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REVIEW ARTICLE

Biofilms in the food system: Novel management strategies

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ABSTRACT

Biofilms are shielding extracellular matrix constituting glycoprotein and polysaccharides created by microorganisms in order to sustain through hostile environment. In food systems due to inadequate sanitary operations food residues accumulate and provide nutrition and harborage to microorganisms, resulting in biofilm formation. These biofilms provide ideal growth environment that support cellular communication and genetic transferal. These characteristics under controlled conditions make biofilms auspicious for biomass production. Traditional detection methods often fail to identify viable but non-culturable (VBNC) bacteria, necessitating advanced techniques like PCR, metagenomics, and electrochemical sensors for accurate monitoring. Various strategies are employed to control biofilm formation, including chemical treatments (e.g., chlorine-based sanitizers, hydrogen peroxide, quaternary ammonium compounds), enzymatic disruption (proteases, glycosidases), and biosurfactants that interfere with bacterial adhesion. Bacteriocins (e.g., nisin) and bacteriophages offer targeted antimicrobial action, while essential oils (e.g., cinnamon, lemongrass) provide natural alternatives with anti-biofilm properties. Quorum sensing inhibition disrupts bacterial communication, reducing biofilm formation and resistance. Emerging technologies like non-thermal plasma and photocatalytic nanoparticles (e.g., TiO_2, ZnO) demonstrate potential for biofilm eradication through reactive oxygen species generation under light exposure. Despite advancements, biofilm elimination remains challenging due to increasing resistance to chemical sanitizers. This review is primarily focused on biofilm prevention and obstruction techniques for food systems including use cell-signaling inhibition strategies, non-thermal plasma treatments and photocatalysis.

KEY WORDS: bacteriophage, quorum sensing inhibition, sanitizer, protease, biosurfactant, steel coating, bacteriocin, essential oil

1. INTRODUCTION

Bacteria have the ability to remain attached to the industrial surfaces and results in formation of biofilms. Food processing surfaces can provide variety of environments which favors the development of biofilms (Carrascosa et al., 2021). Biofilms are protective extracellular matrix composed of glycoprotein and polysaccharides formed by microorganisms to survive hostile environmental conditions such as temperature and chemicals (Al-Tayawi et al., 2023). Biofilms are composed of microbial cells and extracellular polysaccharides commonly formed over the surfaces and equipment in food industry resultantly serve as a major source of contamination. Bacterial species such as *Listeria monocytogen, Escherichia coli* O157:H*7, Campylobacter jejuni, Bacillus cereus, Salmonella* and *Pseudomonas* are serious concern in food industry due to the formation of biofilm. In a food industry " real biofilms" are formed in closed surfaces such as hoses, water or food piping systems such as metal, glass, plastic or rubber surfaces (Liaqat et al., 2023).

Bacteria attached to biofilms can be a source of food safety hazard, if transmitted to food items may result in food spoilage and transmission of diseases (Bai et al., 2021). Due to improper cleaning and sanitation operations such as cleaning in place, residues of food remain in food system. The food residues provide nutrition source to bacteria thus, facilitating formation of biofilms. Moreover, polysaccharides present in biofilms provide protective shield to bacteria from cleaning and sanitizing agents (Shineh et al., 2023). Metabolic interactions between these species contribute to the formations of biofilms, and the production of a dynamic local environment. In food industry, biofilms with mixed-bacterial species are usually stable, with strong biofilm structure, cell-to-cell interactions affect the biofilm formation and resistance to the antimicrobial treatments (Røder et al., 2020).

To amortize the maintenance and production breaks, along with cleaning operational cost; instead of using conventional ways of biofilm detection like agar plating, which is inefficacious against detecting pathogens like *Listera monocytogens* (Buder et al., 2023). These microorganisms have the ability to enter a viable but non culturable state (VBNC). In VBNC state microorganisms lower their metabolic activity and do not divide but are alive and have the ability to become culturable once resuscitated (Liu et al., 2023). Novel techniques like PCR amplification can fill in the purpose of online monitoring biofilm growth and adhesion in food contact surfaces (Yuan et al., 2020).

The other futuristic techniques of biofilm sensing include metagenomics and metatrancriptomics which explain the intricate interactions within the biofilm community (Seneviratne et al., 2020). Multilocous variable number of tandem repeat analysis is employed for genetic analysis of *Stayplococcus aures spp*. in food industry samples (Gana et al., 2022). This method involves PCR amplification of multitudinous *S. aures* loci, which exhibit irresolute number of tandem repeats and gel electrophoresis to differentiate between identified genotypes (Zhang et al., 2023).

Applied in-process biofilm monitoring techniques are based on introducing external agitation into the system; by using suitable detectors and amplifiers, this disturbance can be determined in terms of calibrated values (Stine et al., 2020). At industrial level, parameters like temperature and pressure can be determined using specially designed sensors. For example, thermal pulse analysis is based on detecting and determining temperature fluctuations and thermal conductivity due to biofilm formation in the system. These sensors have precision of determining even few micrometer thick biofilms (Oudebrouckx et al., 2020).

Instruments like BIOX or BIOGORGE are based on electric signal measurement, determine electro-chemical variation and impedance; by measuring coupling current between zinc and stainless-steel electrode bridged by a resistance this mechanism is practiced for dosage optimization of antibiofilm compound in industrial environment (Saboe, 2022). Device like quartz crystal microbalance use vibration signals to analyze the effect of biofilm adhesion (Latag et al., 2023). Q-sense is a commercial QCM analyzer, which by detecting vibrational frequencies sense initial bacterial adhesion to stainless steel surface (Migoń et al., 2020). For industrial use advanced Mechatronic Surface Sensor (MSS) are used, these sensors have two transducers; an actuator and a sensor to measure the propagated waves. The MSS device detect biofilm deposits and delineate biofilms and abiotic deposits (Ashrafi, 2023). MSS device effectively work on industrial materials like copper, glass, stainless steel and PVC (Sliem et al., 2021).

Along with these detection methods, new physical and chemical prevention techniques are used against biofilm formation. Physical methods like ultra-sonication and hot steam and chemical reagents like peracetic acid, sodium hypochlorite, hydrogen peroxide, sodium hydroxide and etc., are used to control biofilms on industrial working surfaces and pipelines. To avoid microbial attachment; cleaning and disinfection methodologies like cleaning in place are implemented using liquid disinfectants (Khan et al., 2021).

2. METHODS OF CONTROLLING BIOFILM FORMATION IN FOOD INDUSTRY

Biofilms are complex communities, their unique characteristics increase the possibility of chemical and physical resistances, making their elimination very difficult in some cases, and favoring their persistence in the industry environment. Therefore, the development of new antibacterial approaches, focused on preventing biofilm formation instead of its elimination is very important in this industrial sector (Khan et al., 2021).

