments, chlorine is commonly used to sanitize equipment, utensils, food contact surfaces, and wash water for fresh produce, poultry, and seafood [8,31,44]. Its main mechanism of action involves oxidation, which disrupts cell membranes, denatures proteins, and inactivates enzymes, ultimately leading to microbial death [58,52]. However, chlorine's efficacy is influenced by several factors, including concentration, pH, temperature, and contact time. The recommended free chlorine concentration for sanitizing in food facilities typically ranges from 50 ppm to 200 ppm, with an optimal pH of 6.0 - 7.5 for maximum activity. The presence of organic matter can significantly reduce chlorine's effectiveness, as it reacts readily with organic compounds, leading to the formation of chlorinated by-products. While effective, chlorine use poses certain challenges, including potential corrosion of equipment, worker safety concerns due to its strong odor and volatility, and the formation of potentially harmful chlorinated disinfection byproducts (DBPs) such as trihalomethanes [86]. Chlorine-based sanitizers are widely used in the food industry due to their strong effectiveness against pathogenic bacteria, including *Salmonella* and *E. coli* [70]. However, concerns over potentially harmful byproducts have led to interest in alternatives such as chlorine dioxide, which offers similar microbial control with reduced chemical risks [44].

Iodophors

Iodophors are complexes of iodine with solubilizing carriers and are widely used in the food industry as sanitizing agents because of their broad-spectrum antimicrobial activity. The antimicrobial activity of these chemicals is primarily attributed to free iodine, which rapidly penetrates microbial cell walls, oxidizing vital cell components leading to cell death. They exhibit broad-spectrum efficacy, acting against bacteria, viruses, fungi, and certain protozoa. *Iodophors* are non-corrosive, non-irritating, provide spot-free drying, and have a long shelf life with visual control through color. However, they act slowly at pH 7.0 and above, vaporize at 120°F, are less effective against bacterial spores than hypochlorite's, may stain some plastics and porous surfaces, and are relatively expensive. Iodophor sanitizers are highly effective broad-spectrum biocides, targeting pathogenic bacteria such as *Salmonella*, *E. coli*, *S. aureus*, as well as viruses, fungi, and parasites. They act by releasing active iodine, which disrupts microbial cell walls, proteins, and DNA [25]. However, their efficacy is reduced in the presence of bacterial spores and organic matter, requiring thorough cleaning beforehand to ensure optimal antimicrobial performance. Recent advancements in polymeric iodophor technology have focused on nano and microparticle carriers for slow iodine release, enhancing surface persistence and reducing reapplication frequency [34]. *Iodophors* are increasingly preferred for their environmental compatibility and lower ecological impact compared to certain chlorine products [17,18,65,66].

Quaternary ammonium compounds (QACs)

QACs are among the most widely used sanitizers in the world due to their broad-spectrum antimicrobial action. QACs are highly effective against a wide range of microorganisms, including Gram-positive and Gram-negative bacteria, yeasts, and molds. QACs are highly effective against foodborne pathogens, including *E. coli*, *Salmonella*, *Listeria*, and *S. aureus*. Their ability to disrupt microbial cell membranes makes them reliable agents for reducing microbial contamination on food as well as non-food contact surfaces. Unlike some harsher sanitizers (e.g., chlorine or peracetic acid), QACs are generally non-corrosive and compatible with a variety of food-processing surfaces such as stainless steel, plastics, and rubber [4,8,31,44]. This reduces equipment wear and prolongs service life. QACs are relatively stable in the presence of organic matter and active over a wide pH range [31,79]. Despite their advantages, QACs are less effective against bacterial spores and viruses. Research has shown that tolerance to QACs is notably higher in strains that produce substantial biofilms, showing a positive correlation between biofilm formation on stainless steel surfaces and increased resistance [83]. QACs usage in food manufacturing facilities must be carefully managed with integrated sanitation programs to ensure their effectiveness, residue formation, regulatory compliance, and long-term sustainability [4,41,107].

