Towards biofilm innovation: how can we tackle challenges and unlock potential?

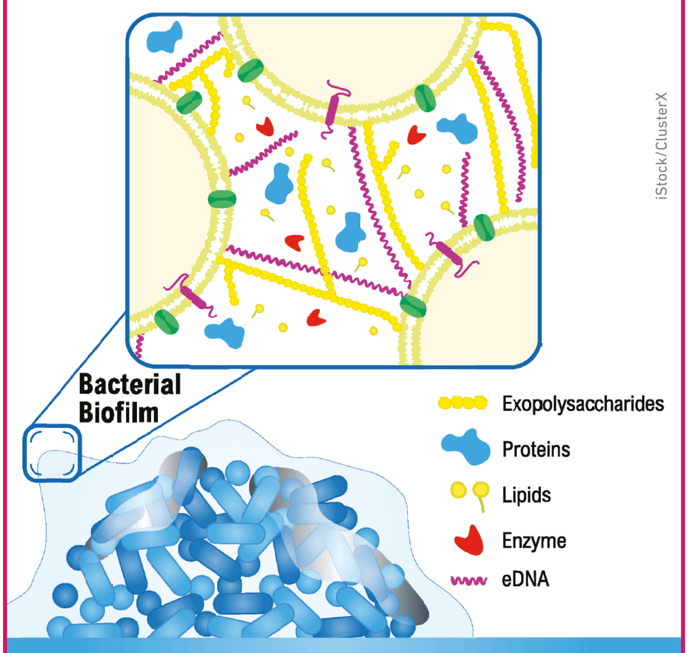
MICROBIOLOGY SOCIETY

What are biofilms?

Biofilms are structured communities of micro-organisms that are attached to each other and typically to a surface in an environment or host [1, 2]. The plaque that forms on our teeth is an example of a biofilm [3].

We often think of micro-organisms as isolated entities, but an estimated 80% of bacterial cells live within biofilms [2, 4, 5]. Biofilms can either contain one or multiple species of bacteria [6]. Multi-species (polymicrobial) biofilms may also contain different types of microbes, like fungi and viruses [7]. Environmental and human-associated biofilms are mostly polymicrobial, forming communities of different micro-organisms that compete, co-operate and communicate with each other [1, 7, 8].

Microbes in a biofilm exist in a matrix-like structure [2]. They create this by producing a sticky layer of slime (known as extracellular polymeric substance, or EPS) which acts like a glue that holds micro-organisms in the biofilm together and to the surface they're on [1, 2].



Extracellular polymeric substance (EPS) is made up of exopolysaccharides, nucleic acids (eDNA and eRNA), proteins, lipids and other biomolecules, such as enzymes. Other substances can also be included from the environment, like minerals or small particles, or from the host, such as DNA [9, 10].

Biofilms thrive in wet areas, which is why they are prevalent in our body (e.g. dental plaque), the built environment (e.g. water pipes) and nature (e.g. underwater surfaces) [2].

The surface of a pond covered with a biofilm.

Every biofilm is unique with their composition, structure and functions shaped by the micro-organisms that form them, the conditions of their environment and the surfaces on which they develop [9]. This diversity is why biofilms carry out such a wide range of functions, with many positive and negative impacts on human, animal and environmental health [1, 2].

