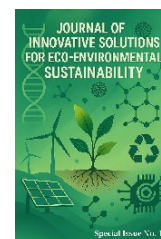




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Review Article

Biofilm Formation in the Food Industry Under Changing Climatic Conditions

Bukola Margaret Popoola^{1,*}, Oyindamola John Samson^{1,*}, Tosin Comfort Olateru²

¹ Department of Microbiology and Biotechnology, Ajayi Crowther University, Oyo, Oyo State, Nigeria

² Department of Biology, The Polytechnic Ibadan, Ibadan, Oyo State, Nigeria

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ABSTRACT

Given the profound implications of biofilm formation in the food industry, including its role as a major driver of food spoilage, foodborne disease outbreaks, and the deterioration of processing equipment, a comprehensive understanding of the factors governing bacterial growth and biofilm development is indispensable. These factors, however, cannot be considered in isolation. Emerging evidence suggests that climate change, through rising global temperatures, altered humidity, fluctuating water availability, and shifts in nutrient dynamics, may further modulate microbial behavior, enhancing the propensity of biofilm formation by pathogens and spoilage organisms. Understanding that biofilms can influence and are influenced by climate change is crucial to their effective management in the food industry. Climate-driven shifts in biofilm behavior may complicate existing safety and hygiene protocols, necessitating more stringent control measures such as climate-adaptive sanitation technologies, infrastructure redesign, and updated monitoring frameworks capable of responding to the rapidly changing microbiological landscape of food-processing environments. Therefore, as the environment becomes more variable and extreme, it is critical to investigate biofilm dynamics to protect public health, manage ecosystems, and ensure sustainable industrial practices. This review aims to describe how climate-driven environmental pressures make biofilm eradication in the food industry particularly challenging, and to address innovative strategies for biofilm management and future research directions towards effective management.

1. Introduction

The phenomenon of biofilm formation has been extensively documented and investigated over several decades. A substantial body of research has elucidated its structural complexity, physiological significance, and role in diverse natural and engineered environments. Numerous studies also have focused on the mechanisms underlying biofilm development, including microbial adhesion, extracellular polymeric substance (EPS) production, and intercellular signaling, highlighting its implications in clinical, industrial, and environmental contexts (Olanbiwoninu and Popoola, 2023; Moyal et al., 2023; Sharma et al., 2023; Cooney et al., 2024; Dawan et al., 2025). Despite this extensive knowledge base, biofilm research remains critically

relevant today due to its direct association with persistent global challenges such as antimicrobial resistance, chronic infections, and contamination of food and water systems. Biofilms exhibit remarkable tolerance to conventional antimicrobial agents and environmental stressors, making them a major concern in healthcare, water distribution infrastructures, and food processing. Furthermore, understanding biofilm dynamics is essential for developing innovative strategies to prevent or control their formation, which is crucial for safeguarding public health, ensuring food safety, and improving the efficiency of industrial processes. Biofilms are structured microbial communities that represent one of the most effective survival strategies employed by microorganisms, enabling them to persist and adapt even in hostile environments (Sharan, 2022). Central to this adaptability

* Corresponding authors.

Email: bm.popoola@acu.edu.ng (B.M.P)

Email: oj.samson@acu.edu.ng (O.J.S.)

is the EPS matrix, which provides structural integrity, facilitates cell-to-cell communication, supports nutrient acquisition, and promotes horizontal gene transfer. These features allow biofilm-associated microorganisms to tolerate environmental stressors and resist antimicrobial agents, enhancing their survival across diverse habitats (Shukla and Monteiro, 2025).

This remarkable strategy, while advantageous to microbes, creates widespread challenges in human activities. In the food industry, biofilms contaminate equipment, compromise hygiene, and contribute to spoilage and foodborne disease outbreaks. Pharmaceutical manufacturing faces risks to sterility, drug potency, and patient safety, while hospitals contend with device-related infections, delayed wound healing, and anti-microbial resistance. Water systems experience biofouling, reduced water quality, and the spread of pathogens. Beyond healthcare and food, biofilms impact the oil and gas industry through corrosion and operational inefficiencies; agriculture and livestock via crop diseases, soil microbiome disruption, and zoonotic risks; and consumer goods such as cosmetics, where biofilms lead to spoilage and reduced efficacy. Other sectors, including biotechnology, marine, textile, and paper industries, are also affected by contamination, corrosion, and product degradation.

1.1. Understanding Biofilm Formation

Biofilms are structured microbial communities encased in an extracellular polymeric substance (EPS) matrix that adhere to biotic and abiotic surfaces (Olanbiwoninu and Popoola, 2023). Their development is influenced by chemical, physical, and biological factors, and proceeds through distinct stages, including initial attachment, microcolony formation, maturation, and dispersal (Öztürk et al., 2023; Elumalai et al., 2024; Swamy and Sharma, 2025) (Figure 1). Although bacteria can exist planktonically, they often adopt a sessile lifestyle at environmental interfaces where nutrient availability and protection from stress favour biofilm formation (Alotaibi, 2021; Kilic, 2025). Following irreversible attachment, bacteria secrete EPS and use surface structures such as fimbriae and other adhesins to initiate microcolony development and assemble a matrix containing polysaccharides, extracellular DNA, proteins, and lipids (Schilcher and Horswill, 2020; Chiba et al., 2022). This matrix limits antimicrobial penetration, buffers chemical insults, and maintains nutrients and oxygen gradients while supporting cell-to-cell communication and spatial organization (Costa et al., 2018; Galdiero et al., 2019). Biofilms, therefore, represent adaptive, highly organized consortia that enhance microbial persistence.

The biofilm life cycle proceeds through five sequential stages. (1) Reversible attachment: planktonic cells make transient contact with abiotic or biotic surfaces through electrostatic interactions, van der Waals forces, hydrophobic effects, and a conditioning film that mediates the bacteria-surface interface. (2) Irreversible attachment and aggregation: cells stabilize their adhesion via surface adhesins and appendages, initiating microcolony formation. (3) Extracellular matrix production: as attached cells proliferate, they secrete EPS that form the structural scaffold of the biofilm; while this matrix contributes to stress tolerance, enhanced resilience also arises from the spatial arrangement of cells, metabolic heterogeneity, and biofilm-specific gene expression. (4) Maturation: biofilms develop a complex three-dimensional architecture, supported by EPS, with channels and gradients that sustain cooperative microbial communities. (5) Ways for bacteria to leave the biofilm: In the later stages of biofilm development, cells can leave the community through desorption, detachment, or dispersion. Desorption involves the release of weakly attached cells, while detachment includes mechanisms such as erosion—the gradual removal of small amounts of biomass—and sloughing, in which larger or intact portions of the biofilm are shed. Dispersion is a distinct, active

process in which the interior of a microcolony becomes fluidized, allowing cells to mobilize and exit through openings in the microcolony wall. These cells then re-enter the bulk liquid as single, planktonic bacteria, enabling the colonization of new surfaces (Petrova and Sauer, 2016) (Figure 1).