Chemical *vs.* Natural/Organic Sanitizers

Chemical sanitizers are widely used in the food industry because of their strong antimicrobial activity, rapid action, and consistent performance. They typically function by disrupting microbial membranes, denaturing proteins, and oxidizing essential cellular components, which makes them effective against a broad range of microorganisms [68,69]. In contrast, natural or organic sanitizers are derived from plant-based or bio-based sources and often rely on mechanisms such as lowering intracellular pH, disrupting cell walls, and interfering with enzymatic systems to inhibit microbial growth [53,55]. A key distinction lies in their origins: Chemical sanitizers are synthetically manufactured and standardized for predictable performance, while natural sanitizers are more variable in composition and may provide additional functional benefits such as antioxidant activity [59,84].

When comparing efficacy and stability, chemical sanitizers generally show superior performance [8,31,44]. They remain effective under diverse processing conditions, including variations in pH, temperature, and organic matter, although their activity can be reduced in the presence of heavy organic loads or microbial biofilms [93,44]. Natural sanitizers, on the other hand, are more sensitive to environmental conditions and often require higher concentrations or combination strategies to achieve microbial reductions comparable to their chemical counterparts [73,94]. Safety considerations also distinguish the two categories. Chemical sanitizers, despite their effectiveness, may leave residues, contribute to antimicrobial resistance, and pose occupational or environmental risks if not managed carefully [12,25,44]. Natural sanitizers are generally recognized as safe, with minimal residue concerns, and are viewed more favorably by consumers seeking clean-label and ecofriendly products [106]. However, they can alter the sensory quality of foods due to strong odors or flavors, which is a limitation less frequently encountered with chemical sanitizers.

From a regulatory perspective, chemical sanitizers benefit from long standing approval and standardized usage guidelines set by food safety authorities, ensuring clear parameters for industry application [11,16]. Natural sanitizers, however, face more challenges in regulatory acceptance due to variability in their composition and limited large-scale validation studies [86]. Even so, the rising demand for sustainable, consumer driven solutions have fueled growing interest in natural sanitizers, along with research into technologies that can enhance their stability and antimicrobial performance. Thus, while chemical sanitizers remain the primary choice for industrial applications due to reliability and regulatory clarity, natural sanitizers represent an emerging alternative that aligns with global trends toward safer and greener food safety practices [8,31,44] as shown in Table 1.

Table 1: Commonly used chemical and natural sanitizing agents employed in the food industry: Advantages and limitations.

Cleaning Agents	Advantages	Limitations	References
Chlorine	Broad-spectrum antimicrobial activity; fast acting; cost-effective; widely available; effective against a broad range of pathogens including bacteria, viruses, and fungi; low cost makes it suitable for large-scale applications.	Reduced effectiveness in presence of organic matter; Can form harmful disinfection by-products; requires monitoring of concentration and pH for optimal efficacy.	79, 11, 95, 59, 76, 31,
Quaternary ammonium compounds (Quats or QACs)	Non-corrosive; good residual activity; stable storage; provides residual antimicrobial effect; effective in alkaline conditions.	Limited effectiveness against spores; requires rinsing in some food applications; residues can cause off-flavor in food if not rinsed properly.	95, 41, 31, 107
Peracetic acid (PAA)	Highly effective against bacteria, viruses, and spores; eco-friendly; breakdown products remain active in the presence of organic matter; effective at low temperatures.	Corrosive to metals at high concentrations; pungent odor with strong odor can be irritating; require careful handling and ventilation.	16, 79
Iodophors	Fast acting: effective across a wide range of microorganisms; retains activity in the presence of some organic matter; visual color indicator helps monitor coverage.	Discoloration of the surfaces; potential for allergic reactions in sensitive individuals; may require rinsing.	65, 66
Lactic acid	Naturally occurring; effective against many bacteria; suitable for organic food processing; enhances flavor preservation; biodegradable and environmentally friendly.	Limited activity against spores and viruses may alter product flavor; may cause corrosion of certain metals at high concentrations.	43, 110
Acetic acid	Low-cost; naturally occurring; effective against many bacteria and fungi; safe for use in organic food processing; multifunctional as a preservative and sanitizer.	Strong odor; limited activity against spore; strong vinegar odor may be undesirable in some products.	103, 31
Sodium hypochlorite	Readily available; broad-spectrum antimicrobial; fast acting; effective in cold water; rapidly reduces microbial load.	Corrosive to metals; effectiveness reduced by organic matter; rapidly inactivated by organic matter; strong odor can be unpleasant.	11, 59
Benzalkonium chloride	Long-lasting residual effect; effective against gram-positive bacteria good detergent properties; adheres well to surfaces for prolonged action.	Limited activity against gram-negative bacteria and spores; potential resistance development; not effective at low temperatures; some pathogens can develop resistance.	54
Ethanol	Fast acting; evaporates without residue; effective against many bacteria and enveloped viruses; quick-drying; suitable for sanitizing small tools and hand-contact surfaces.	Highly flammable; less effective against spores and non-enveloped viruses; evaporates quickly, reducing contact time; cost may be higher for large-scale use.	30
Nisin	Effective against *Listeria monocytogenes*; natural antimicrobial; suitable for integration into food contact surfaces; natural and food-grade; minimal impact on sensory qualities of food; suitable for use in hurdle technology.	Lower solubility in water; ineffective against gram-negative bacteria unless combined with other treatments.	6, 84
Grapeseed extract	Increased flexibility and antimicrobial activity; natural origin; provides antimicrobial and antioxidant benefits; can enhance product quality; effective against viruses, contains natural polyphenols with antioxidant benefits; may extend product shelf life.	Excess use causes cross contamination with food products; efficacy varies by source and processing; limited residual activity.	100
Polyurethane nanocomposite (PUC) coating	Long-lasting anticorrosive properties; reduces bacterial surface colonization; stable in saline environments; provides a durable, antimicrobial surface that can reduce cleaning frequency.	Leads to biofilm development; may require specialized application and re-coating over time.	31