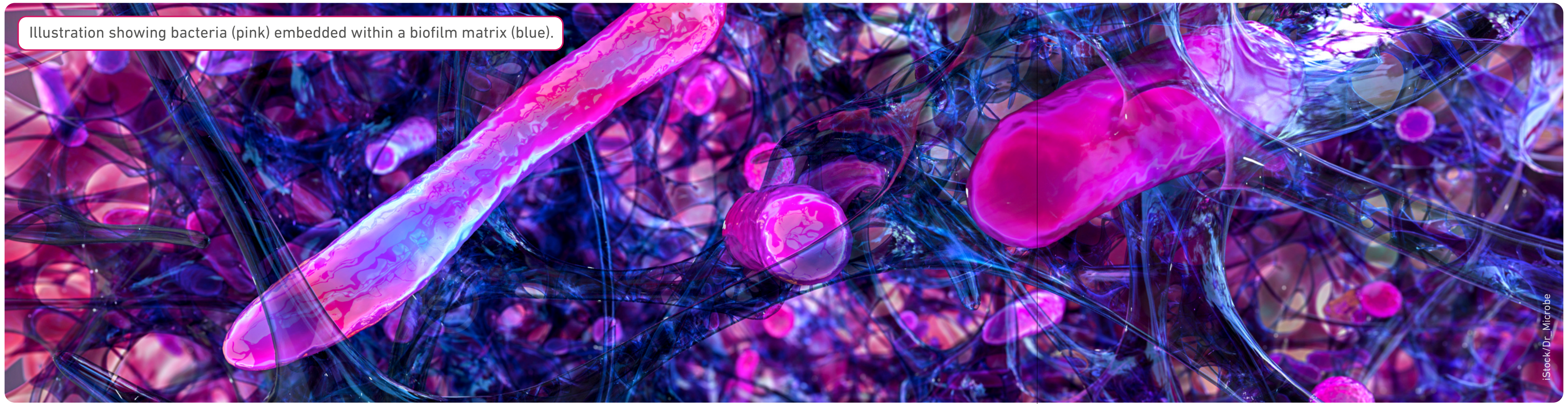


Illustration showing bacteria (pink) embedded within a biofilm matrix (blue).

Why should we care about biofilms?

We can't fully understand micro-organisms until we understand biofilms.

Living within a biofilm offers micro-organisms both protection and unique properties that they would not have on their own [2]. The protective slime means that bacteria in biofilms are more resistant to various stresses – including environmental (e.g. changes in temperature and pH), chemical (e.g. antimicrobials and disinfectant) and mechanical (e.g. brushing) – than single-cell, floating bacteria [1, 11–13].

This means biofilms are difficult and costly to get rid of [14]. However, finding ways to remove them is essential: when biofilms contain pathogenic (disease-causing) micro-organisms, their presence can contaminate medical equipment, drinking water and food products [11, 15–17]. They can also cause physical blockages, as well as corrode and damage the surfaces they attach to, leading to costly repairs and halts to industry [16–19].

On the other hand, biofilms can have extremely useful applications [14]. As a unique community, biofilms develop capabilities that go beyond those of their individual micro-organisms [2]. These unique functions can be harnessed, e.g. to remove contaminants in wastewater treatment or improve plant growth and crop yields [14, 20, 21].

The potential of biofilms is not yet fully understood. We need more research to understand how to: 1) effectively exploit their benefits, and 2) get rid of them where they are not wanted or are detrimental.

Biofilms vs. microbiomes

You might have heard of microbiomes – communities of micro-organisms that live in and on hosts, such as humans, animals and plants, or within environments like soil and oceans.

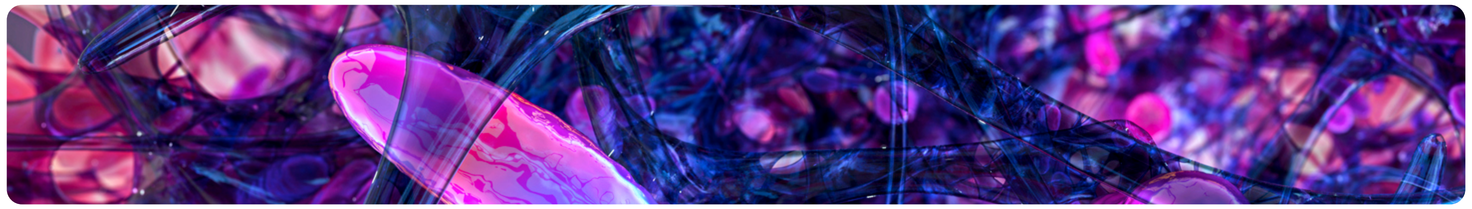
Like microbiomes, biofilms are complex, dynamic and interactive microbial systems [4].

The distinction is that biofilms are physical structures adhered to a surface [4]. Because biofilms often form within microbiomes, the two are closely connected and can directly affect each other's behaviour and function [4]. For example, the oral microbiome inhabits the hard and soft tissues of our mouth and is fundamental for maintaining oral health [3].

