UF | IFAS Extension UNIVERSITY of FLORIDA

UF/IFAS PEER REVIEWED FSHN26-2
doi.org/10.32473/EDIS-FS473-2026

Biofilms and Their Impact on the Food Industry[1]

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Summary

Biofilms are assemblages of microbial cells that attach to surfaces, where they can be tough to remove and cause problems in many industries. This fact sheet explores how biofilms form and why they are a concern for the food and agriculture industry. Biofilms help microbes survive and have been linked to food poisoning outbreaks, leading to substantial financial losses. Biofilms can form due to environmental conditions, the types of surfaces they attach to, and farming or food processing methods. To prevent and control biofilms, food businesses use standard cleaning routines and newer technologies. Understanding and tackling biofilms is key to keeping food safe.

What is a biofilm?

Microbes are tiny living organisms that cannot be seen with the naked eye. They include bacteria, viruses, fungi, and algae. They live in soil, in water, and on plant surfaces. Microbes play key roles in nature by recycling nutrients, breaking down organic material, and supporting ecosystems. They are also useful in industries for making antibiotics and fermented products.

Biofilms are clusters of microbes, mainly bacteria, that stick to surfaces and form a protective, slimy layer. This layer helps them survive harsh conditions and can be found in all kinds of natural environments. Biofilm formation happens in steps: bacteria (i) attach loosely to a surface, (ii) attach more firmly, (iii) grow into a mature biofilm, and then eventually (iv) break apart and spread (Sauer et al. 2022). During the initial stage of formation, the cells reversibly attach to surfaces in food and farming environments. Biofilms form on surfaces like plastic, stainless steel, and wood. Over time, the bacteria create a slimy protective layer (Flemming 2016) composed of sugars, proteins, DNA, and fats (Di Martino 2018). This layer helps bacteria survive and communicate through a process called "quorum sensing" (Cámara et al. 2022; Miller and Bassler 2001), which allows them to share DNA, become more resilient, and, in some cases, become more harmful (Preda and Săndulescu 2019).

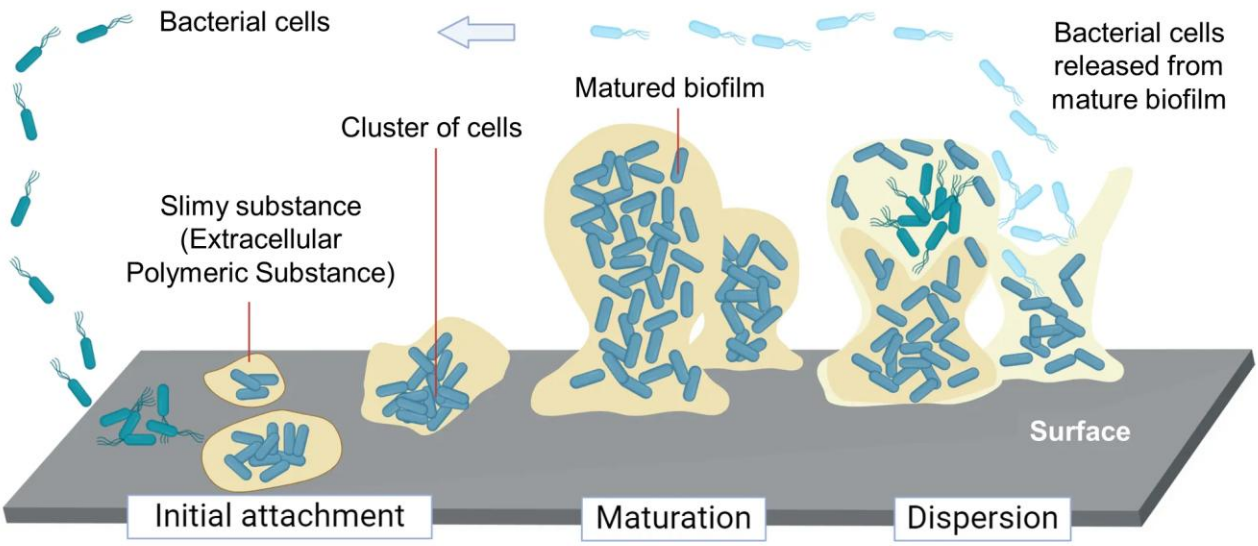

Figure 1. Steps involved in biofilm formation.
Credit: Created in BioRender by T. Gu, https://app.biorender.com/illustrations/67e5e2c3ace98d70bd2dc0a0?slideId=7037366f-a798-4b5e-a733-ed7034324d1a