2.1. Chemical Treatment

To eliminate biofilms various time and concentration dependent chemical sanitizers are used, which directly targets microbial population to attain safety levels for humans, this process is known as sanitization (Yuan et al., 2021). Food processing machinery is essentially sanitized to avert the risks of cross-contamination among food batches (Holah, 2023). On industrial scale chlorine-based sanitizers are commonly used, in use of similar chemicals arise the problem of bacterial resistance. For example, Chlorine resistance in *S. enteric* is directly linked to its cellulose producing characteristics (Moye et al., 2020). Liquid ClO_2 is the most extensively used sanitizer in food processing facilities, however, gaseous ClO_2 exhibits better results in elimination of species *Bacillus cereus* (Deng et al., 2020). Liquid ClO_2 has been proved to be more effectual at a concentration of 50-1000 ppm against *E. Coli* in the procedures aided by stressors like drying after chemical treatment (Hsu, 2020).

In milk processing industries *S. auresus* and *S. enterica* creates the major havoc. To control their biofilm formation on polypropylene and steel surfaces, chemical sanitizers like sodium hypochlorite have been found to be effective (Verma and Agarwal, 2022). However, same chemical concentrations and sanitizing conditions have been found to be ineffective against biofilms formed by pathogenic strains like *Cronobacter sakazakii* (Guo et al., 2020).

Chemical agents with strong oxidizing potential like hydrogen peroxide are extensively used in Cleaning in Place procedures in food processing industry. At a concentration of 2 to 7% H_2O_2 produce free radicals which destroy the biofilms effectively (Farjami et al., 2022). To enhance the efficiency of H_2O_2, it is used in conjunction with acetic acid, which produce a potential antioxidant peracetic acid. This combination at a concentration of about 5 % have been found highly effective against pathogens like *L. monocytogenes* and *S. aureus* populations (Stearns et al., 2022). Similarly, ozone gas exhibit strong oxidizing potential, which has been found to be effective against protozoans, viruses and biofilms. Ozone works by directly destroying the microbial cell envelops. On industrial scale ozone is massively used to eradicate mold growth from stainless steel surfaces (Ziyaina and Rasco, 2021).

Quats (Quaternary ammonium compounds) a water soluble, cationic sanitizer, that cause bacterial lysis by destroying bacterial cell membrane (Mohapatra et al., 2023). Some strains of *L. monocytogenes* have qacH and bcrABC genes which provide them with an additional advantage against quats, to eliminate such quats resistant strains stronger sanitizers are used, to enhance the effect of this cationic sanitizer (Cheng et al., 2023). Usually to cope up with such situation multi-faceted approach is adapted by using sanitizers like sodium hypochlorite, hydrogen peroxide, iodophor, benzalkonium chloride in combination with steam heating, which not only eliminate biofilms formed by pathogens like *E. coli* O157:H7, *S. enterica* and *L. monocytogenes*, but also reduce the treatment time and sanitizer concentration (Yuan et al., 2021).

Pathogenic strains like *Campylobacter jejuni* are usually resistant against biocides like acetic acid, trisodium phosphate, and sodium hypochlorite (Thames et al., 2020). In addition to this resistance, this bacterial strain has an additional advantage of producing biofilms composed of amyloid fibers, exoproteins and exopolysaccharides based extracellular matrix (Zhang et al., 2021). To deal with these strains, antibiotics with covalently linked carbohydrate carriers like chitosan are used (Yan et al., 2021). Extensive use of chemical sanitizer on industrial scale has resulted in resistance development in bacteria against these chemicals. Therefore, development of novel alternate techniques to eradicate these biofilms is the need of the hour (Yuan et al., 2020).

2.2. Biosurfactants

Amphiphilic compounds of microbial origin, with ability to alter hydrophobic properties of bacterial surface are called biosurfactant. Biosurfactants work by affecting building and adhesion characteristics of biofilms (Markande et al., 2021). For example, *B. licheniform* produce cyclic non-ribosomal lipopeptide, lichenysin, which on industrial scale is used in different concentrations against different bacteria (Shleeva et al., 2023). Adhesion potential of Methicillin-resistant *S. aureus* is reduced to 50% at a concentration of 8.3 mg/mL, for *C. jejuni* at a concentration of 188.5 mg/mL, while microbes like *Y. enterocolitica*, *C. albicans* can be controlled at a concentration of 16.1 mg/mL and 17.2 mg/mL, respectively (Liaqat et al., 2023).

Compounds like Fengycin, iturin produced by *B. amyloliquefaciens* and surfactin produced by *B. subtilis* reduce surface tension, thus altering binding properties of target surface, enter the cell membrane, increase membrane permeability by disrupting it, resulting in cell swelling which ultimately leads to death (Aranda et al., 2023).

2.3. Enzymatic Disruption

Against biofilm formation use of enzymes is both effective and environmental friendly because of their biodegradable and low toxic nature. Enzymes have a potential contrivance against biofilms. Various companies are now producing eco-friendly enzyme-based detergents (Mahnashi et al., 2022). Various enzymes like trypsin, pepsin and serine proteinase accelerate protein lysis in biofilm matrix, while glycosidases like dextranase, amylases and pectinases interacts with polysaccharides in the biofilms, resulting in effective removal (Chandel et al., 2022). Similarly, Pectin methylesterase, is used to control biofilm formation in bioreactors as well as in machines and lines in food industry (Ghosh et al., 2021).

In commercial detergents enzymes like lyases, amylases, cellulases and glycocidases are commonly used (Singh, 2021). For complete destruction of *S. enterica* biofilms, commonly found in meat industry, immersion technique is employed using cellulase enzyme in combination with cetyltrimethyl ammonium bromide (Zhu et al., 2022). Alpha-amylase, has exhibited degrading potential against *S. aureus* biofilms (Wakui et al., 2024).

Due to narrow substrate specificities proteases have shown the evidence of effectiveness against organic material-based biofilms (Asma et al., 2022). In this case to ensure complete removal, enzyme treatment is followed by mechanical procedures (Michelin et al., 2020). For Example, to achieve 96% removal of *E. coli* biofilms in dairy processing equipment of stainless-steel, enzyme trypsin extracted from porcine pancreas and prostease XXIII from *Aspergillus oryzae* is used in conjunction with 10 sec exposure of ultrasonic waves (Galié et al., 2018).