Gallic acid	Inhibits biofilm formation; derived from natural sources; eco-friendly; also exhibits antioxidant properties; safe for use in organic food processing.	Increases the moisture content of food; high concentrations may affect food taste or color.	61
Hydrogen Peroxide	Strong oxidizing agent; eco-friendly; decomposition into water and oxygen; effective against a wide range of microbes but no harmful residues; compatible with many surfaces; approved for organic food processing.	Leads to browning of fresh food on contact surface; can be unstable when exposed to light or heat; may bleach surfaces.	12, 16
Triclosan	Broad-spectrum antimicrobial activity; effective at low concentrations; widely used in surface sanitization	Concentration dependent and microbes can develop resistance	98
Chlorine dioxide	Effective at low concentrations; stable across a wide pH range; less corrosive than chlorine; penetrates biofilms effectively; less odor than chlorine.	Can be unstable during storage; requires careful handling, short shelf-life once prepared; unsafe for workers at higher concentration; generation equipment needed for on-site use.	11, 55, 73
Ozone	Powerful oxidizing agent; leaves no chemical residue; effective against biofilms; approved for direct food contact in some countries; rapid decomposition prevents chemical residues.	Unstable and must be generated on-site; can cause material degradation; can irritate respiratory system; requires specialized generation equipment.	49, 96, 108
Neutral electrolyzed water	Environmentally friendly; non-toxic residues; effective against a broad spectrum of pathogens; safe for workers; can be generated on-site from salt and water.	Effectiveness reduced in presence of organic matter; short shelf-life; limited stability; less effective on heavy biofilms.	6
Citric acid	Generally recognized as safe; effective pH reduction for microbial inhibition; chelating ability for mineral removal; non-toxic and environmentally safe; effective for scale removal in equipment.	Limited direct bactericidal effect may require combination with other agents; limited antimicrobial effect on its own against resilient pathogens.	109

Alternate technologies for cleaning and sanitization

Traditional chemical sanitizers, including QACs, chlorine, and *iodophors*, are effective in controlling microbial contamination in food processing environment. However, their extensive use raises concern about environmental toxicity, chemical residues, and long-term sustainability. As a result, alternative technologies for cleaning and sanitization are gaining attention in the food industry. Some of the potential alternative sanitizing technologies include, but are not limited to, cold plasma, pulse filed, enzymatic cleaners, high ultrasound, cryogenic etc.