As biofilms grow, they form structured layers that protect bacteria from harsh conditions, including cleaning and sanitation agents. When mature, biofilms release bacteria into the environment, allowing them to spread and potentially contaminate the food being grown or processed (Sauer et al. 2022). Biofilms play a key role in bacterial survival but also pose serious food safety challenges that require multiple coordinated efforts and strategies to control.

Why are biofilms important?

According to the U.S. Food and Drug Administration (FDA) and Centers for Disease Control and Prevention, a foodborne illness outbreak is defined as two or more people becoming sick after consuming the same food or drink, except in cases of botulism or chemical poisoning, where a single case constitutes an outbreak (FDA 2022; CDC 2021). These illnesses pose serious risks to public health and have considerable social and economic impacts. Despite the United States having one of the world's safest food systems, about one in every six individuals nationwide falls ill from contaminated foods each year. This results in 128,000 hospitalizations and 3,000 deaths annually (Scallan et al. 2011). Foodborne illnesses can cause symptoms ranging from mild to severe, including diarrhea, vomiting, nausea, abdominal cramps, joint pain, and fatigue. In addition to these symptoms, foodborne illnesses can lead to severe complications such as kidney failure, liver disease, gastrointestinal disorders, brain and nervous system issues, reactive arthritis, paralysis, and even death. Furthermore, these bacterial communities aid in microbial survival, which increases the risk of foodborne illness. This raises concerns since, notably, the National Institutes of Health reports that over 80% of microbial infections, though not limited to foodborne cases, are generally associated with biofilms (NIH 2002, 2007).

Various foodborne pathogens are found to have the ability to form biofilms both in the field and in food-processing environments (Cha and Ha 2022; Rossi et al. 2022; Roy et al. 2022). For instance, *Listeria monocytogenes*, a bacterium known to cause foodborne illnesses, has been identified as having biofilm-forming characteristics and has been reported to cause recurring contamination across different food products and supply chains (Kyere et al. 2020; Lee et al. 2019; Redding et al. 2024; Wang et al. 2022). In 2011, a multistate outbreak of *Listeria monocytogenes* linked with cantaloupe occurred in the United States, infecting 147 people and resulting in 143 hospitalizations and 33 deaths (CDC 2018). This event was the deadliest listeriosis outbreak in U.S. history. The FDA's Establishment Inspection Report (EIR) stated that "environmental swabs that were collected from the firm's cantaloupe processing equipment and surrounding areas were also found to be positive for *Listeria monocytogenes* which matches the current outbreak's strains" (Miser 2011). The report also mentioned that the surfaces of cantaloupe processing equipment had dirt and residue buildup which appeared to be "uncleanable" (Miser 2011). This buildup on equipment surfaces is often associated with biofilm formation, thus a *Listeria* biofilm in this facility was generally regarded as one of the potential causes of this deadly outbreak. Similarly, a 2024 listeriosis outbreak associated with deli meat was also attributed to *Listeria* biofilm buildup due to "inadequate sanitation practices" (USDA-FSIS 2025).

Besides the public health burden, studies indicate that biofilms contribute to a staggering estimated global economic burden of over 5 trillion USD annually (Highmore et al. 2022). The food and agriculture sectors incur roughly 324 billion USD annually, and water-related issues contribute an additional 90 billion USD annually (Cámara et al. 2022). The economic impact on the food and agriculture sectors mainly stems from food processing activities, which make up about 94% of the total $324 billion economic burden.