Dental biofilms (plaque) are part of the oral microbiome, forming exclusively and rapidly on tooth surfaces, and if not removed by adequate brushing, can lead to tooth decay and gum disease [3].

Biofilms are densely packed with micro-organisms and serve as hot spots of microbial activity, they can be thought of as the 'engines' of microbiomes, driving metabolism and biogeochemical (carbon, nitrogen and water) cycles [5, 14, 22].

Find out more about microbiomes in our briefing 'Where are microbiomes, and why are they important?'.



What challenges do biofilms pose? And how can we solve them?

Biofilms are involved in many challenges across multiple sectors including healthcare, food and drink production, water supply, transport and aquaculture [2]. As a result, they have substantial economic, social and environmental impacts, which are estimated to cost $5 trillion globally every year [2]. To put it into perspective, this cost is larger than the GDP of some countries, including the UK which was $3.64 trillion in 2024 [23]. Biofilm research focuses on discovering new and effective ways to prevent, detect, manage and engineer biofilms [14, 24].

Healthcare

The economic impact of biofilms on human health is estimated at $7.2 billion in the UK and $387 billion globally [25]. This burden is driven in part by the resilience of biofilms to antimicrobials, biocides and cleaning [1, 13].

When bacterial cells are within a biofilm, they are 10 to 1,000 times more resistant to antibiotics [11]. The protective mechanisms of the slimy EPS matrix are the main contributor to this increased resistance as it is not easily penetrated by antimicrobials, preventing them reaching micro-organisms [1, 11].

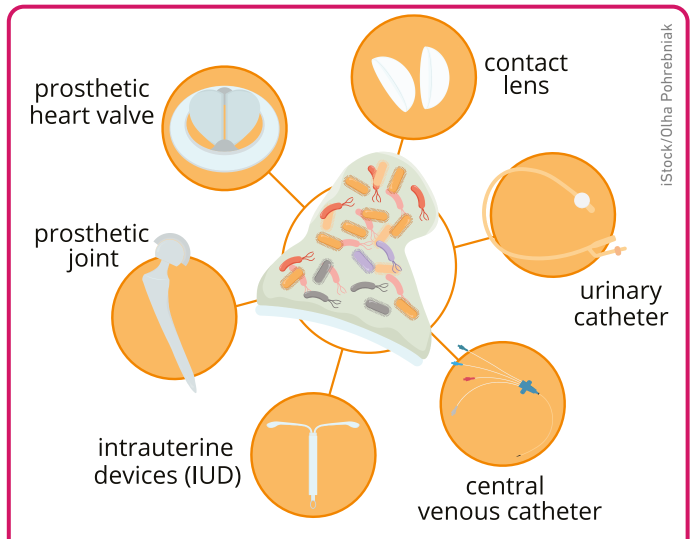
Biofilms also often contain a variety of microbes with varying susceptibility to antimicrobials due to differences in metabolism, protective mechanisms, or the presence of antimicrobial resistance (AMR) genes [11, 13]. As these microbes are immobilised and held closely together, biofilms facilitate cell-to-cell interactions and sharing of AMR genes [13]. **As a result, biofilms are major reservoirs of resistance genes and drivers of AMR [1, 13].** AMR is an urgent global threat, with bacterial AMR estimated to cause 39 million deaths between 2025 and 2050 — this is equivalent to 3 deaths every minute [26].

How can we disrupt biofilms to combat antimicrobial resistance (AMR)

Biofilm-disrupting agents are a novel approach to managing biofilms. As alternatives to existing antimicrobials, they could also help combat AMR.