Cold plasma technology

Cold plasma is an emerging technology gaining attention for its versatility in generating antimicrobial surfaces and materials [81,45]. It offers a chemical-free approach to microbial inactivation, making it a promising alternative for food processing, packaging, and sanitation applications while minimizing environmental impact and supporting sustainable hygiene practices. Unlike traditional wet technologies, the cold plasma can be applied on a wide range of materials, including polymers, metals, and ceramics making it suitable for temperature sensitive and moisture sensitive equipment [75,112] Cold plasma generates a variety of Reactive Oxygen Species (ROS) which are capable of eliminating bacterial loads, including spores and pathogenic microorganisms [22,102]. Ramos along with the team developed bi-layer protein films treated with cold plasma and coated with carnauba wax, which helped in enhancing packaging quality by improving tensile strength and water vapor permeability [86]. Other work demonstrated the efficacy of a micro-plasma system with Gliding Arc Discharge (GAD) for decontaminating stainless steel, polyethylene terephthalate, and silicone surfaces [27]. The GAD is favored for its minimal equipment and operational costs while effectively inactivating bacteria. Plasma polymer films, deposited *via* plasma enhanced chemical vapor deposition offer excellent properties such as adjustable characteristics, strong adhesion, and highly crosslinked structures. There are variety of plasma technologies as per the requirements and the type of materials. Other studies have employed multi-frequency harmonic cold plasma treatment demonstrating effective cleaning and sanitization of food transport conveyor belts and contact surfaces [90]. It showed the involvement of Atmospheric Pressure Plasma (APP) jets which significantly reduced the biofilm formation on collagen casing, polypropylene, and polyethylene terephthalate surfaces against *L. monocytogenes*, *E. coli* O157 and S. Typhimurium [9,51,90]. These plasma-treated polymers are reactive due to the presence of free radical-rich surfaces, that allow controlled functionalization of material properties without altering them[22,46,47]. Plasma pre-treatment also facilitates the incorporation of antimicrobial substances [11,29,101].

Intense pulsed light

Intense pulsed light (PL) is a non-thermal surface decontamination method that employs short, high-energy flashes of broad-spectrum, UV-rich light from xenon lamps [35]. It inactivates microorganisms by damaging nucleic acids and generating reactive species, making it suitable for treating food-contact surfaces and disinfecting post-lethality food contact surfaces. Recent studies show PL can substantially reduce pathogenic microorganisms (up to ~1-2 log CFU/cm^2 reductions of *Listeria* and *Salmonella* under optimized condition) on meat and RTE food products. However, its impact on product quality, including color and lipid oxidation, is highly dependent on treatment parameters such as fluence, irradiance, pulse width, and the number of pulses. PL is especially useful for hard, exposed surfaces and thin sliced or surface-exposed foods where light penetration is sufficient; however, shadowing, surface roughness and organic soils can limit efficacy and favor combined hurdle approaches (e.g., PL plus drying, mild chemical sanitation, or packaging modifications) to control biofilms and residual contamination. Overall, recent studies highlight PL as a promising, rapid, and chemical-free sanitation method, provided device parameters are carefully optimized and combined with other sanitation practices [19,39,106].

High-Intensity Ultrasound (HIUS) technology

High-intensity ultrasound (HIUS) is increasingly being explored as an innovative, non-chemical sanitation technology in the food industry [14,21,22]. This technique relies on the generation of sound waves at frequencies above human hearing, typically ranging from 20 kHz to 100 kHz [113,13,21]. In liquid media, ultrasound induces cavitation, where collapsing microbubbles release localized energy as shock waves, turbulence, and microjets, enhancing microbial inactivation and cleaning efficiency. These mechanical effects can disrupt microbial cell walls, enhance the penetration of cleaning agents, and detach biofilms from surfaces, making HIUS a highly effective approach for sanitation [108,113]. In comparison to conventional chemical sanitizers, ultrasound offers the advantage of minimizing residues and lowering environmental toxicity, supporting sustainable food production practices. It has demonstrated effectiveness in cleaning and sanitizing food-contact surfaces, processing equipment, and even delicate products such as fruits and vegetables, without com-promising quality attributes [7,13,21]. While HIUS technology presents notable advantages, further research is required to enhance its cost-effectiveness, scalability, and practicality for broader adoption in industrial sanitation and food processing applications.