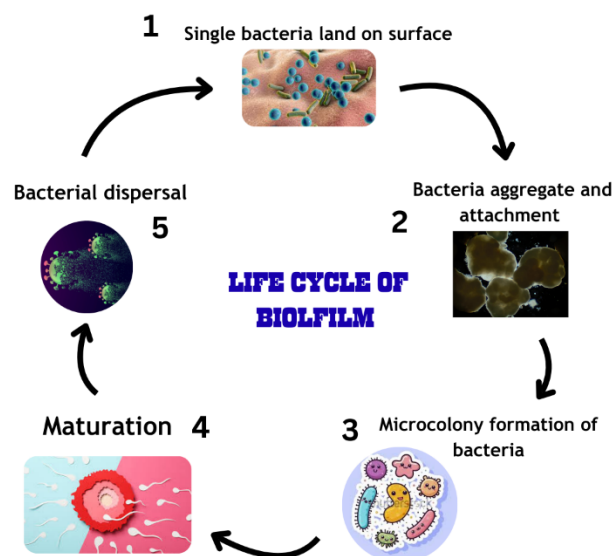


Figure 1. Stages of biofilm development by a single bacterial species on a solid surface

It is worth noting that the persistence and resilience of biofilms are influenced by both surface properties, such as charge, roughness, and hydrophobicity, and environmental factors, including temperature, pH, nutrient availability, and humidity (Kilic, 2025). Once established, biofilms shield microorganisms from chemical and physical removal, allowing them to survive, spread, and compromise product quality and safety. Understanding the factors that promote biofilm formation and persistence is essential for developing strategies to control biofilms, safeguard human health, maintain industrial productivity, and protect infrastructure.

1.2. Factors Affecting Biofilm Formation

A detailed examination of factors that affect biofilm formation provides insight into the mechanisms underlying bacterial growth, surface attachment, and EPS-mediated biofilm development. These factors include the nature of the attachment surface, interactions with associated microbial communities, electrostatic properties of the surfaces involved, and prevailing environmental conditions (Carrascosa, 2021) (Figure 2). Critical to this process are bacterial extracellular components and environmental cues that regulate autoaggregation and subsequent biofilm formation. Specifically, outer membrane proteins, lipopolysaccharides, and surface-associated proteinaceous structures such as pili and fimbriae (owing to their strategic location at the cell surface) play central roles in mediating bacterial adhesion and determining autoaggregation phenotypes (Moyal, 2023).

Surface charge is another important determinant of microbial adhesion and subsequent biofilm formation. Electrostatic approaches have demonstrated that positively charged surfaces can artificially facilitate attachment of viable cells, including strains that do not typically form biofilms, by coating substrates with non-toxic polyelectrolytes (Deev et al., 2021). Early studies showed that *Pseudomonas aeruginosa* attached and grew approximately twice as effectively on positively charged poly(methacrylate) surfaces compared with negatively charged ones (Gottenbos et al., 1999; Zheng et al., 2021). These findings

have since been confirmed across numerous bacterial species and surface types (Zhu et al., 2015; Kovacevic et al., 2016; Guo et al., 2018). Thus, surface charge density not only influences initial microbial adhesion but also affects the stability and robustness of biofilms, particularly in industrial settings such as food processing environments.

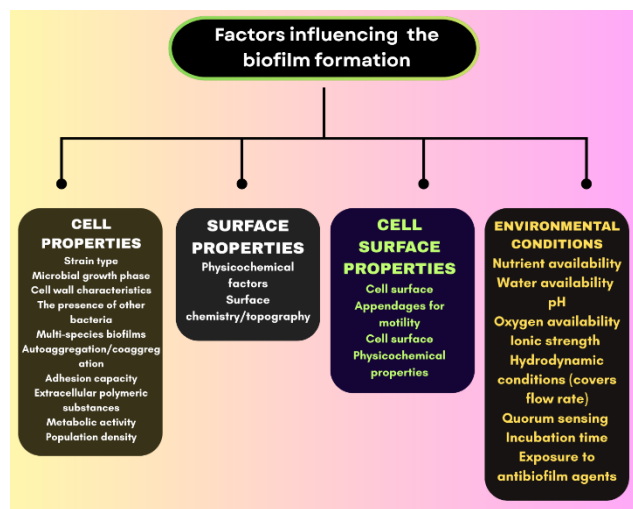


Figure 2. Stages Factors Affecting Biofilm Formation

Beyond charge, other environmental conditions influence the transition from reversible to irreversible attachment. Adhesion can be transient or permanent, depending on the forces involved. On abiotic surfaces, attachment is typically governed by nonspecific physicochemical interactions, such as hydrophobic forces, van der Waals interactions, and electrostatic attraction, whereas adhesion to biotic surfaces relies on specific receptor–ligand interactions mediated by surface-associated adhesins (Berne et al., 2015). These combined factors define how bacteria colonize surfaces and establish resilient biofilm communities.

In addition to physicochemical and environmental factors, microbial regulatory systems also influence how biofilms develop and persist. One such system is quorum sensing (QS), a communication mechanism in which microorganisms produce, release, and detect chemical signaling molecules to coordinate gene expression in response to population density (Dufour et al., 2010). Although QS is not itself an environmental or surface-derived factor, it plays a significant role in shaping microbial behaviours relevant to biofilm-associated lifestyles. QS regulates a variety of traits that support biofilm development, including motility, nutrient acquisition, conjugation, virulence expression, and the production of secondary metabolites (Kilic, 2025). These interactions occur both within (intraspecific) and between (interspecific) species and may be synergistic or antagonistic, influencing bioluminescence, sporulation, antimicrobial resistance, and microbial maturation (Mohana Sheela et al., 2019). Importantly, QS signaling molecules differ across bacterial groups: Gram-negative bacteria commonly rely on N-acyl homoserine lactones (AHLs), Gram-positive bacteria use oligopeptides, and autoinducer-2 (AI-2) functions as a universal interspecies signal in both groups (Liu et al., 2022a). The importance of QS in coordinating pathogenic behaviours has been demonstrated in microorganisms such as *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Burkholderia pseudomallei*, *Burkholderia cenocepacia*, and *Vibrio cholerae* (Kilic, 2025). A well-studied example is the *las* QS system in *Pseudomonas aeruginosa*, which controls the synthesis of N-(3-oxododecanoyl)-L-homoserine lactone and is required for full biofilm development (Danese, 2002). The surrounding physicochemical environment influences QS activity. Surface wetness enhances signal diffusion and metabolic activity, supporting coordinated biofilm growth,

whereas dry or hydrophobic surfaces hinder signaling molecule movement and delay maturation. Surface roughness can create protective microrecesses that shelter cells, concentrate QS signals, and promote irreversible adhesion. In contrast, smoother surfaces reduce initial bacterial attachment and may limit localized accumulation of signaling molecules, thereby slowing biofilm establishment.