- **The drug XF has shown to be highly effective at killing biofilms. In a skin model, XF completely stopped the growth and reproduction (viability) of Methicillin Resistant *Staphylococcus aureus* (MRSA) and reduced the viability of *Pseudomonas aeruginosa* by 90% [27].**
- **Nanoparticles are extremely small particles, about 100,000 times smaller than the width of a human hair. Their tiny size allows them to penetrate, disrupt and destroy biofilms. They can also be used to carry substances such as antimicrobial peptides – natural molecules found in humans, animals and plants that act as the first line of defence against pathogens [28, 29].**
- **Phages are viruses that infect bacteria and produce EPS-degrading enzymes that can destroy biofilms [28].**

Biofilm formation on internal medical devices – such as artificial hips, internal catheters and dental implants – can lead to serious infections and often necessitate replacement of devices, incurring significant cost to the NHS [15, 25, 30]. Biofilms can also grow on the external medical equipment used in hospitals – such as ventilators, external catheters and dialysis machines – potentially causing infections and even death [31, 32].



Biofilm and medical devices

How do we prevent, detect and manage biofilms in healthcare?

- Anti-biofilm structures in nature, e.g. structures on dragonfly wings and shark skin, have inspired novel surface coatings for implants [33]. Antimicrobials can also be applied to the surface of medical devices to prevent biofilms from forming [14, 34].
- A combination of different methods is used to accurately detect biofilm infection of implanted prosthetic joints [35]. In a process known as sonication, low-frequency ultrasound waves are passed through a liquid containing a surgically removed prosthetic to disrupt any biofilms, releasing micro-organisms into the liquid [35, 36]. Microbiological and genetic analysis can then be used to detect micro-organisms and identify the infection [35, 36].
- Interventions, such as physical abrasion and device replacement, are used to manage biofilm infection of medical devices [14, 34].

Imbalances in the micro-organisms within microbiomes and biofilms are also associated with diseases in the mouth, skin, gut and vagina, including tooth decay, gum disease, eczema, acne, inflammatory bowel disease and bacterial vaginosis [3, 25, 37–39]. Find out more about microbiomes in our briefing **'Where are microbiomes, and why are they important?'**.

Industry

Food and drink

Biofilms can form on the hard surfaces commonly used in food and drink production – including factory equipment, transport containers, dispensing systems and storage areas – or directly on food products [14, 17]. Micro-organisms in biofilms are more resistant to the various physical, mechanical and chemical processes used in production processes [17]. As a result, biofilms can lead to the downstream contamination of food and drink products, compromising their safety, quality and shelf life [14, 17].

This can increase food waste and production costs if discovered during manufacturing or even result in disease outbreaks and expensive product recalls [14, 17]. Biofilms can also corrode metal surfaces in factories, leading to costly repairs and halts to production [17].

Water supply

The formation of biofilms in drinking water distribution systems can block and degrade pipes, as well as alter the clarity, taste and smell of the water [16]. The greatest concern for water companies, however, is that biofilms are potential reservoirs for pathogens, such as *Pseudomonas* and *Legionella* species, which can cause serious illness [16, 40, 41]. Pathogens found in biofilms, such as *Legionella*, are the leading cause of hospitalisations from waterborne diseases in the United States [42]. In 2014 alone, contaminated drinking water was linked to 1.13 million illnesses, responsible for the majority (40%) of all hospitalisations from waterborne illnesses [42].

How do we prevent and manage biofilms in water industries?

- The application of antifouling coatings to ship surfaces is a widespread practice to prevent biofilm formation [19].
- The novel application of these marine coatings to drinking water pipes is being explored to manage biofilms [43].
- Cleaning ship surfaces is a simple but effective method for managing biofilms [19].

Marine transport

Biofouling is the build-up of unwanted biological matter on surfaces, including bacteria in biofilms and larger organisms such as barnacles and seaweeds [40]. Marine biofilms and biofouling can damage the surface of ships, such as the hull, as well as increase drag and slow ships down [19]. When ships travel at a slower speed, they consume more fuel, leading to increased fuel costs and greenhouse gas emissions. This is associated with costs of roughly $5 billion a year [14, 19].

Aquaculture

Marine biofilms and biofouling can also form on the surfaces of fish, natural surfaces in the environment and infrastructure (such as nets, floats, cages and ropes) [25]. This is a major issue in aquaculture, with the management of biofilms and biofouling accounting for 5-10% of production costs [25].

How do we prevent and detect biofilms in aquaculture?