S. aureus biofilms can easily be controlled by protease-based formulations while resistant strains like *P. aeruginosa* biofilms require complex mixtures of cellulase and amylase along with protease enzymes (Boyce and Walsh, 2023). Serine proteases like subtilisin produced by *Bacillus spp*. attack protein adhesion of biofilm to the stainless-steel surfaces (Yunus et al., 2024). Some new industrial detergent formulations, have been found to be more effective at high temperature i.e., 95°C against biofilms (Cremer et al., 2023). *S. aureus* and pathogens other pathogens like *E. coli* and *L. monocytogene* during biofilm formation produce additional shield protect exogenous DNA, which can be removed by using DNase enzyme from bovine source (Wang et al., 2023).

On commercial scale to enhance the effectiveness of enzyme-based detergents, various chemical sanitizers and physical aids like ultrasound waves are used for removal of biofilms generated by different species like *E. coli* or *Bacillus spp*. These combined techniques not only ensure the effective removal but also reduce the expensive enzyme usage in the process (Borges et al., 2020).

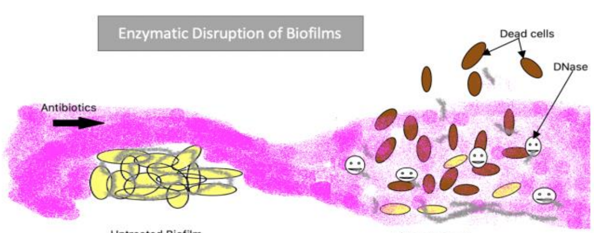

Figure 1: Enzymatic disruption of biofilms

2.4. Bacteriocins

Proteinaceous toxins, bacteriocins, produced by bacteria to compete with other bacterial strains, through their growth retardation, can be used as potential tool against biofilm formation on food processing surfaces (Nisa et al., 2023). Bacteriocins improves the food quality by extending the product keeping time, act as a shield against foodborne pathogens, reduce the required concentration of chemical preservative and treatment time (Mokoena et al., 2021). For example, nisin obtained from probiotic *Lactococcus lactis*, is a polycyclic peptide containing 34 amino acids, manifested strong research-based evidence of their antimicrobial properties (Małaczewska et al., 2021), and has been approved to be safe food additive by various reputed organizations like World Health Organization (1969) and Food and Drug Administration (1988); as peptides are safe for both human and animal use (Eghbal et al., 2020). In addition, nisin also alter the surface tension, thus prevent *L. monocytogen* biofilm formation and adhesion when used in the form of mist (Alonso et al., 2020).

Probiotics with GRAS status are more frequently employed for both research and commercial production of bacteriocins, to restrict bacterial colonization (Todorov et al., 2022). For example, inventive bacteriocins like pedocins produced by *Enterococcus spp*. are vigorously active against *L. monocytogenes*, lactocins produced by *Lactococcus spp*. has been found to be active against *Brochothrix thermosphacta* (Xu et al., 2022). Similarly, garvicin produced by *Lactococcus garvieae* have exhibited strong evidence of antimicrobial potential against resistant strains of *Brochothrix thermosphacta* (Kingkaew and Tanasupawat, 2023).

2.5. Bacteriophages

Virus infected bacteria possess strong prokaryote cell specific antimicrobial potential, innocuous against eukaryotes like plants, animals and human. Due to this advantage phage therapy is being considered as effective and safer alternate to antibiotics (Ling et al., 2022). Bacteriophages are consistently proving their potential as anti-biofilm agent for commercial scale use. For example, Listex P100 is a Listera based commercial bacteriophage used against biofilms found on equipment surfaces in meat industry, has already attained the status of GRAS (Generally regarded as Safe) by the Department of Agriculture (USA) (Kawacka et al., 2020). Similar commercial products like SalmofreshTM and ScoShieldTM are effective against biofilms produced by *S. enterica* or *E. coli*, respectively (Santana et al., 2023).

Complex extracellular matrix of biofilm, provides an intricate structural support, thus limiting the phage entry in the biofilm. However, this phage diffusion obstacle is naturally aided by enzymes like exopolysaccharide depolymerases (Domingues et al., 2021). This enzyme elevates the invasion and dispersion mechanism of phage into the biofilm matrix (Visnapuu et al., 2022). Enzymes like endolysins and peptidoglycan hydrolases (viron origined) has been found effective due their biofilm penetration properties (Bin Hafeez et al., 2021). Another limiting factor for phage performance in commercial process is the interactions between chemical sanitizers and phage metabolic process, which can have both positive and negative effect upon chemical interaction (Fernandes et al., 2024).

To summarize, both phages and their derived proteins have compelling commercial use for biofilm eradication (Amankwah et al., 2021). But still for efficacious results and standard cleaning procedural development more research is needed in the field. In addition, aspects of human safety and environmental impact of these infected bacteria need strong research-based grounds, due to their uncontrolled propagation and phage purification complexities before their implementation in food processing establishments (Tian et al., 2021).

2.6. Essential Oils

Essential oils are the natural bioactive components of plants, responsible for their protection against pests. Their complex chemical profile consists of monoterpenoids (like limonene, camphor, pinene, carvacrol, borneol, thujone), sesquiterpenoids like humulene, caryophyllene) and flavonoids (like cinnamaldehyde). Bioactive component profile of plants varies from specie to specie, and exhibit varying potential of anti-microbial, anti-fungal, anti-biofilm properties. With the increase in consumer awareness regarding adverse effects synthetic additives, people prefer foods prepared in systems involving natural additives and disinfectants (Saeed et al., 2022).

It is evident from research references that cinnamon essential oil microemulsion containing cinnamaldehyde reduce *S. aureus* biofilm (Didehdar et al., 2022). Similar results are obtained from *Salvia officinalis* oil containing thujone, pinene and camphor at a concentration of 5% (Farahpour et al., 2020).

Essential oils of *Holarrhena antidysenterica* and *Andrographis paniculata* essential oil at a concentration of 50 mg/mL has been found to be effective against pathogens like *S. enterica, E. coli*, and *P. aeruginosa* by reducing their population up to 80%, by damaging bacterial cell membrane by cinnamaldehyde (Pattnaik et al., 2024). Lemongrass oil with bioactive component citral act as anti-adhesion and anti-biofilm agent against *Cronobacter sakazakii* (Viktorová et al., 2020). Citral directly attack the bacterial communication signaling mechanism, thus disrupting its biofilm formation ability, as well as its virulence (Gonçalves et al., 2023). This bioactive component also effects the formation of locomotory organs in bacterial cells (Gonçalves et al., 2020).

2.7. Quorum Sensing Inhibition

Due to coordinate gene expression bacteria quorum sense using their ability to detect and respond to cell population density (Smith and Schuster, 2022), for this communication various signaling paths are involved in biofilm formation and resistance against antimicrobial agents i.e., through protein and another organic molecule exchange and electrical signal transmission (Lahiri et al., 2022). The most efficient bacterial communication channels are quorum sensing and cyclic di-GMP signaling (Khan et al., 2023). In quorum sensing, in response to elevated concentrations signaling molecules acyl homoserine lactones, peptides and the autoinducer-2, bacteria regulate their gene their expression accordingly; including signals that regulate biofilm formation (Nag et al., 2022). In cyclic di-GMP signaling, higher concentrations of cGMP stimulate the extracellular polymeric compound formation, thus reducing in bacterial cell mobility, resulting in biofilm formation (Poulin and Kuperman, 2021).