1.3. Biofilms in Food Processing Environments

In food-processing environments, biofilms often form on stainless steel, plastic, rubber, and other contact surfaces due to continuous exposure to moisture, nutrients, and inadequate cleaning (Rosario et al., 2024). These microbial communities serve as reservoirs for spoilage organisms and can harbour important foodborne pathogens such as *Listeria monocytogenes*, *Salmonella* spp., *Escherichia coli* O157:H7, and occasionally *Campylobacter* spp. Although direct epidemiological links between biofilms and specific foodborne outbreaks are limited, extensive evidence shows that biofilms facilitate the persistence and survival of these pathogens in food-processing environments, thereby increasing the risk of product contamination and subsequent outbreaks (Moura et al., 2016; Fagerlund et al., 2017; Yang et al., 2023b). Furthermore, biofilm-forming microorganisms readily colonize factory settings and pose significant risks to human health due to their capacity to establish resilient biofilm structures. Common industrial materials such as wood, glass, stainless steel, polyethylene, rubber, and polypropylene provide suitable artificial substrates for attachment and persistence (Carrascosa et al., 2021). The behaviour of bacterial communities within these biofilms differs markedly from that of planktonic cells, particularly in their tolerance to cleaning and disinfection procedures. Such biofilms not only accelerate corrosion of metallic surfaces and contribute to undesirable odours and off-flavours but also frequently harbour pathogenic and toxigenic species of concern, including *Escherichia coli*, *Listeria monocytogenes*, *Campylobacter jejuni*, *Salmonella enterica*, *Pseudomonas aeruginosa*, *Bacillus cereus*, and *Staphylococcus aureus* (Table 1).

The development of biofilms allows these bacteria to persist despite routine sanitation, presenting ongoing risks to food safety and shelf life (Popa et al., 2025). Their ability to form biofilms is intricately linked to their resilience against environmental stresses, including desiccation, sanitizers, and temperature fluctuations. Potentially harmful bacteria originating from wild game meat have also been identified as new sources of contamination in food chains. They can also contribute to the production of biofilms and persist in processing conditions (Bucur et al., 2024). It is worth noting that microbial cells within the biofilm have different phenotypic characteristics compared to their planktonic (free-floating) counterparts, such as a 1000-fold greater resistance to antimicrobial treatments. This resistance hampers decontamination efforts and enables repeated contamination cycles, leading to frequent product recalls and compromised consumer safety (Koo et al., 2017).

Essentially, biofilm production is not restricted to single-species populations; multi-species communities are more widespread in real-world food environments. These heterogeneous biofilms benefit from synergistic interactions, such as metabolic cooperation and common resistance mechanisms, which enhance biofilm robustness, structural integrity, and ecological adaptability (Ban-Cucerzan et al., 2025). Furthermore, biofilms facilitate horizontal gene transfer, accelerating the dissemination of antibiotic resistance genes within and between species. This escalating AMR challenge poses a significant risk to food safety and public health (Ban-Cucerzan et al., 2025).

Table 1. Major Biofilm-Forming Pathogens in the Food Industry

S/N	Pathogen	Biofilm Traits	Mechanisms of Action	Food Industry Relevance	Food Safety Concern	Selected References
1.	<i>Listeria monocytogenes</i>	Forms biofilms on stainless steel, glass, plastic; tolerant to refrigeration	EPS secretion; LuxS/AI-2 quorum sensing; stress response regulation	Dairy, RTE meats, seafood, equipment surfaces	Listeriosis (high mortality in immunocompromised, elderly, pregnant women)	Liu et al., 2017; Xu et al., 2025
2.	<i>Salmonella enterica</i>	Robust biofilms on steel, polystyrene, glass; survives desiccation	Curli fimbriae, cellulose (regulated by csgD); enhanced stress resistance	Poultry, eggs, produce, dry foods (nuts, spices)	Salmonellosis (global foodborne outbreaks)	Steenackers et al., 2012; Musa et al., 2024
3.	<i>Escherichia coli</i> (O157:H7, STEC)	Produces curli and cellulose; resistant to sanitizers	Shiga toxin; EPS-mediated protection; enhanced resistance in biofilms	Meat, raw milk, produce, water	Hemorrhagic colitis; hemolytic uremic syndrome (HUS)	Vogeeler et al., 2014; Alshammari et al., 2023
4.	<i>Bacillus cereus</i>	Endospore-forming; biofilms at air-liquid and solid-liquid interfaces	EPS production; spore-mediated persistence; toxin (cereulide, enterotoxins)	Rice, dairy, starch-rich foods	Diarrheal and emetic syndromes	Majed et al., 2016; Yang et al., 2023a
5.	<i>Campylobacter jejuni</i>	Fragile in planktonic form but survives in biofilms; forms on steel and glass	Flagella-mediated motility; EPS aids aerotolerance	Poultry and poultry-processing facilities	Campylobacteriosis (leading cause of gastroenteritis worldwide)	Pokhrel et al., 2022

1.4. Stages of Biofilm Development in Food-Processing Environments

Biofilm development generally follows the same universal stages: conditioning film formation, initial attachment, maturation, and desorption, detachment, or dispersion. However, in the food industry, this process differs significantly because of the nature of industrial operations, the composition of food residues, and the characteristics of processing surfaces. These unique conditions create mechanisms and ecological dynamics that diverge from classical biofilm models developed in laboratory or natural ecosystems. Biofilm development in food-processing environments begins with the rapid formation of a conditioning film, arising from organic and inorganic residues originating from food particles, processing water, and product remnants. This residue-rich layer quickly changes surface charge, hydrophobicity, and roughness, thereby creating highly favourable conditions for microbial adhesion (Shineh et al., 2023; Lorite et al., 2011; Raya et al., 2022). Such conditioning films develop more quickly and with greater nutrient availability than in most natural settings, making food-contact surfaces especially permissive to biofilm establishment.

Microorganisms transported by diffusion, convection, or active motility then interact with this layer, initially forming reversible contacts that transition to irreversible adhesion. It is worth noting that attachment efficiency is influenced by the physicochemical properties of the substratum and electrostatic interactions. Although bacterial cells generally carry a net negative charge, extracellular polymeric substances (EPS) bridge interactions between cells and surfaces, stabilizing adhesion on both positively and negatively charged materials and facilitating early biofilm development (Tong et al., 2010). After stable attachment, cells proliferate and form microcolonies within an EPS-rich matrix. As the biofilm matures, hydrodynamic shear forces, which fluctuate widely during processing and cleaning, periodically remove portions of the biofilm and help define an equilibrium biofilm thickness shaped by nutrient supply and operational conditions (Wang et al., 2022). This dynamic, shear-

influenced growth contrasts with the more uniform flow conditions typically described in laboratory biofilm models.

Within mature biofilms, microorganisms experience enhanced stress tolerance, metabolic cooperation, and coordinated community-level regulation. QS plays a central role in these processes, regulating genes involved in EPS production, virulence, and stress adaptation. In food-processing environments, QS contributes to the persistence of major contaminants, including *Listeria monocytogenes* and *Pseudomonas* spp., by enabling resistance to cleaning-in-place (CIP) procedures and continued colonization of equipment surfaces (Bai and Ravishankar, 2011). This operational coupling of QS regulation with industrial cleaning cycles is a feature not commonly emphasized in general biofilm descriptions. The final stage, desorption, detachment, or dispersion occurs when cells detach from the matrix in response to cues such as nutrient depletion or shear stress (Rumbaugh et al., 2020). Dispersed cells spread to new locations within the facility, enabling recolonization and perpetuating contamination cycles. Hence, this dynamic phase plays a critical role in perpetuating contamination cycles, as liberated cells can disseminate across equipment surfaces, colonize fresh niches, and reinitiate biofilm development. Notably, dispersed cells often exhibit heightened tolerance to antimicrobials, further complicating cleaning and sanitation efforts in the food industry.