Biofilms in Food and Agriculture

Biofilm-forming bacteria associated with foodborne illnesses include *Listeria monocytogenes* (Gu et al. 2021, 2024), *Escherichia coli* (Zhao et al. 2022), *Salmonella* spp. (Roy et al. 2022), *Bacillus cereus* (Kwon et al. 2017), *Staphylococcus aureus* (Guo et al. 2023), and others (Klančnik et al. 2021; Lucero-Mejía et al. 2020; Simões et al. 2023). In the food industry, biofilm formation can result in pathogen transfer, leading to cross-contamination during farming, packing, or processing.

Farming and Agriculture

Microbial contamination may occur on farms through various pathways, including irrigation water, animal intrusion, contaminated farm workers, and agricultural tools. Among these pathways, irrigation water quality has significant implications for pathogen introduction as it serves as a reservoir of diverse microorganisms (Simões et al. 2023).

Agricultural water plays a pivotal role in biofilm formation within irrigation systems. Using water sources like reclaimed water and untreated surface water may transfer biofilm-forming bacteria onto produce (Wang et al. 2022; Song et al. 2021). Similarly, the irrigation technique could also influence microbial transfer and biofilm formation. For instance, overhead irrigation was shown to have a higher pathogen transfer rate than drip irrigation systems (Fonseca et al. 2011). The material used in piping, plumbing, or irrigation systems also affects biofilm formation (Jang et al. 2011).

To mitigate the contamination risk of these harmful bacteria (i.e., pathogens), the FDA introduced the Food Safety Modernization Act (FSMA), including the Produce Safety Rule (PSR) (FDA 2024b). The FDA recently updated the PSR preharvest water requirements, replacing the previous microbial load criteria with a risk assessment model. This model assesses the entire irrigation water distribution system, agricultural practices, and land use (FDA 2024a). However, while this framework allows for the mitigation of multiple contamination risks, it does not explicitly address the potential for biofilm formation in agricultural water distribution systems. Consequently, biofilms may persist within the water system even when surface water meets FSMA standards, leading to an additional pathway for contamination. Therefore, including biofilms in agricultural water system risk assessments is essential to ensure overall food safety. It is important to highlight that the PSR also addresses worker training and hygiene, agricultural water usage, the prevention of animal intrusions, the management of biological soil amendments, and the sanitation of equipment, tools, and facilities (FDA 2024b).

Food Processing

Biofilms are persistent communities of microorganisms that frequently grow at food processing facilities. They are commonly found in drains due to consistently high moisture levels (Dzieciol et al. 2016). Biofilms can also develop on food contact surfaces, although routine cleaning and sanitation make it less likely. When formations do occur on food contact surfaces, these biofilms present a higher risk of illness because they can transfer pathogens directly to the food product. Food residues on equipment surfaces containing proteins, fats, and carbohydrates can create an ideal environment for microbial attachment and biofilm formation (Sharan et al. 2022).

Biofilms are a major challenge in the food industry as microbes are exposed to different biotic surfaces (food matrices) and abiotic surfaces like stainless steel, wood, plastics, rubber, and so forth, requiring different sanitation and cleaning protocols. Moreover, other environmental factors, such as pH, temperature, or moisture availability, also contribute to the promotion and persistence of biofilms (Chamberland et al. 2019; Govaert et al. 2018; Saá Ibusquiza et al. 2015). Food processors who handle different commodities often face unique challenges associated with biofilms.

During postharvest operations, it is important to mitigate cross-contamination risks while washing, cutting, trimming, and packaging (Cornell College of Agriculture Science, n.d.). In meat processing plants, drains and processing equipment can inadvertently create environments favorable to the growth of biofilm-forming bacteria (Chitlapilly Dass et al. 2020). It is important to note that implementing effective sanitation and cleaning measures can significantly reduce this risk. During carcass processing and cleaning operations, bacterial cell buildup on surfaces, in hoses, and in drains may occur. However, proactively addressing these concerns and maintaining proper sanitation protocols can ensure a hygienic processing environment (Agüeria et al. 2021). Moreover, drainage systems have become a primary focus for environmental pathogen swabbing programs in modern food safety management plans because they are common areas for biofilm development (FDA 2023).