- A novel marine antifouling technology is being developed as a more efficient and environmentally friendly alternative to current approaches [44]. This would work by disrupting cell-to-cell communication between marine microbes, with potential applications for the protection of infrastructure in the marine (ship hulls and sensors) and aquaculture industry (nets, floats, cages and ropes) [25, 44].
- Novel sensors are being developed to monitor water environments and detect underwater biofilms [44]. The sensors will include smart antifouling windows and enhanced biofilm detection, with applications for the marine and freshwater sectors [44].

Where are biofilms useful?

It is important to remember that biofilms can also have extremely useful applications.

Biofilm communities play a central role in wastewater treatment and can remove heavy metals, pharmaceuticals, micro-organisms and dyes from contaminated sites [14, 45–47]. While biofilms can naturally emerge in wastewater treatment plants, many plants use reactors which provide the ideal environment for biofilm growth to increase and concentrate their activity [47]. Biofilms develop on the surfaces within reactors, where wastewater continuously flows over them, enabling micro-organisms to break down contaminants.

An emerging area of research aims to engineer biofilms to optimally treat wastewater, such as reducing greenhouse gas emissions from wastewater treatment plants [14, 46].

Biofilm communities occur in the soil surrounding plant roots where they offer protection to the roots and promote crop growth and health [48, 49]. Biofilm-derived biofertilisers can promote plant growth and crop yield, offering a low-cost alternative to synthetic fertilisers [20].

Probiotics are live micro-organisms that can be ingested or applied to modulate and restore balance to microbiomes. Probiotics in a biofilm form have shown increased resistance to temperature, pH and mechanical forces compared to single-cell, floating probiotics. They are therefore more likely to reach their target site, such as the gut, in a metabolically active condition [21]. Find out more about probiotics in our **microbiome briefing**.

Micro-organisms are widely used in a process known as bioleaching, a type of biomining, to mine economically important elements from rocks to use in electronic industries and alloy production [50]. Following a study conducted on the International Space Station that showed biofilm-forming bacteria could perform bioleaching in Mars and Earth gravity conditions, biofilms could hold the key to mining beyond Earth [50].

The waterline of a boat, showing biofouling on the hull.

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What can the UK government do to support innovation in biofilms?

The UK is a world leader in biofilm research and innovation [51]. This has been recognised by the establishment of the National Biofilms Innovation Centre (NBIC) in 2017 [51]. The NBIC brings together leading research institutes and industry partners to deliver breakthrough science and technologies to control and exploit biofilms [52]. In five years – from 2017 to 2022 – the NBIC delivered a total impact of approximately £204 million across the UK economy, including job creation and research fund output [52].

To further advance biofilm research and build capacity, the UK government could consider the following actions:

- Provide sustained funding for interdisciplinary research hubs, such as the NBIC and Quadram Institute.
- Give researchers access to critical infrastructure (including state of the art equipment in labs, such as large-scale fermenters), as well as early-career training and education (such as bioinformatics and basic microbiology skills) [14].
- Provide support for independent biobanks to collect, maintain and store biofilm samples.
  - This would harmonise the work, ensuring quality assurance and robustness by giving the research community access to the same set of samples. Consequently, there would be consistency across studies, making it easier to compare results. Companies could also test their products against standardised biofilms to establish function claims, accelerating the research to market pipeline [14].
- Work with regulators to address challenges and improve biofilm-related standards [53].
  - The International Biofilm Standards Task Group has a mission to drive the international development, harmonisation and implementation of biofilm test methods and standards in health care, the built environment and industrial systems [54].
  - The Medicines and Healthcare products Regulatory Agency (MHRA) is working to develop physical standards to support biofilm studies and translation of research to applications. The MHRA actively encourages innovation, with no particular method being required to obtain market approval for anti-biofilm products. What matters is good controls, reproducibility and pre-clinical and clinical data.
- Establish commitments relating to biofilm control in the UK National Action Plan on AMR, recognising that biofilms are a key driver of AMR [55].

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Biofilms removing pollutants in the wastewater treatment process. The clumps on the water surface are known as activated sludge flocs, a type of biofilm.

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