Overall, biofilm formation in the food industry proceeds through a residue-driven, shear-modulated, stress-selected, and QS-enhanced pathway. This process involves successive stages of conditioning film formation, irreversible microbial attachment, persistent growth despite routine cleaning, and eventual dispersal, leading to the establishment of mature and highly recalcitrant biofilms. Such biofilms pose substantial economic and public health risks and differ fundamentally from those formed in natural or laboratory environments. These distinctions highlight the necessity for prevention and control strategies that are specifically tailored to food-processing environments.

Hence, given the numerous challenges associated with biofilm formation, it is crucial to recognize that their physiological and structural heterogeneity arises from steep gradients in nutrients,

oxygen, and redox conditions, as well as the accumulation of metabolic by-products. These microenvironmental variations shape metabolic diversity, drive spatial differentiation of cellular activity, and ultimately define the ecological complexity of biofilm communities. Thus, biofilm development is best understood as a complex, dynamic, and adaptive process in which microbial collectives establish structured habitats that optimize survival under fluctuating environmental pressures, especially in a world experiencing global warming.

2. Climate Change and Its Impact on Biofilm Formation in the Food Industry

Climate change has been shown to modify environmental conditions and interaction patterns in ways that may facilitate the expansion of biofilm ranges (Cooney et al., 2024). In the food processing industry, for instance, biofilms pose significant hygiene and safety concerns, especially as changing climatic conditions alter the microbial ecology and environmental parameters that influence biofilm formation and persistence. Moreover, ongoing climate change results in increasingly frequent and intense extreme events, which are already altering the structure and function of many ecosystems (Gampe et al., 2021). However, most studies on severe events have focused on assessing the effects of current climate change, with far less attention given to how past climate anomalies shape ecological communities' responses to future perturbations (Cant et al., 2023). Extreme weather patterns and increasing climatic variability are expected to alter the taxonomic and functional diversity of ecosystems, reducing their capacity to withstand future disturbances or imbalances in the Earth's climate system (Smith and Boers, 2023)].

Climate change introduces a cascade of interconnected environmental stressors that collectively reshape the ecology of biofilm formation in food production systems (Figure 3). Rising temperatures accelerate bacterial growth, enabling biofilms to form and mature more rapidly on food-contact surfaces. Fluctuations in humidity and water activity create microenvironments that favour persistent colonization. Extreme weather events, such as flooding, can transport pathogens and spoilage organisms from contaminated water sources directly into food-processing environments, turning them into hotspots for biofilm development. Additionally, nutrient-rich agricultural runoff and changing water quality further exacerbate the problem by providing microbes with the resources needed to multiply and strengthen biofilm communities. Moreover, these stressors act as selective pressures that enhance stress adaptation mechanisms and drive the emergence of AMR, complicating sanitation efforts and threatening food safety. Furthermore, changes in the chemical environment can also influence microbial community composition, affecting the prevalence of biofilm-forming strains and their overall community behaviour. Summarily put together, climate change introduces the following range of environmental stressors (environmental factors) that can influence biofilm development and control:

2.1. Temperature Fluctuations

Temperature is a critical determinant of microbial survival, physiology, and biofilm structure. Shifts in temperature can affect nucleic acids, proteins, and membrane lipids, necessitating adaptive stress-response pathways such as heat-shock and cold-shock proteins to maintain cellular integrity (Moon et al., 2023). Experimental studies have demonstrated temperature-dependent biofilm responses in foodborne pathogens. For instance, *Listeria monocytogenes* strains ST8 and ATCC 19112 formed more robust biofilms at 15–25 °C compared with 5 °C, with increased bacterial motility and extracellular protein and polysaccharide production (Li et al., 2025). Similarly, *Bacillus* species exhibited up to 90%

greater biofilm biomass at 37–45 °C relative to 30 °C, linked to enhanced EPS and amyloid fiber production, which stabilized biofilm architecture under thermal stress (Rajitha et al., 2021).

These findings demonstrate that temperature affects not only the rate of biofilm development but also microbial community structure, extracellular polymeric substance (EPS) production, and biofilm architecture. Elevated temperatures, for example, have been reported to accelerate biofilm accumulation and alter microbial community composition in aqueous systems (Alabdullatif, 2024). Moreover, opportunistic foodborne pathogens such as *Pseudomonas* spp. and *Listeria monocytogenes* exhibit enhanced biofilm formation under thermal stress, which promotes survival on stainless steel and polymeric surfaces and further complicates food safety management (Olanbiwoninu and Popoola, 2023; Manville et al., 2023).

2.2. Temperature-pH Interaction

Temperature-pH Interaction refers to the way both factors together influence a biological, chemical, or environmental process, not just individually. The interaction between temperature and pH further shapes biofilm formation. Studies using *Vibrio vulnificus*, *Vibrio parahaemolyticus*, *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, and *Vibrio cholerae* have shown that biofilm biomass and extracellular virulence factor secretion are maximized under specific temperature–pH combinations, often in the mild alkaline range (Han et al., 2016; Song et al., 2017; Çam and Brinkmeyer, 2020). Such interactions demonstrate that pH, alongside temperature, acts as a key environmental driver modulating pathogen persistence and biofilm robustness.

2.3. Relative Humidity (RH)

Beyond temperature, relative humidity (RH) plays a pivotal role in biofilm resilience. RH is a critical abiotic factor influencing biofilm dynamics on food-contact surfaces, and its effects are often non-linear. Evidence from heterotrophic plate count studies indicates that both very high and very low RH levels can support robust biofilm development across entire coupon surfaces, whereas intermediate RH levels tend to suppress biofilm growth, leading to either stable or declining bacterial attachment over time (Else et al., 2003). This phenomenon has been studied across several foodborne pathogens, such as *Listeria monocytogenes*. Renner and Weibel (2011) demonstrated that moderate RH (~50%) promotes survival on stainless steel surfaces, whereas very low RH (11%) causes significant reductions in viability. This suggests that controlling RH in processing areas could limit *Listeria* persistence. The study on *Salmonella enterica* showed that RH interacted with temperature to influence pathogen persistence. Higher RH values (30–70%) and elevated temperatures decreased decimal reduction times (DRTs), thereby shortening survival, and indicating that desiccation stress is a major determinant of *Salmonella* viability on dry surfaces (Bashir et al., 2022). In moisture-rich environments, elevated RH enables biofilm-forming bacteria such as *Pseudomonas aeruginosa* and *Salmonella* spp. to delay desiccation-induced stress responses, thereby prolonging their survival on food-contact surfaces. This extended persistence facilitates their establishment in cold storage facilities and processing areas characterized by high water activity, where they continue to pose a risk of food and equipment contamination (Ban-Cucerzan et al., 2025).

High relative humidity further supports biofilm stability by preserving the integrity of the EPS matrix, which plays a central role in protecting embedded microorganisms. The matrix shields biofilm-associated cells from shear forces and mechanical stress while maintaining biofilm architecture (Hasan and Aggarwal, 2025). Acting as a physical and chemical barrier, the EPS also protects microbial communities against desiccation, ultraviolet

radiation, and antimicrobial agents, thereby enhancing resistance to antibiotics and disinfectants (Seviour, 2019).