Small molecules like terpenoid saponin, nitric oxide generating compounds, azathioprine and sRNAs hinders cGMP biosynthesis (Souza et al., 2021). Using this property, QS inhibition techniques are designed against biofilms involved in food systems (Lu et al., 2022). QS mediator functioning is disrupted, this communication gap results in decreased levels of resistance against antimicrobial compounds, thus, reducing biofilm formation (Lamin et al., 2022). Bactericidal strategies, involves cell-to-cell communication disruption inhibitors to occupy QS receptor sites (Rasmussen et al., 2005), QS signal degeneration using enzymes (Xue et al., 2022), sRNAs based post-transcriptional alteration QS genes expression (Juszczuk-Kubiak et al., 2024) and hindering QS signals generation (Zhou et al., 2020).

Enzyme paraoxonases isolated from mammalian sera blocks bacterial communication pathways by using the mechanism of quorum quenching (Hemmati et al., 2020). In *P. aeruginosa* a significant signal molecule, the lactone ring of N-acyl homoserine lactone is hydrolyzed (Khalid et al., 2022).

Paraoxonases also have plant and fungal origin (Salari et al., 2021). Halogenated furanones extracted from *Delisea pulchra* (red algae) have shown the evidence of QS inhibitory activity (Tang et al., 2020). Disulfide compounds and rosmarin extracted form garlic and rosmarinic acid respectively, disrupt the quorum sensing mechanism of *P. aeruginosa*, resulting in prevention of biofilm formation (Li et al., 2022; Kernou et al., 2023).

2.8. Non-thermal Plasma

Non-thermal plasma is a laboratory restricted, expensive technique (George et al., 2021). Non-thermal plasma is usually a low temperature, partially ionized gas, produced by mixing UV light with ozone, helium, nitrogen, oxygen and water under atmospheric pressure and electrical discharge (Yepez et al., 2020) for a period of 10 mins has been found effective against the biofilm forming Gram-negative (*Pseudomonas spp*., *S. enterica*) and Gram-positive (*Bacillus spp*.) species (Liu et al., 2022).

2.9. Photocatalysis

Versatile nanoparticles exhibit strong photocatalytic characteristics, which involves the use of specific light wavelengths to initiate and accelerate chemical reactions which destroy microbial cells because of reactive oxygen species formed (Soleimani et al., 2021). Similarly, TiO_2 NPs, coated on polysteryrene surface, destroy bacterial cells of pathogenic species like *P. aeruginosa E. coli*, *Enterococcus faecalis* and *S. aureus*, due to 1% reactive Fe and N reaction initiated upon exposure to sunlight (Younis et al., 2023). Upon UV light exposure these reactive molecules directly attack and destroy biofilms produced by these pathogens (Jing et al., 2022). TiO_2 NPs coatings with silver active molecules has been found more effective against biofilm formation in beverage industry steel surfaces and lines against Gram negative *Pseudomonas fluorescens* than in the case of Gram-positive ones *Lactobacillus paracasei* (MARINE et al., 2020; Mandal & Banerjee, 2020).
ZnO NPs produced from *Ulva lactuca* water-based extract absorbs light of 325 nm wavelength, results in 80% reduction of *Proteus vulgaris*, *B. licheniformis*, *Bacillus pumilus* and *E. coli* biofilms due reactive oxygen species (Mahamuni-Badiger et al., 2020). 430 nm wavelength exposure for 2-3 hours can cause 5.2 log CFU/cm^2 reduction of resistant biofilms of *L. monocytogenes* generated at a temperature of 16˚C, aging 10 days on steel and glass surface (Vengatesan, 2023). This innovative technology demonstrates modified self-disinfecting industrial surfaces of steel and glass (Hosseini et al., 2020).

Table 1: Exhibits the novel management strategies used against biofilms

Technique	Mode of Action	Examples	References
Chemical Treatment	Cellular oxidation	H_2O_2 , Chlorine, Peracetic acid	Srey et al., 2013
Biosurfactants	Altering binding properties of target surface	Fengycin, surfactin	Zhao et al.,2017
Enzymatic Disruption	Disrupt biofilm extracellular matrix	Lyases, amylases, cellulases and glycocidases	da Silva and De Martinis, 2013 Coughlan et al., 2016
Bacteriocins	Alters the structure of cell membrane	Lactocins, garvicin	Castellano et al., 2017
Bacteriophages	Cause cell lysis	Listex P100, Salmofresh TM, ScoShield TM	Iacumin et al., 2016 Gutiérrez et al., 2016
Essential Oils	Damage bacterial cell membrane	Limonene, camphor, pinene, carvacrol, borneol, thujone	Raffaella et al., 2017 Shi et al., 2017
Quorum Sensing Inhibition	sRNAs based post-transcriptional alteration and hindering QS signals generation	Saponin, nitric oxide	Pérez-Martínez and Haas, 2011 Koh et al., 2013
Non-thermal Plasma	Bactericidal effect	Partially ionized ozone, helium, nitrogen	Scholtz et al., 2015
Photocatalysis	Specific light wavelengths accelerate chemical reactions which destroy microbial cells	ZnO NPs, TiO2 NPs	Priha et al., 2011 Chorianopoulos et al., 2011

3. CONCLUSION

In food processing systems biofilm formation result in crucial public health problems. Biofilms are of varying nature depending on the forming agent i.e., bacteria, fungi algae and etc. Commercial food systems rely on cost effective treatments against biofilms like chemical methods using sodium hydroxide or sodium hypochlorite solutions. Physical treatments involving mechanical removal, hot water and steam for biofilm elimination from pipelines and work surfaces. These techniques do not ensure complete biofilm removal, thus arising the need of novel methodologies like using quorum sensing inhibitors, which destroy quorum sensing signal molecules, e.g., paraoxonases. Bioactive compounds of plant essential oils are also effective against biofilm matrix disruption. Elevated hydrostatic pressure up to 900 MPa in along with thermal treatments (50–100°C) has been found to be effective against biofilms and heat resistant spores. Similarly, non-thermal plasma treatments are expensive but effective in biofilm control. All these novel techniques promise an optimistic future for controlling biofilms formation in the food industry.