Similarly, microorganisms in the dairy industry can accumulate in milk transport pipelines. Implementing robust sanitation measures is essential to preventing contamination and microbial persistence. Cross-contamination can occur during processing, pasteurization, and packaging, potentially leading to biofilm formation. Better sanitation practices, clean-in-place (CIP) routines, and enhanced facility design can effectively control this risk (Fusco et al. 2020).

Moreover, it is important to recognize that, although conditions may be favorable for developing multi-organism biofilms, including organisms such as *Escherichia coli*, *Listeria monocytogenes*, and *Staphylococcus aureus* (Chitlapilly Dass et al. 2020; Dutra et al. 2018), diligent sanitation efforts can effectively prevent their proliferation. These efforts focus on maintaining strict cleaning practices and implementing preventive measures. With these practices, we can ensure food safety standards and deliver safer products to consumers.

Prevention and Control of Biofilms

Food industries have been implementing various preventive control measures to mitigate the risk of biofilms. The most effective approach involves avoiding potential cell accumulation through routine sanitation and cleaning procedures. This step is crucial as it eliminates organic or inorganic residues in the industry. Sanitation preventive controls and good manufacturing practices (GMPs), including sanitation standard operating procedures (SSOPs), are designed to establish, develop, and implement measures for preventing contamination or adulteration of products, as outlined in the FDA's FSMA Final Rule for Preventive Controls for Human Food (PCHF) (FDA 2025). For example, a GMP in 21 CFR 117 covers cleaning and sanitation practices before, during, and after food processing.

According to Schmidt et al. (2012), the choice of cleaning and sanitation procedure largely depends on the surface materials/finishes, the nature of food products, the amount of food residue present, and the equipment design within processing facilities. Equipment or food contact surfaces are generally cleaned and sanitized following this order: rinse-clean-rinse-sanitize (Schmidt 2012). Standard cleaning and sanitation practices in the food industry include using hot water, wetting agents, detergents, and food-grade acids or alkaline cleaners (Goff and Hartel 2013). Acid and alkaline cleaners prove most effective in industries such as meat, poultry, or dairy, where protein and fat deposits are prevalent. In addition, industries employ various sanitizers for equipment sanitation, including chlorine, peroxide, quaternary ammonium compounds, and ozone. These cleaners and sanitizers may be used individually or in combination for better results.

In the case of more persistent biofilms, effective reduction of microbial deposition and subsequent biofilm reduction relies on thorough cleaning (Fagerlund et al. 2020). Manual cleaning or scrubbing with brushes, detergent, and water is essential to prevent or remove any microbial accumulations, including biofilms (Fagerlund et al. 2020). The machines and equipment used in food processing facilities must be well-engineered and strategically positioned to ensure thorough cleaning in every niche. Proper equipment design is crucial to facilitate thorough cleaning, often necessitating the dismantling and cleaning of various internal components (Goff and Hartel 2013). For equipment that cannot be disassembled, it is critical to have a proper CIP protocol, ensuring thorough biofilm removal (Goff and Hartel 2013). However, the effectiveness of these cleaners and sanitizers is highly dependent on the food contact surface properties, exposure time, temperature, concentration, organic matter, pH, and water properties (Schmidt 2012). The PCHF rule, which deals with processed foods; the PSR, which deals with produce; and the Hazard Analysis Critical Control Point (HACCP), which deals with seafood, meat, and juices, are all regulatory programs aimed at reducing the potential risk associated with foodborne pathogens (FDA 2024c).

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[1] This document is FSHN26-2, one of a series of the Department of Food Science and Human Nutrition, UF/IFAS Extension. Original publication date March 2026. Visit the EDIS website at https://edis.ifas.ufl.edu for the currently supported version of this publication.

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