Understanding these RH–biofilm interactions is essential for food processors aiming to design effective environmental control strategies, especially in dry-processing facilities, dairy plants, and storage environments where condensation events can transiently increase local RH. By maintaining RH at levels that are suboptimal for biofilm development, typically mid-range humidity, processors can passively reduce microbial persistence and facilitate cleaning and sanitation efficiency.

2.4. Nutrient Fluxes

Nutrient availability is another critical determinant of biofilm development. Nutrient enrichment, often resulting from food residues or agricultural runoff, promotes EPS production and the formation of structurally complex, resilient biofilm communities. In *Salmonella enterica*, nutrient-rich conditions favour pellicle biofilm formation at the air–liquid interface, while nutrient limitation leads to denser, surface-associated biofilms optimized for adhesion and nutrient scavenging (Ban-Cucerzan et al., 2025).

The type of available nutrients also plays a critical role. In *Bacillus licheniformis*, supplementation with simple sugars such as glucose or maltose significantly enhances biofilm biomass and cell adhesion, primarily through carbon catabolite-mediated regulation of genes associated with biofilm development (Li et al., 2024). It is worth noting that nutrient stress can also trigger a survival response in various bacterial species, actively reinforcing biofilm formation as a protective measure (Fazeli-Nasab et al., 2022). This not only helps the community withstand harsh conditions but also enhances AMR. Mechanistically, nutrient stress activates stress-response pathways (such as *rpoS*-mediated regulation), boosts efflux pump activity, and induces biofilm-specific resistance genes, collectively making the biofilm community far harder to eradicate (Shree et al., 2023).

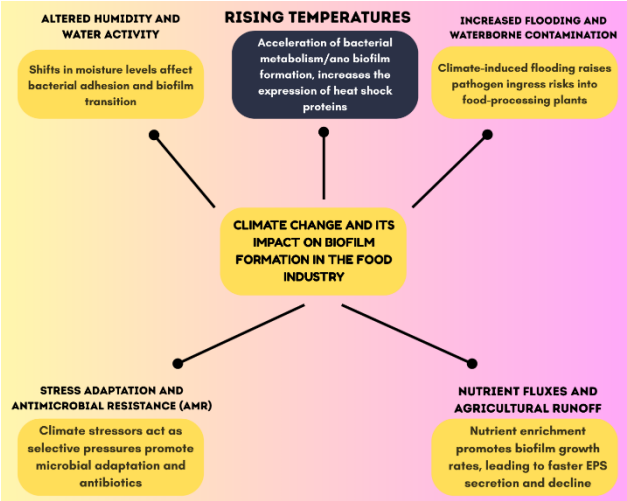


Figure 3. Climate Change and its Impact on Biofilm Formation in the Food Industry

Finally, in food-processing environments, fluctuations in temperature, pH, relative humidity, and nutrient availability interact with microbial physiology and surface properties to shape biofilm formation and resilience. Temperature regulates microbial activity and EPS production, while pH interacts with temperature to influence biofilm structure and phenotypes. Relative humidity impacts microbial survival and attachment, and nutrient fluxes drive biofilm architecture and stress responses. Together, these environmental factors facilitate the persistence of key foodborne pathogens, including *Listeria monocytogenes*, *Salmonella enterica*, *Escherichia coli* O157:H7, and *Pseudomonas* spp., emphasizing the need for targeted, environment-specific strategies to control biofilms effectively.

Table 2. Climate-Driven Environmental Factors and Microbial Responses Influencing Biofilm Formation

S/N	Climate-Driven Factor	Microbial Response	Reference
1.	Temperature Fluctuations	Enhanced biofilm accumulation and community shifts	Alabdullatif, 2024
2.	Humidity Fluctuations	Increased adhesion, EPS production shields microbes from shear stress and mechanical stresses, antimicrobial resistance	Hasan and Aggarwal, 2025; Seviour, 2019
3.	Temp + pH fluctuations	Modulated biofilm growth and antimicrobial resistance	Çam and Brinkmeyer, 2020
4.	Nutrient Fluxes	Activates stress-response pathway and induces biofilm-specific resistance genes	Shree et al., 2023

Climate change intensifies environmental stressors that stimulate adaptive microbial responses, ultimately enhancing biofilm formation, structural complexity, antimicrobial resistance, and environmental persistence (Table 2). These studies underscore that climate-driven environmental changes are potent modulators of biofilm biology, in essence, enhancing formation, altering architecture, and reducing susceptibility to control measures. Therefore, understanding these mechanisms is essential for adapting food safety and sanitation strategies to future climatic realities.

3. Challenges in Biofilm Management under a Changing Climate in the Food Industry

Biofilm management in food-processing environments is inherently challenging, and the added pressures of climate change further intensify biofilm persistence, resistance, and ecological

complexity. Variability in temperature, humidity, water activity, and nutrient inputs alters microbial physiology and community behaviour in ways that accelerate biofilm development and reduce the effectiveness of sanitation. These environmental pressures interact with physiological and structural heterogeneity already present in biofilms, such as steep nutrient, oxygen, and redox gradients and accumulated metabolic by-products, to heighten their resilience (Carrascosa et al., 2021; Shineh et al., 2023; Tong et al., 2010).

3.1. Exposure to Climate Stressors

Biofilm development is not a random occurrence but a highly orchestrated, stepwise process that allows microorganisms to thrive in challenging environments, a survival strategy that becomes even more advantageous under climate-driven stressors. Exposure to climate stressors, including heat, desiccation, UV

radiation, rising temperature, salinity shifts, etc., selects for microorganisms with heightened stress-response capabilities. These strains typically produce thicker EPS matrices, upregulate osmotic and thermal stress regulators, and exhibit increased resistance to disinfectants (Elafify et al., 2024). Raw materials exposed to heat stress or drought often arrive with altered microbiomes, dominated by stress-hardened bacteria, which adds to the microbial burden entering processing facilities (Kaba et al., 2020). Consequently, food-processing environments receive constant inputs of bacteria already primed for attachment, survival, and horizontal gene transfer (Ban-Cucerzan et al., 2025). Rising temperatures for instance, is a primary and direct climate stressor. Temperature, as a dominant climate signal, accelerates microbial growth and EPS production, enabling pathogens such as *Listeria monocytogenes*, *Salmonella enterica*, *Escherichia coli* O157:H7, *Vibrio* spp., and *Pseudomonas* spp. to form biofilms more rapidly and mature between cleaning cycles. This effect is especially pronounced in tropical regions where elevated ambient temperatures already shorten bacterial doubling times (Bucur et al., 2023; Ban-Cucerzan et al., 2025).

Humidity fluctuations and condensation are now more common in climate-stressed facilities, promoting early-stage adhesion and stabilization of conditioning films formed from organic and inorganic residues (Lorite et al., 2011; Raya et al., 2022). Climate-driven changes in water availability and quality further contribute to biofilm establishment. Drought increases dissolved solids and organic content, while flooding introduces nutrient-rich agricultural runoff and high microbial loads. When such compromised water is used for washing, processing, or sanitation, it seeds biofilms that are structurally complex and more chemically resistant (Wang et al., 2022; Bai and Ravishankar, 2011). These conditions can also introduce new or previously uncommon heat-tolerant and waterborne species, fostering multi-species biofilms that exhibit metabolic cooperation, quorum-sensing regulation, and enhanced collective defense strategies (Rumbaugh et al., 2020).