4. REFERENCES:

1. Al-Tayawi, T. S., Adel, E. M., & Omer, F. H. (2023). An Overview of Biofilm as a Virulence Factor for Bacteria to Survive in the Harsh Environment. *International Journal of Medical Science and Clinical Research Studies*, *3*(06), 1188-1197.
2. Alonso, V. P. P., Harada, A. M. M., & Kabuki, D. Y. (2020). Competitive and/or cooperative interactions of Listeria monocytogenes with Bacillus cereus in dual-species biofilm formation. *Frontiers in microbiology*, *11*, 500982.
3. Amankwah, S., Abdella, K., & Kassa, T. (2021). Bacterial biofilm destruction: A focused review on the recent use of phage-based strategies with other antibiofilm agents. *Nanotechnology, science and applications*, 161-177.
4. Aranda, F. J., Teruel, J. A., & Ortiz, A. (2023). Recent advances on the interaction of glycolipid and lipopeptide biosurfactants with model and biological membranes. *Current Opinion in Colloid & Interface Science*, 101748.
5. Ashrafi, A. (2023). Biosensors, mechatronics, & microfluidics for early detection & monitoring of microbial corrosion: A comprehensive critical review. *Results in Materials*, 100402.
6. Asma, S. T., Imre, K., Morar, A., Imre, M., Acaroz, U., Shah, S. R. A., ... & Zhu, K. (2022). Natural strategies as potential weapons against bacterial biofilms. *Life*, *12*(10), 1618.
7. Bai, X., Nakatsu, C. H., & Bhunia, A. K. (2021). Bacterial biofilms and their implications in pathogenesis and food safety. *Foods*, *10*(9), 2117.
8. Bin Hafeez, A., Jiang, X., Bergen, P. J., & Zhu, Y. (2021). Antimicrobial peptides: an update on classifications and databases. *International journal of molecular sciences*, *22*(21), 11691.
9. Borges, A., Meireles, A., Mergulhão, F., Melo, L., & Simões, M. (2020). Biofilm control with enzymes. In *Recent trends in biofilm science and technology* (pp. 249-271). Academic Press.
10. Boyce, A., & Walsh, G. (2023). Enzymes for cleaning-in-place in the dairy industry. In *Enzymes Beyond Traditional Applications in Dairy Science and Technology* (pp. 491-518). Academic Press.
11. Buder, C., Meemken, D., Fürstenberg, R., Langforth, S., Kirse, A., & Langkabel, N. (2023). Drinking Pipes and Nipple Drinkers in Pig Abattoir Lairage Pens—A Source of Zoonotic Pathogens as a Hazard to Meat Safety. *Microorganisms*, *11*(10), 2554.
12. Carrascosa, C., Raheem, D., Ramos, F., Saraiva, A., & Raposo, A. (2021). Microbial biofilms in the food industry—A comprehensive review. *International Journal of Environmental Research and Public Health*, *18*(04), 2014.
13. Chandel, H., Wang, B., & Verma, M. L. (2022). Control of biofilm formation during food processing. In *A Complete Guidebook on Biofilm Study* (pp. 199-227). Academic Press.
14. Cheng, Y., Mousavi, Z. E., Pennone, V., Hurley, D., & Butler, F. (2023). Association between the Presence of Resistance Genes and Sanitiser Resistance of Listeria monocytogenes Isolates Recovered from Different Food-Processing Facilities. *Microorganisms*, *11*(12), 2989.
15. Cremer, J., Kaltschmidt, B. P., Kiel, A., Eberhard, J., Schmidt, S., Kaltschmidt, C., ... & Anselmetti, D. (2023). Aging of industrial polypropylene surfaces in detergent solution and its consequences for biofilm formation. *Polymers*, *15*(5), 1247.
16. Deng, L. Z., Mujumdar, A. S., Pan, Z., Vidyarthi, S. K., Xu, J., Zielinska, M., & Xiao, H. W. (2020). Emerging chemical and physical disinfection technologies of fruits and vegetables: a comprehensive review. *Critical reviews in food science and nutrition*, *60*(15), 2481-2508.
17. Didehdar, M., Chegini, Z., Tabaeian, S. P., Razavi, S., & Shariati, A. (2022). Cinnamomum: The new therapeutic agents for inhibition of bacterial and fungal biofilm-associated infection. *Frontiers in Cellular and Infection Microbiology*, *12*, 930624.
18. Domingues, R. A. C. (2021). *Characterization of Novel Acinetobacter Baumannii Phagederived Depolymerases with Antivirulence Properties* (Doctoral dissertation, Universidade do Minho (Portugal)).
19. Eghbal, N., Chihib, N. E., & Gharsallaoui, A. (2020). Nisin. In *Antimicrobials in food* (pp. 309-338). CRC Press.
20. Farahpour, M. R., Pirkhezr, E., Ashrafian, A., & Sonboli, A. (2020). Accelerated healing by topical administration of Salvia officinalis essential oil on Pseudomonas aeruginosa and Staphylococcus aureus infected wound model. *Biomedicine & Pharmacotherapy*, *128*, 110120.
21. Farjami, A., Jalilzadeh, S., Siahi-Shadbad, M., & Lotfipour, F. (2022). The anti-biofilm activity of hydrogen peroxide against Escherichia coli strain FL-Tbz isolated from a pharmaceutical water