Surface functionalization

Surface functionalization is emerging as a promising approach to enhance sanitation in the food industry by imparting antimicrobial properties directly into equipment and contact surfaces. Unlike conventional sanitizers that require repeated application, functionalized surfaces are engineered with antimicrobial coatings, nanomaterials, or chemical modifications that actively inhibit microbial attachment and growth over extended periods [85,97]. This approach not only reduces the risk of biofilm formation but also minimizes the frequency of chemical sanitizer use, thereby lowering chemical residues and environmental impact. Materials such as silver nanoparticles, quaternary ammonium-functionalized polymers, photocatalytic coatings (e.g., titanium dioxide) and poly-N, N-[4,5-dihydroxy-1,2-phenylene) bis(methylene)] bisacrylamide (POHABA) have shown strong antimicrobial activity against *S. aureus*, *E. coli*, *C. albicans*, and *S. subtilis* [97,111]. Despite its effectiveness, surface functionalization faces limitations, including high implementation costs, complex manufacturing processes, and potential alteration of surface properties affecting food quality. Furthermore, its durability and antimicrobial performance under rigorous industrial cleaning can be variable, necessitating ongoing monitoring and maintenance to maintain efficacy.

Dual-functional antimicrobial surface coating

Dual-functional antimicrobial surfaces use the strategies to prevent microorganism attachment by combining the need such as killing microbes or removing dead microorganisms [63,64]. Usually, these coatings include bactericidal and microorganism resistant properties that act as a spacer/non-biofouling agents like hydrophilic polymers or anti-adhesive layers, or by embedding antimicrobial agents in non-fouling matrices [4,16,60]. Researcher developed a dual-functional polyurethane nanocomposite (PUC) coating that has antimicrobial and anticorrosive properties using π-π interactions and *in situ* graphene oxide integration [3]. These coating showed prolonged anticorrosive activity in NaCl (5%) solution and reduced bacterial colonization significantly. Another study reported the development of a dual-functional coating for aluminum surfaces, incorporating lysozyme into a superhydrophobic layer. This approach achieved significant pathogen reductions, including 6.5 log CFU/mL for *Salmonella* Typhimurium and 4 log CFU/mL for L. innocua, compared to untreated aluminum surfaces [61,111].

Natural antimicrobial surface coating

Natural antimicrobial surface coatings, derived from animals, plants, bacteria, fungi, and algae, are applied to food contact surfaces to inhibit microbial growth and biofilm formation [88,34]. They enhance food safety in processing areas, packaging, and storage equipment, offering a non-toxic, ecofriendly alternative to chemical sanitizers in food establishments. Polyphenols are the plant-based compounds that play a significant role in plant defense against pathogens and environmental conditions. These are categorized into flavonoids and non-flavonoids. Among them flavonoids such as flavanols, flavones, and isoflavones have good interactions with different polyphenol compounds while non-flavonoids include benzoic acid derivatives, cinnamic acid derivatives, stilbenes, and lignans. Colon and Nerin reviewed how these flavonoids can interact with green tea polyphenols on their antioxidant capacity, with catechins contributing to synergistic effects. Picchio along with other co-authors found that tannic acid efficiently crosslinked casein protein, enhancing physicochemical properties for food packaging hence it can be considered as the alternate cleaning and sanitizing agents [24,80].

Enzyme products

Enzymatic cleaning agents such as proteases, lipases, and amylases, are increasingly used in food manufacturing facilities due to their ability to break down complex organic residues, such as proteins, fats, and carbohydrates, which are common sources of microbial contamination. By effectively removing organic matter, enzymatic cleaners reduce microbial load and biofilm formation on processing equipment, utensils, conveyor belts, and other food contact surfaces, thereby enhancing overall hygiene and food safety. Unlike conventional chemical sanitizers, enzymatic agents work under mild conditions, minimizing damage to sensitive equipment and reducing chemical residues in the environment. They are particularly useful in hard-to-reach areas where traditional cleaning may be less effective, such as cracks, joints, and porous surfaces. Furthermore, enzymatic cleaners are biodegradable and environmentally friendly, aligning with sustainability goals in food production. Their use also helps prevent the buildup of resistant microbial communities by targeting the underlying organic matrix rather than relying solely on biocidal action. Overall, enzymatic cleaning agents provide an efficient, safe, and eco-conscious approach to maintaining high sanitation standards in food establishments, complementing routine cleaning and sanitation protocols while improving operational hygiene [38,57,87].

Recent studies have highlighted the effectiveness of enzyme-based cleaners in various food processing environments. For instance, research indicates that enzymes can efficiently degrade Extracellular Polymeric Sub-stances (EPS) that constitute biofilms, thereby enhancing the removal of microbial contaminants from surfaces [38,87]. Additionally, the application of enzyme treatments has been shown to reduce the microbial load on surfaces and improve the overall hygiene of processing facilities.