Furthermore, following biofilm irreversible attachment, microorganisms proliferate and form microcolonies, where EPS production intensifies. This sticky polymeric network facilitates quorum sensing, enabling cells to coordinate gene expression, upregulate stress-response pathways, and optimize community survival (Fazeli-Nasab, 2022). This is followed by the biofilm entering the maturation phase, developing a three-dimensional architecture with fluid-filled channels that distribute nutrients, remove waste, and shield the population from external perturbations (Akter et al., 2025).

The EPS matrix forms a hydrated barrier that retains nutrients, prevents desiccation, and restricts the penetration of detergents, disinfectants, and antimicrobial agents (Ban-Cucerzan et al., 2025). Under climate-related stress, this barrier can become increasingly reinforced. Elevated temperatures, for instance, may induce the expression of heat-shock proteins and molecular chaperones that stabilize cellular proteins and enhance bacterial survival (Vinod Kumar et al., 2017). Likewise, pH fluctuations arising from processes such as ocean acidification or fermentation by-products can activate acid tolerance responses, leading to increased EPS production and improved biofilm stability. Under stressed conditions, bacteria can activate osmotic stress regulators (e.g., OmpR-EnvZ system), which may boost EPS synthesis and biofilm thickness as a shield against water loss (Zhang et al., 2025). An additional challenge arises from the physiological heterogeneity characteristic of mature biofilms, where gradients in nutrient and oxygen availability create distinct microenvironments that support slow-growing or metabolically dormant persister cells. These cells exhibit intrinsic tolerance to antibiotics and sanitizers, which predominantly target actively dividing bacteria (Shree et al., 2023). As a result, biofilms can survive intensive cleaning procedures and rapidly re-establish, leading to persistent contamination in food-processing environments.

In essence, elevated ambient temperatures can shorten the bacterial lag phase, thereby accelerating biofilm initiation and establishment. Concurrently, fluctuations in relative humidity increase surface moisture, creating favourable conditions for microbial adhesion and early biofilm development. Extreme climatic events, such as flooding, can further intensify this process by introducing additional nutrients and novel microbial populations, which promote rapid colonization. Collectively, these climate-driven factors undermine the effectiveness of conventional cleaning and sanitation regimes, elevate microbial loads, and shorten biofilm-free intervals between cleaning cycles. As climate change increases the frequency and intensity of such environmental stressors, the challenges associated with biofilm control are likely to become more pronounced.

3.2. Antimicrobial and Disinfectant Resistance

It has been established that climate change is not only reshaping ecosystems but also altering the microbial communities that colonize food-processing environments. Shifts in temperature, humidity, and nutrient availability can favour the growth of pathogens and spoilage organisms over commensal or competitive microbes, changing the balance of the microbial ecosystem. More importantly, climate-driven alterations are increasingly linked to rising levels of AMR. Studies report that warming trends and altered precipitation patterns are associated with increased prevalence of AMR across multiple bacterial species, including *Escherichia coli*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*, and *Staphylococcus aureus* (Kaba et al., 2020). The failure of antimicrobials to clear biofilm-associated bacteria is partly due to the adsorption and inactivation of active compounds by the EPS matrix, reducing their bioavailability at target sites (Elafify et al., 2024). Moreover, stress conditions induce upregulation of efflux pumps and biofilm-specific resistance genes, further lowering susceptibility.

Importantly, as predicted by Grilo et al. (2021), regions most vulnerable to climate variability are likely to face disproportionately higher AMR burdens, exacerbating the persistence and resilience of biofilms on food-contact surfaces. Moreover, biofilms formed under these conditions act as genetic reservoirs that actively facilitate horizontal gene transfer (HGT) through transformation, conjugation, and transduction. This process enables the rapid exchange of resistance determinants and virulence factors, thereby accelerating the emergence of multidrug-resistant bacteria on food-contact surfaces. This climate-driven microbial shift has profound implications, as it may harbour more resistant and virulent strains, complicating cleaning, disinfection, and risk management in the food industry. However, disinfectants such as hypochlorites, peroxides, and quaternary ammonium compounds (QACs) remain widely used in the food industry, although their efficacy is markedly reduced against mature biofilms (Carrascosa et al., 2021). Emerging agents, including chlorine dioxide and alkyl amines, show potential but remain susceptible to resistance mechanisms, highlighting the need for continuous monitoring of their performance in food-processing environments. Biofilms formed under these conditions also serve as genetic reservoirs, actively facilitating horizontal gene transfer (HGT) through transformation, conjugation, and transduction. This process enables the rapid exchange of resistance determinants and virulence factors, accelerating the emergence of multidrug-resistant bacteria on food-contact surfaces.

3.3. Regulatory and Monitoring Systems

Regulatory and monitoring systems face additional pressures as the emergence of new environmental pathogens and atypical contamination patterns increasingly outpace traditional HACCP frameworks, which were designed under assumptions of relatively

stable environmental conditions. Many current monitoring programs fail to account for climate-driven risks or the altered behaviour of biofilms under fluctuating temperature, humidity, and water-quality stressors. According to the Intergovernmental Panel on Climate Change (IPCC), global average temperatures have already increased by 1.1 °C since pre-industrial times (IPCC, 2021), and evidence indicates that the current trend of rising temperatures, coupled with more frequent, intense, and prolonged extreme heat events, is likely to continue unless significant global mitigation efforts are undertaken (Amoadu et al., 2023). These climatic changes exacerbate operational challenges in food-processing facilities. Rising energy demands associated with increased cooling and sanitation place additional burdens on food-processing operations. As energy costs escalate, routine measures such as hot-water washdowns or extended cleaning cycles become less feasible, allowing biofilms to reestablish more rapidly between sanitation events. While replacing high-GWP (global warming potential) refrigerants with natural fluids in the refrigeration sector can lower greenhouse gas emissions (Faraldo and Byrne, 2024), this change does not fully alleviate the operational and financial pressures of increased cooling demand. Compounding these challenges, worker-related issues, including heat stress and climate-driven labour shortages, further reduce the frequency and thoroughness of cleaning, undermining biofilm control and food safety.

Climate change also disrupts supply chains, resulting in longer transport times and increased opportunities for cross-contamination. Temperature abuse during transit, especially under high ambient heat or unstable power supply, accelerates initial bacterial adhesion and biofilm initiation on food-contact surfaces. Similarly, climate-driven changes in raw materials alter their native microbiomes and increase initial contamination loads, further complicating biofilm management. Refrigeration and cooling systems have become increasingly relied upon as rising temperatures intensify across the food industry. Condensation on cooling coils, drains, and pipelines promotes chronic moisture accumulation, an ideal substrate for the survival and spread of *Listeria*, *Salmonella*, *E. coli* O157:H7, and *Pseudomonas* spp. (Bucur et al., 2023). This creates interconnected reservoirs of contamination capable of reseeding cleaned surfaces.