system. *Journal of Water and Health*, *20*(10), 1497-1505.
22. Fernandes, S., Gomes, I. B., Simões, M., & Simões, L. C. (2024). Novel chemical-based approaches for biofilm cleaning and disinfection. *Current Opinion in Food Science*, 101124.
23. c, S., García-Gutiérrez, C., Miguélez, E. M., Villar, C. J., & Lombó, F. (2018). Biofilms in the food industry: health aspects and control methods. *Frontiers in microbiology*, *9*, 315815.
24. Gana, J., Gcebe, N., Pierneef, R., Moerane, R., & Adesiyun, A. A. (2022). Multiple-locus variable-number tandem repeat analysis genotypes of Listeria monocytogenes isolated from farms, abattoirs, and retail in Gauteng Province, South Africa. *Journal of Food Protection*, *85*(9), 1249-1257.
25. George, A., Shen, B., Craven, M., Wang, Y., Kang, D., Wu, C., & Tu, X. (2021). A Review of Non-Thermal Plasma Technology: A novel solution for CO2 conversion and utilization. *Renewable and Sustainable Energy Reviews*, *135*, 109702.
26. Ghosh, S., Sarkar, T., & Chakraborty, R. (2021). Formation and development of biofilm-an alarming concern in food safety perspectives. *Biocatalysis and Agricultural Biotechnology*, *38*, 102210.
27. Gonçalves, A. S., Leitão, M. M., Simões, M., & Borges, A. (2023). The action of phytochemicals in biofilm control. *Natural Product Reports*, *40*(3), 595-627.
28. Goncalves, E. C., Assis, P. M., Junqueira, L. A., Cola, M., Santos, A. R., Raposo, N. R., & Dutra, R. C. (2020). Citral inhibits the inflammatory response and hyperalgesia in mice: The role of TLR4, TLR2/Dectin-1, and CB2 cannabinoid receptor/ATP-sensitive K+ channel pathways. *Journal of natural products*, *83*(4), 1190-1200.
29. Guo, D., Wang, S., Li, J., Bai, F., Yang, Y., Xu, Y., ... & Shi, C. (2020). The antimicrobial activity of coenzyme Q0 against planktonic and biofilm forms of Cronobacter sakazakii. *Food microbiology*, *86*, 103337.
30. Hemmati, F., Salehi, R., Ghotaslou, R., Samadi Kafil, H., Hasani, A., Gholizadeh, P., ... & Ahangarzadeh Rezaee, M. (2020). Quorum quenching: A potential target for antipseudomonal therapy. *Infection and Drug Resistance*, 2989-3005.
31. Holah, J. (2023). Hazard control by segregation in food factories. In *Hygienic Design of Food Factories* (pp. 259-286). Woodhead Publishing.
32. Hosseini, S. (2020). Self-Cleaning surfaces for different purposes: Review of production methods and future prospects. In *International conference on materials enginnering and metallurgy*.
33. Hsu, H. Y. (2020). UTILIZATION OF EMULSION CHEMISTRIES FOR DELIVERY AND ANTIVIRAL APPLICATION OF CARVACROL.
34. Jing, Z., Lu, Z., Santoro, D., Zhao, Z., Huang, Y., Ke, Y., ... & Sun, W. (2022). Which UV wavelength is the most effective for chlorine-resistant bacteria in terms of the impact of activity, cell membrane and DNA?. *Chemical Engineering Journal*, *447*, 137584.
35. Juszczuk-Kubiak, E. (2024). Molecular Aspects of the Functioning of Pathogenic Bacteria Biofilm Based on Quorum Sensing (QS) Signal-Response System and Innovative Non-Antibiotic Strategies for Their Elimination. *International Journal of Molecular Sciences*, *25*(5), 2655.
36. Kawacka, I., Olejnik-Schmidt, A., Schmidt, M., & Sip, A. (2020). Effectiveness of phage-based inhibition of Listeria monocytogenes in food products and food processing environments. *Microorganisms*, *8*(11), 1764.
37. Kernou, O. N., Azzouz, Z., Madani, K., & Rijo, P. (2023). Application of rosmarinic acid with its derivatives in the treatment of microbial pathogens. *Molecules*, *28*(10), 4243.
38. Khalid, S. J., Ain, Q., Khan, S. J., Jalil, A., Siddiqui, M. F., Ahmad, T., ... & Adnan, F. (2022). Targeting Acyl Homoserine Lactones (AHLs) by the quorum quenching bacterial strains to control biofilm formation in Pseudomonas aeruginosa. *Saudi Journal of Biological Sciences*, *29*(3), 1673-1682.
39. Khan, F., Jeong, G. J., Tabassum, N., & Kim, Y. M. (2023). Functional diversity of c-di-GMP receptors in prokaryotic and eukaryotic systems. *Cell Communication and Signaling*, *21*(1), 259.
40. Khan, J., Tarar, S. M., Gul, I., Nawaz, U., & Arshad, M. (2021). Challenges of antibiotic resistance biofilms and potential combating strategies: a review. *3 Biotech*, *11*, 1-15.
41. Kingkaew, E., & Tanasupawat, S. (2023). 1 Application peptides from of antimicrobial lactic acid bacteria in food preservation and human health. *Antimicrobials in Food Science and Technology*, 1.
42. Lahiri, D., Nag, M., Sheikh, H. I., Sarkar, T., Edinur, H. A., Pati, S., & Ray, R. R. (2021). Microbiologically-synthesized nanoparticles and their role in silencing the biofilm signaling cascade. *Frontiers in microbiology*, *12*, 636588.
43. Lamin, A., Kaksonen, A. H., Cole, I. S., & Chen, X. B. (2022). Quorum sensing inhibitors applications: a new prospect for mitigation of microbiologically influenced corrosion. *Bioelectrochemistry*, *145*, 108050.
44. Latag, G. V., Nakamura, T., Palai, D., Mondarte, E. A. Q., & Hayashi, T. (2023). Investigation of three-dimensional bacterial adhesion manner on model organic surfaces using quartz crystal microbalance with energy dissipation monitoring. *ACS Applied Bio Materials*, *6*(3), 1185-1194.
45. Li, W. R., Zhang, Z. Q., Yao, J. W., Liao, K., Zhu, L. P., Shi, Q. S., ... & Xie, X. B. (2022). Diallyl trisulfide attenuates Pseudomonas aeruginosa virulence via inhibiting quorum sensing. *International Biodeterioration & Biodegradation*, *173*, 105463.
46. Liaqat, Atif, Muhammad Farhan Jahangir Chughtai, Adnan Khaliq, Umar Farooq, Muhammad Shahbaz, Ayesha Ali, Kanza Saeed et al. "Applications of biosurfactants in dairy industry." In *Applications of Next Generation Biosurfactants in the Food Sector*, pp. 509-526. Academic Press, 2023.
47. Ling, H., Lou, X., Luo, Q., He, Z., Sun, M., & Sun, J. (2022). Recent advances in bacteriophage-based therapeutics: Insight into the post-antibiotic era. *Acta Pharmaceutica Sinica B*, *12*(12), 4348-4364.