These findings underscore the potential of enzymatic cleaners to complement traditional cleaning methods, offering a more targeted and environmentally friendly approach to sanitation in the food industry. Despite their effectiveness, enzymatic cleaning agents face several limitations and challenges when applied on a large scale in food establishments. One major drawback is their higher cost compared to conventional chemical sanitizers, which can be a significant concern for large processing facilities with extensive equipment and high cleaning volumes [57,87]. Enzymatic cleaners are also sensitive to environmental conditions such as temperature, pH, and water hardness; suboptimal conditions can reduce their activity, limiting their practical application across diverse industrial settings [38,87]. Furthermore, incomplete removal of enzymes from surfaces can occasionally lead to residual activity that may interact with food components or cleaning chemicals, potentially impacting food quality. Collectively, these factors make the large-scale adoption of enzymatic cleaning agents challenging, requiring careful planning, process optimization, and integration with other sanitation measures.

Ozone technology

Ozonated waters are very effective in killing the bacteria on cleaned surfaces and treat water in closed system, such as those containing food products like fruits and vegetables [13,96]. It is also used to keep cooling water clean for recycling after cooking packaged products. Compared to chlorine, ozonated water disinfects at just 2°C and breaks down organic matter, reducing the risk of biofilm formation. It eliminates a broad range of bacteria, including *E. coli*, *Salmonella*, *Listeria*, as well as mold, fungi, yeasts, viruses, and mycotoxins [14,29,33,49].

Cryogenics

Cryogenics, the science of producing and applying extremely low temperatures, has emerged as a promising alternative for sanitation in food processing plants, offering significant advantages over conventional chemical sanitizers. Traditional sanitizing agents, such as QACs, chlorine-based solutions, and *iodophors*, while effective against a broad spectrum of microorganisms, can pose risks including chemical residues, corrosion of equipment, and environmental pollution. Cryogenic sanitization, typically utilizing liquid nitrogen or carbon dioxide, provides a physical approach to microbial inactivation without relying on chemical reactions [49]. The extremely low temperatures cause rapid freezing of microbial cells, resulting in structural damage, membrane disruption, and eventual cell death. Despite the relatively high cost associated with the production or procurement of dry ice, it remains particularly advantageous for applications in the meat, cheese, and chocolate industries. However, its use is generally unsuitable for products such as vegetables due to quality and textural limitations. Furthermore, this method is particularly advantageous for food surfaces and equipment that are sensitive to moisture or harsh chemicals, as it minimizes water use and eliminates chemical residues that could compromise food quality or safety.

Studies show this method reduces cleaning time from hours to minutes and significantly lowers labor costs in bakery and bottling operations. Nevertheless, it requires careful management of CO_2 concentrations for operator safety and may have high initial equipment costs, though rental options can mitigate this challenge [28].

CONCLUSION

Effective cleaning and sanitization remain cornerstone practices for ensuring food safety in processing environments, particularly given the persistent challenges posed by microbial contamination and biofilm formation. Traditional chemical sanitizers, including chlorine, *iodophors*, and QACs, continue to provide broad-spectrum antimicrobial activity and remain widely used due to their accessibility and established regulatory acceptance. However, their efficacy can be compromised by environmental factors such as pH, temperature, organic matter, and surface type, and their extensive use raises concerns regarding chemical residues, environmental impact, and microbial resistance. Emerging technologies offer promising alternatives to traditional chemical-based sanitation. Non-thermal methods such as cold plasma, intense pulsed light, high-intensity ultrasound, and cryogenics pro-vide environmentally friendly, chemical free options for microbial control while maintaining food quality. Additionally, surface functionalization, dual-functional antimicrobial coatings, and natural or enzymatic cleaning agents enhance the intrinsic antimicrobial properties of contact surfaces, reducing biofilm formation and minimizing chemical usage. While these technologies demonstrate significant potential, challenges such as high implementation costs, scalability, and operational optimization remain barriers to widespread industrial adoption. Integrating traditional chemical sanitizers with novel and sustainable approaches presents a viable strategy to strengthen food safety management. Tailored sanitation programs combining conventional and emerging methods can improve microbial inactivation, mitigate biofilm related risks, and support environmentally responsible food production. Continued research and technological innovation are essential to optimize these interventions, reduce operational limitations, and ensure practical, cost-effective solutions for the food industry.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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