Collectively, these climate-amplified pressures heighten biofilm resilience, increase antimicrobial resistance (Shree et al., 2023), and elevate the risk of persistent contamination, foodborne outbreaks, and economic loss. Addressing these challenges will require climate-adaptive sanitation technologies, improved predictive modeling, infrastructure redesign, and updated monitoring frameworks capable of responding to the rapidly changing microbiological landscape of food-processing environments.

4. Strategies for Effective Biofilm Management

4.1. Preventative Approaches

The first line of defense against biofilm development in food processing facilities is hygienic design. Equipment and surfaces should be engineered with smooth, non-porous materials that minimize microbial attachment (Liu et al., 2023). In climates characterized by high humidity and fluctuating temperatures, condensation and surface roughness can accelerate biofilm growth (Calero Preciado et al., 2021; Shineh et al., 2023). Hygienic design includes sloped surfaces to prevent water stagnation, avoidance of dead spaces in pipelines, and the use of stainless steel or polymer coatings with anti-adhesive properties. Such designs reduce the frequency of microbial colonization and simplify sanitation processes (Samuel et al., 2022).

Timely detection of biofilms is critical to effective management (Mayer et al., 2024). Traditional culture-based methods are often too slow to capture biofilm dynamics in real-

time (Kulshrestha and Gupta, 2024). Recent advancements include biosensors, ATP bioluminescence, and qPCR-based assays for rapid biofilm detection (Mutschlechner et al., 2024; Cheliukanov et al., 2025). Under climate stress, biofilm communities may adapt by producing more extracellular polymeric substances (EPS), making them harder to detect. Therefore, integrated sensor systems capable of real-time monitoring in pipelines and surfaces are increasingly essential. The adoption of smart monitoring tools enhances early interventions before biofilms mature into resistant structures (Sharma et al., 2023).

Predictive modeling plays a vital role in anticipating biofilm risks under changing climatic conditions (Taiwo et al., 2024). Temperature fluctuations altered humidity levels, and variable water quality influences microbial growth and adhesion (Calero Preciado et al., 2022). Computational models using environmental parameters can forecast potential hotspots for biofilm formation (Dishan et al., 2024). Integrating artificial intelligence (AI) with predictive microbiology, food processors can proactively adjust cleaning regimes and allocate resources more efficiently. Such approaches reduce downtime, conserve water and energy, and enhance resilience against biofilm outbreaks (Kuppusamy et al., 2024).

4.2. Sanitation and Disinfection

Routine cleaning practices may no longer suffice as climate change intensifies microbial adaptation. Enhanced cleaning regimes involve a combination of mechanical, chemical, and automated approaches (Bose et al., 2024). For example, Clean-in-Place (CIP) systems with pressurized water jets, optimized detergents, and circulation cycles are critical. With higher ambient temperatures, microbial metabolic rates accelerate, necessitating shorter cleaning intervals. Enhanced regimes also consider the role of climate-induced water scarcity, promoting cleaning methods that are water-efficient yet highly effective (Pant et al., 2023).

Enzymatic cleaners represent a sustainable alternative to harsh chemicals. These cleaners degrade biofilm matrix components such as proteins, polysaccharides, and lipids, weakening the structural integrity of biofilms (Fernandes et al., 2024). They are particularly useful against mixed-species biofilms that thrive under variable climatic conditions. Enzyme formulations can be tailored to target specific biofilm-forming bacteria relevant to dairy, meat, or seafood processing. Moreover, enzymatic approaches align with green technology initiatives by reducing reliance on chlorine and quaternary ammonium compounds (Atanasković and Šenerović, 2024).

Thermal interventions remain a widely used strategy. Hot water, steam, and dry heat are applied to inactivate biofilm-forming microbes. However, climate variability can challenge the efficacy of these methods, as higher baseline temperatures may allow thermotolerant microbes to proliferate (Anumudu et al., 2024). Adjusting treatment duration and intensity becomes crucial to ensuring effectiveness. Energy-efficient technologies such as targeted steam cleaning can minimize costs while maintaining efficacy, offering a climate-smart alternative to conventional high-energy thermal treatments (Mun et al., 2025).

Emerging disinfection technologies are gaining traction as alternatives or complements to conventional methods. Ultrasound disrupts biofilm structure through acoustic cavitation, making microbes more vulnerable to antimicrobials (Choi et al., 2025). Ultraviolet (UV) light provides a chemical-free solution by damaging microbial DNA and preventing replication (Yemmireddy et al., 2022). Cold plasma generates reactive oxygen and nitrogen species capable of penetrating biofilm matrices (Zhu et al., 2020). Magnetic nanoparticles, on the other hand, exhibit antimicrobial activity and can be functionalized for targeted delivery of cleaning agents (Samson et al., 2025a). These

novel approaches are particularly relevant under climate-driven microbial adaptations, offering sustainable, non-toxic, and residue-free disinfection solutions (Samson et al., 2025b).

4.3. Biocontrol Measures

Biocontrol agents represent a biologically sustainable strategy for biofilm management. Bacteriophages specifically target and lyse pathogenic bacteria within biofilms, leaving beneficial microbes unaffected (Faruk et al., 2025). Climate variability can alter microbial diversity, creating new niches for opportunistic pathogens; bacteriophages offer precision-targeted solutions in such contexts. Competitive microbes, including lactic acid bacteria and *Bacillus* species, inhibit pathogen colonization through nutrient competition, production of biosurfactants, and antimicrobial peptides (Onajobi et al., 2023; Fashogbon et al., 2024; Reuben and Torres, 2024; Samson et al., 2024). Together, bacteriophages and competitive microbes provide eco-friendly alternatives to chemical disinfectants while reducing selective pressure for antimicrobial resistance (Tian et al., 2021).

Natural antimicrobials, such as plant-derived essential oils, organic acids, and bacteriocins, complement biocontrol strategies. They are particularly attractive to consumers demanding clean-label products (Bukvicki et al., 2023). Climate change may increase fungal and bacterial contamination risks; natural antimicrobials provide resilience by targeting broad microbial groups (Bonaterra et al., 2022). Incorporating such compounds into packaging materials or surface coatings further extends their biofilm-preventing potential.

Table 3. Comparison of Novel Biofilm Management Technologies

Technology	Mechanism of Action	Advantages	Limitations	Climate Relevance	References
Ultrasound	Acoustic cavitation disrupts EPS	Enhances penetration of antimicrobials; residue-free	Limited penetration in complex geometries	Useful under humid conditions where EPS is denser	Shao and LI (2025)
UV Light	DNA damage prevents microbial replication	Chemical-free; fast action	Limited penetration; shadowed areas remain untreated	Effective for surface disinfection in variable climates	Raeiszadeh and Taghipour (2021)
Cold Plasma	Generates ROS/RNS to inactivate microbes	Broad-spectrum; minimal residue	High equipment cost; safety concerns	Suitable for rapid treatment under fluctuating conditions	Cheng et al. (2020)
Magnetic Nanoparticles	Antimicrobial activity; targeted delivery	Functionalizable; reusable	Potential toxicity; regulatory hurdles	Promising for precision cleaning with limited water use	Anderson et al. (2019)
Bacteriophages	Infect and lyse specific bacteria	Highly specific; eco-friendly	Narrow host range; resistance may develop	Valuable against emerging pathogens in climate-stressed systems	Liu et al. (2022b)
Competitive Microbes	Outcompete pathogens via resource competition & antimicrobials	Natural; improves microbial balance	Variable effectiveness; environmental sensitivity	Supports resilience in changing microbial ecosystems	De Wit et al. (2022)