48. Liu, D., Huang, Q., Gu, W., & Zeng, X. A. (2022). A review of bacterial biofilm control by physical strategies. *Critical Reviews in Food Science and Nutrition*, *62*(13), 3453-3470.
49. Liu, J., Yang, L., Kjellerup, B. V., & Xu, Z. (2023). Viable but nonculturable (VBNC) state, an underestimated and controversial microbial survival strategy. *Trends in Microbiology*.
50. Lu, J., Hu, X., & Ren, L. (2022). Biofilm control strategies in food industry: Inhibition and utilization. *Trends in Food Science & Technology*, *123*, 103-113.
51. Mahamuni-Badiger, P. P., Patil, P. M., Badiger, M. V., Patel, P. R., Thorat-Gadgil, B. S., Pandit, A., & Bohara, R. A. (2020). Biofilm formation to inhibition: Role of zinc oxide-based nanoparticles. *Materials Science and Engineering: C*, *108*, 110319.
52. Mahnashi, M. H., Muddapur, U. M., Turakani, B., Shaikh, I. A., Al Awadh, A. A., Alshahrani, M. M., ... & Shakeel Iqubal, S. M. (2022). A review on versatile eco-friendly applications of microbial proteases in biomedical and industrial applications. *Science of Advanced Materials*, *14*(4), 622-637.
53. Małaczewska, J., & Kaczorek-Łukowska, E. (2021). Nisin—A lantibiotic with immunomodulatory properties: A review. *Peptides*, *137*, 170479.
54. Mandal, A., & Ray Banerjee, E. (2020). Nanotechnology and functional food. *Nanomaterials and Biomedicine: Therapeutic and Diagnostic Approach*, 85-112.
55. MARINE, N. F. CHAPTER SEVEN PROMISING PERSPECTIVES FOR NANOTECHNOLOGY FROM MARINE MICROBIAL SOURCES AMUTHA SANTHANAM, B. CLARA GNANA. *Microbial Biodiversity*, 86.
56. Markande, A. R., Patel, D., & Varjani, S. (2021). A review on biosurfactants: properties, applications and current developments. *Bioresource Technology*, *330*, 124963.
57. Michelin, M., Gomes, D. G., Romaní, A., Polizeli, M. D. L. T., & Teixeira, J. A. (2020). Nanocellulose production: exploring the enzymatic route and residues of pulp and paper industry. *Molecules*, *25*(15), 3411.
58. Michelin, M., Gomes, D. G., Romaní, A., Polizeli, M. D. L. T., & Teixeira, J. A. (2020). Nanocellulose production: exploring the enzymatic route and residues of pulp and paper industry. *Molecules*, *25*(15), 3411.
59. Migoń, D., Wasilewski, T., & Suchy, D. (2020). Application of QCM in peptide and protein-based drug product development. *Molecules*, *25*(17), 3950.
60. Mohapatra, S., Yutao, L., Goh, S. G., Ng, C., Luhua, Y., Tran, N. H., & Gin, K. Y. H. (2023). Quaternary ammonium compounds of emerging concern: Classification, occurrence, fate, toxicity and antimicrobial resistance. *Journal of Hazardous Materials*, *445*, 130393.
61. Mokoena, M. P., Omatola, C. A., & Olaniran, A. O. (2021). Applications of lactic acid bacteria and their bacteriocins against food spoilage microorganisms and foodborne pathogens. *Molecules*, *26*(22), 7055.
62. Moye, Z. D., Das, C. R., Tokman, J. I., Fanelli, B., Karathia, H., Hasan, N. A., ... & Sulakvelidze, A. (2020). Treatment of fresh produce with a Salmonella-targeted bacteriophage cocktail is compatible with chlorine or peracetic acid and more consistently preserves the microbial community on produce. *Journal of food safety*, *40*(2), e12763.
63. Nag, M., Lahiri, D., Ghosh, A., Das, D., & Ray, R. R. (2021). Quorum sensing. *Biofilm-mediated diseases: Causes and controls*, 21-45.
64. Nisa, M., Dar, R. A., Fomda, B. A., & Nazir, R. (2023). Combating food spoilage and pathogenic microbes via bacteriocins: A natural and eco-friendly substitute to antibiotics. *Food Control*, *149*, 109710.
65. Oudebrouckx, G., Vandenryt, T., Nivelle, P., Bormans, S., Wagner, P., & Thoelen, R. (2020). Introducing a thermal-based method for measuring dynamic thin film thickness in real time as a tool for sensing applications. *IEEE Transactions on Instrumentation and Measurement*, *70*, 1-10.
66. Pattnaik, S., Mishra, M., & Naik, P. K. (2024). Alternative Strategies for Combating Antibiotic Resistance in Microorganisms. In *Antimicrobial Photodynamic Therapy* (pp. 65-109). CRC Press.
67. Poulin, M. B., & Kuperman, L. L. (2021). Regulation of biofilm exopolysaccharide production by cyclic di-guanosine monophosphate. *Frontiers in Microbiology*, *12*, 730980.
68. Røder, H. L., Olsen, N. M., Whiteley, M., & Burmølle, M. (2020). Unravelling interspecies interactions across heterogeneities in complex biofilm communities. *Environmental Microbiology*, *22*(1), 5-16.
69. Saboe, D. (2022). *Monitoring Key Water Quality Parameters in Water Resources Systems Using Bioactive Electrodes*(Doctoral dissertation, Arizona State University).
70. Salari, N., Rasoulpoor, S., Hosseinian-Far, A., Razazian, N., Mansouri, K., Mohammadi, M., ... & Shabani, S. (2021). Association between serum paraoxonase 1 activity and its polymorphisms with multiple sclerosis: a systematic review. *Neurological Sciences*, *42*, 491-500.
71. Santana, M. F. D. S. E. D., & Pimentel Filho, N. D. J. (2023). Biofilmes de patógenos na indústria de alimentos: uma revisão sobre a sua formação e controle.
72. Seneviratne, C. J., Suriyanarayanan, T., Widyarman, A. S., Lee, L. S., Lau, M., Ching, J., ... & Ramage, G. (2020). Multi-omics tools for studying microbial biofilms: current perspectives and future directions. *Critical Reviews in Microbiology*, *46*(6), 759-778.
73. Shineh, G., Mobaraki, M., Perves Bappy, M. J., & Mills, D. K. (2023). Biofilm formation, and related impacts on healthcare, food processing and packaging, industrial manufacturing, marine industries, and sanitation–A review. *Applied Microbiology*, *3*(3), 629-665.
74. Shleeva, M. O., Kondratieva, D. A., & Kaprelyants, A. S. (2023). Bacillus licheniformis: a producer of antimicrobial substances, including Antimycobacterials,

which are feasible for medical applications. *Pharmaceutics*, *15*(7), 1893.
75. Singh, B. K. (2021). An overview of enzymes and their use in the detergent industry. *Asian Journal of Research in Social Sciences and Humanities*, *11*(12), 71-76.
76. Sliem, M. H., Fayyad, E. M., Abdullah, A. M., Younan, N. A., Al-Qahtani, N., Nabhan, F. F., ... & Arora, D. (2021). Monitoring of under deposit corrosion for the oil and gas industry: a review. *Journal of Petroleum Science and Engineering*, *204*, 108752.
77. Smith, P., & Schuster, M. (2022). Antiactivators prevent self-sensing in Pseudomonas aeruginosa quorum sensing. *Proceedings of the National Academy of Sciences*, *119*(25), e2201242119.
78. Soleimani, M., Ghasemi, J. B., Ziarani, G. M., Karimi-Maleh, H., & Badiei, A. (2021). Photocatalytic degradation of organic pollutants, viral and bacterial pathogens using titania nanoparticles. *Inorganic Chemistry Communications*, *130*, 108688.
79. Souza, G. M., de Oliveira Vieira, K. C., Naldi, L. V., Pereira, V. C., & Winkelstroter, L. K. (2021). Green synthesized nanoparticles as a promising strategy for controlling microbial biofilm. *Nanotechnology for Advances in Medical Microbiology*, 1-28.
80. Stearns, R., Freshour, A., & Shen, C. (2022). Literature review for applying peroxyacetic acid and/or hydrogen peroxide to control foodborne pathogens on food products. *Journal of Agriculture and Food Research*, *10*, 100442.
81. Stine, J. M., Beardslee, L. A., Sathyam, R. M., Bentley, W. E., & Ghodssi, R. (2020). Electrochemical dissolved oxygen sensor-integrated platform for wireless in situ bioprocess monitoring. *Sensors and Actuators B: Chemical*, *320*, 128381.
82. Tang, J., Wang, W., & Chu, W. (2020). Antimicrobial and anti-quorum sensing activities of phlorotannins from seaweed (Hizikia fusiforme). *Frontiers in Cellular and Infection Microbiology*, *10*, 586750.
83. Thames, H. T., & Theradiyil Sukumaran, A. (2020). A review of Salmonella and Campylobacter in broiler meat: emerging challenges and food safety measures. *Foods*, *9*(6), 776.
84. Tian, F., Li, J., Nazir, A., & Tong, Y. (2021). Bacteriophage–a promising alternative measure for bacterial biofilm control. *Infection and Drug Resistance*, 205-217.
85. Todorov, S. D., Popov, I., Weeks, R., & Chikindas, M. L. (2022). Use of bacteriocins and bacteriocinogenic beneficial organisms in food products: benefits, challenges, concerns. *Foods*, *11*(19), 3145.
86. Vengatesan, A. (2023). *Evaluation of Photosensitizer Curcumin as a Surface Sanitizer on Food Contact Surface Typical of the Cold Smoked Fish Industry and as a Treatment Method for Reduction of Listeria monocytogenes Population in Cold Smoked Salmon* (Doctoral dissertation, Rutgers The State University of New Jersey, School of Graduate Studies).
87. Verma, N., & Agarwal, V. (2022, December). A Review on Current Strategies for Biofilm Control in Food Industry. In *conference BioSangam 2022: Emerging trends in Biotechnology (BIOSANGAM 2022)* (pp. 123-132). Atlantis Press.
88. Viktorová, J., Stupák, M., Řehořová, K., Dobiasová, S., Hoang, L., Hajšlová, J., ... & Ruml, T. (2020). Lemon grass essential oil does not modulate cancer cells multidrug resistance by citral—its dominant and strongly antimicrobial compound. *Foods*, *9*(5), 585.
89. Visnapuu, A., Van der Gucht, M., Wagemans, J., & Lavigne, R. (2022). Deconstructing the phage–bacterial biofilm interaction as a basis to establish new antibiofilm strategies. *Viruses*, *14*(5), 1057.
90. Wakui, K., Rosyidah, A. L., Maensiri, D., Taweeyanyongkul, K., & Nantapong, N. (2024). Degradation of Biofilm Formed by Opportunistic Pathogens using Amylase Extracted from Bacillus tequilensis. *Brazilian Archives of Biology and Technology*, *67*, e24220200.
91. Wang, S., Zhao, Y., Breslawec, A. P., Liang, T., Deng, Z., Kuperman, L. L., & Yu, Q. (2023). Strategy to combat biofilms: a focus on biofilm dispersal enzymes. *npj Biofilms and Microbiomes*, *9*(1), 63.
92. Xu, M. M., Kaur, M., Pillidge, C. J., & Torley, P. J. (2022). Microbial biopreservatives for controlling the spoilage of beef and lamb meat: Their application and effects on meat quality. *Critical Reviews in Food Science and Nutrition*, *62*(17), 4571-4592.
93. Xue, B., Shen, Y., Zuo, J., Song, D., Fan, Q., Zhang, X., ... & Wang, Y. (2022). Bringing Antimicrobial Strategies to a New Level: The Quorum Sensing System as a Target to Control Streptococcus suis. *Life*, *12*(12), 2006.
94. Yan, D., Li, Y., Liu, Y., Li, N., Zhang, X., & Yan, C. (2021). Antimicrobial properties of chitosan and chitosan derivatives in the treatment of enteric infections. *Molecules*, *26*(23), 7136.
95. Yepez, X. V., Misra, N. N., & Keener, K. M. (2020). Nonthermal plasma technology. *Food safety engineering*, 607-628.
96. Younis, A. B., Haddad, Y., Kosaristanova, L., & Smerkova, K. (2023). Titanium dioxide nanoparticles: Recent progress in antimicrobial applications. *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology*, *15*(3), e1860.
97. Yuan, L., Hansen, M. F., Røder, H. L., Wang, N., Burmølle, M., & He, G. (2020). Mixed-species biofilms in the food industry: current knowledge and novel control strategies. *Critical reviews in food science and nutrition*, *60*(13), 2277-2293.
98. Yuan, L., Sadiq, F. A., Wang, N., Yang, Z., & He, G. (2021). Recent advances in understanding the control of disinfectant-resistant biofilms by hurdle technology in the food industry. *Critical reviews in food science and nutrition*, *61*(22), 3876-3891.
99. Yunus, J., Wan Dagang, W. R. Z., Jamaluddin, H., Jemon, K., Mohamad, S. E., & Jonet, M. A. (2024). Bacterial biofilm growth and perturbation by serine protease from Bacillus sp. *Archives of microbiology*, *206*(4), 138.
100. Zhang, C., Wang, C., Zhao, S., & Xiu, Z. (2021). Role of c-di-GMP in improving stress resistance of alginate-chitosan microencapsulated Bacillus subtilis

cells in simulated digestive fluids. *Biotechnology Letters*, *43*, 677-690.

101. Zhang, F., Wu, S., Dai, J., Huang, J., Zhang, J., Zhao, M., ... & Wu, Q. (2023). The emergence of novel macrolide resistance island in Macrococcus caseolyticus and Staphylococcus aureus of food origin. *International Journal of Food Microbiology*, *386*, 110020.

102. Zhou, L., Zhang, Y., Ge, Y., Zhu, X., & Pan, J. (2020). Regulatory mechanisms and promising applications of quorum sensing-inhibiting agents in control of bacterial biofilm formation. *Frontiers in microbiology*, *11*, 589640.

103. Zhu, T., Yang, C., Bao, X., Chen, F., & Guo, X. (2022). Strategies for controlling biofilm formation in food industry. *Grain & Oil Science and Technology*, *5*(4), 179-186.

104. Ziyaina, M., & Rasco, B. (2021). Inactivation of microbes by ozone in the food industry: A review. *African Journal of Food Science*, *15*(3), 113-120.