5. Future Research Directions

5.1. Climate-Resilient Sanitation Protocols

The accelerating pace of climate change demands sanitation strategies that remain effective under variable environmental conditions. Temperature fluctuations, increased humidity, and water scarcity are expected to intensify microbial persistence and biofilm resilience in food processing environments (Al-Sharify et al., 2025). Future research should focus on designing climate-resilient sanitation protocols that adapt to these conditions. For instance, dynamic cleaning schedules could be developed based on real-time environmental monitoring, ensuring interventions are timely and resource efficient. These protocols would incorporate

4.4. Policy and Training

Human factors play a decisive role in biofilm control. Staff should be trained to recognize climate-driven risks such as higher microbial growth rates at elevated temperatures or water stress conditions that compromise sanitation efficiency (Jeyachandran, 2025). Training programs should emphasize adaptive cleaning protocols, proper use of novel technologies, and consistent documentation practices. Regular refresher courses strengthen the workforce’s ability to respond effectively under dynamic climatic scenarios (Tshitangano, 2024).

Standard operating procedures (SOPs) serve as the backbone of biofilm management programs. They must be updated regularly to incorporate new sanitation technologies and reflect evolving climatic conditions. SOPs should specify cleaning frequencies, monitoring tools, and corrective actions when biofilms are detected. By standardizing operations, food facilities minimize variability in hygiene practices and ensure compliance with international safety standards (Wade et al., 2023).

Regulatory frameworks require continuous adaptation to climate change’s impact on food safety. National and international authorities, such as WHO and FAO, are emphasizing resilience in food safety systems (Béné, 2020). Compliance with HACCP and ISO standards remains mandatory, but regulators are increasingly encouraging industry adoption of eco-friendly and technologically advanced disinfection methods (Ezzatpanah et al., 2022). Adhering to these evolving standards not only enhances food safety but also strengthens consumer trust in food systems (Table 3).

water-saving cleaning methods, sustainable detergents, and energy-efficient thermal treatments to balance food safety with environmental responsibility (Mohanty et al., 2024).

Sustainability is emerging as a cornerstone of food safety. Current practices often rely on chemical disinfectants that pose environmental risks and may drive microbial resistance. Future research should explore eco-friendly alternatives, such as enzymatic cleaners, natural antimicrobials, and low-energy novel technologies like ultrasound and cold plasma (Meade et al., 2021). By integrating lifecycle assessments into sanitation strategies, researchers can identify methods that minimize environmental impact while maintaining efficacy. Climate-resilient sanitation will thus not only safeguard food safety but also contribute to broader sustainability goals (Corvalan et al., 2020).

5.2. Smart Sensors and AI: A Transformative Approach

The integration of smart sensors and artificial intelligence (AI) offers unprecedented opportunities for proactive biofilm management. Smart sensors can continuously monitor critical parameters such as temperature, humidity, pH, and microbial load on food contact surfaces (Ramadan et al., 2025). When coupled with AI, these sensors can analyze complex datasets in real-time, predicting biofilm formation risks and recommending timely interventions. Such systems shift sanitation from reactive to predictive, reducing the likelihood of large-scale contamination events (Mishra et al., 2024).

AI-powered predictive models can learn from historical data and environmental conditions to identify high-risk zones within processing plants (Fazle et al., 2023). In the practical sense, machine learning algorithms can recognize patterns in microbial growth during warm, humid seasons and recommend intensified cleaning regimes in advance (Sundui et al., 2021). This predictive capacity enables food processors to optimize resource use while enhancing safety. In the long term, AI systems could be integrated into facility management platforms, providing automated alerts and decision-support tools for managers (Abdelalim et al., 2025).

Biofilms are not homogeneous but rather complex microbial communities shaped by environmental conditions. Traditional microbial detection methods often overlook these dynamics (Røder et al., 2020). Future research should prioritize microbiome analysis through metagenomics, transcriptomics, and metabolomics to unravel microbial interactions within biofilms. Such insights will help in identifying keystone species that drive resilience and persistence under climate stress (Seneviratne et al., 2020). Understanding these microbial networks will also support the development of targeted interventions, such as introducing competitive microbes or bacteriophages to disrupt biofilm stability.

5.3. Linking Microbiome Insights with Sanitation Strategies

Integrating microbiome analysis into sanitation strategies provides a more nuanced approach to biofilm management. Instead of blanket disinfection, interventions can be designed to selectively suppress harmful species while promoting beneficial microbes that maintain ecological balance (Fortune and Paterson, 2020). In actual scenerio, microbiome-informed sanitation could leverage competitive microbes that naturally inhibit pathogens, reducing reliance on harsh chemicals. This approach aligns with the broader movement toward precision microbiology, where interventions are guided by detailed microbial community profiles (Callens et al., 2022).

The successful implementation of climate-resilient sanitation protocols, smart sensors, and microbiome-informed strategies require supportive policies and standards. Regulatory bodies must update guidelines to accommodate novel disinfection technologies and AI-driven systems (Dewasiri et al., 2025). Future research should therefore include policy integration, ensuring that food processors are not only technologically capable but also compliant with evolving international food safety standards. Such alignment will facilitate global adoption of advanced biofilm management strategies (Charlebois et al., 2024).

Ultimately, future research must adopt a holistic perspective that integrates climate resilience, technological innovation, microbiome science, and policy frameworks. This convergence ensures that food processing industries remain adaptive to environmental challenges while maintaining high standards of food safety. By investing in smart sanitation ecosystems powered by AI and informed by microbiome research, the sector can transition toward proactive, sustainable, and climate-ready biofilm management strategies.

6. Conclusion

Biofilm formation remains one of the most formidable challenges in food processing, and climate change is amplifying this problem. Climate change alters the ecological and physiological drivers of biofilm development, intensifying challenges for food safety, hygiene, and equipment integrity. The viability of environmental stressors is critical for modulating the attachment of bacterial cells to surfaces and biofilm formation, and therefore, they are considered essential factors for preventing or minimizing biofilm formation. Climate change introduces multiple interconnected stressors that influence microbial attachment, growth, and biofilm resilience in food-processing environments. These include rising temperatures, altered humidity and water activity, flooding events and agricultural runoff, nutrient fluxes, and fluctuating temperature and pH. Together, these climate-driven drivers not only increase the prevalence and robustness of biofilms but also amplify the risk of foodborne outbreaks, cross-contamination, and equipment deterioration, economic losses, posing significant challenges for food safety management under a warming world. Understanding these mechanistic links is crucial for designing future-proof sanitation strategies in the food industry. Hence, addressing these challenges requires a multidisciplinary approach that combines a deeper understanding of biofilm biology with adapting existing cleaning and monitoring strategies, innovative cleaning technologies, surface engineering, and climate-adaptive management strategies, including fostering a culture of climate-aware hygiene to mitigate biofilm-associated risks effectively. Investment in research and policy development is also critical to mitigate the increasing risks posed by biofilms in a warming world.

Declarations

Data Availability Statement

All data generated in this review have been reported in the manuscript

Competing Interests

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