Microbial Biofilms Harnessing the Power of Complex Microbial Communities for Industrial Applications

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Abstract:
These biofilms have great promise for industrial applications and play crucial roles in several natural and artificial systems. The use of microbial biofilms in industrial settings is examined in this abstract, which also places an emphasis on techniques to improve biofilm development and performance through surface modification and quorum sensing manipulation.Due to their versatility, durability, and cooperative behaviour, biofilms have attracted interest and are useful in a variety of industrial industries. They work in the food business, bioenergy generation, agriculture industry and biosensor.The production and performance of microbial biofilms need to be improved in order to fully realise their potential. Techniques for surface modification provide a promising way to customise the characteristics of biofilms.It is possible to modify the topography, hydrophobicity, and charge of the substrate to affect how quickly biofilms form after initial microbial attachment.The method of cell-to-cell communication known as quorum sensing (QS) directs the development and behaviour of biofilms. Controlling QS pathways enables fine-grained regulation of biofilm growth.In conclusion, because of their cooperative nature and adaptable functioning, microbial biofilms show enormous promise for industrial applications. The importance of surface modification and quorum sensing modulation as tactics to improve biofilm performance

Introduction

Biofilms are one of the most broadly distributed and successful forms of life on earth, driving biogeochemical cycle processes of most elements in water, soil, sediment and subterranean habitats. Biofilms are defined as “aggregates of microorganisms in which cells are frequently embedded in a self-made matrix of extracellular polymeric substances (EPS) that are attached to each other and or a surface.” [1] and biofilm growon environmental abiotic surfaces. [4.5]Extracellular polymeric substances (EPS) in biofilms are essential for the development of physical and social connections, an accelerated pace of gene exchange, and resistance to antibiotics.[3] Biofilm have proved their potential in a variety of applications, including bioremediation, waste water treatment, biocorrosion control, biocatalysts, biofilm-based sensors, bioenergy and food sector. [2.]Polysaccharides, proteins, and DNA make up the majority of the extracellular matrix, which functions as a network to connect the biofilm population.Additionally, EPS helps keep water and nutrients inside the biofilm community. [9-10]. Signalling molecules are used by the population of microbes in biofilms to communicate with one another while also promoting adhesion, growth, and resistance to biocides andmicrobial communicationwith cells is mediated by signal molecules [11,12,13]The formation of a biofilm is a complicated procedure which include Reversible attachment, irreversible attachment, microcolonies formation, maturation and detachment of biofilm [14]The conditioning layer will formed during reversible attachment which serve as foundation for the establishment of a biofilm.In irreversible attachment, number of bacterial cells that are adsorbed reversibly on the surface and remain immobilized in real time and become irreversibly adsorbed.[15]A biofilm typically contains more than form of micro community and requires coordination between them. This coordination is necessary for substrate exchange distribution of critical metabolic product and excretion of toxic chemicals. (16) The micro colonies grow and merge to produce the initial layer of cells surrounding the surface. (17). The biofilm uses cell signalling method known as quorum sensing at high cell density. QS is necessary for biofilm maturation process because bacteria monitor cell density and regulate collective behaviour. Cells from the biofilm disperse into the surrounding environment and return to a planktonic condition [18].A number of elements are known to have a significant impact on the production of biofilms like Several cell surface adhesins and cell aggregation promote biofilm formation.[19]Extracellular polymeric substance (EPS) is essential for biofilm formation and development because they act as the glue that binds the biofilm together and allow microbial adherence to surface [20-21]. Most bacterial produce biofilms best at pH levels ranging from slightly acidic to neutral [22].A sufficient supply of nutrients also promotes the synthesis of extracellular polymeric substances, such as polysaccharides and protein, which help to maintain the structural integrity of the matrix [23].Surface characteristics such as roughness, hydrophobicity, charge and composition all have a significant impact on biofilm formation. On various substrates, these surface features can either encourage or prevent biofilm growth. [24]. Microbial interaction is crucial in biofilm communities, where diverse microorganisms cooperate, compete and communicate within the extracellular matrix[27].Cooperation and synergy in microbial interaction are essential in biofilm communities, allowing for the creation and maintenance of these complex structures.[25-26].In biofilm. Close cell- cell contact produces a favourable environment for host gene transfer. Host gene transfer is widely recognised to occur with increasing competence in biofilm[28].

Strategies to improve the capacity and performance of biofilm formation

1. Surface modification

Surface modification has emerged as an essential strategy for reducing or increase biofilm development. This modification comprises permanently changing the characteristics of surfaces through chemical or physical techniques, hence altering interaction with environment and influencing microbial adhesion[6].

a. Organosilanecoated surface modification.

Organosilanes are silanes or monomeric silicon-based compound with at least one silicon carbon link.it has been discovered to improve the physical, chemical and mechanical properties of surfaces, as well as to improve microbial adhesion.The addition of aminopropyltrietoxysilane to stainless steel improved the positive charge and yeast cell adhesion.Organosilanes were used to test the adherence of several industrial brewing yeast strains [6].

b. Chemical coating

Chemical coating is a versatile and frequently used approach for changing the properties of material surfaces for a variety of applications, including biofilm growth and management.These coating can be customised to provide specific functions such as improved biofilm adhesion, antibacterial characteristics or biofilm suppression.For example, Hydrophilic coating have been utilised to improve the biofilm formation of certain beneficial microbes in wastewater treatment and bioremediation processes by creating a favourable environment for microbial attachment and growth. [29-30]

c. Plasma treated surface modification

Plasma alters the surface of metallic objects by atomic or molecular scale chemical or physical reactions.For this procedure, argon, nitrogen, oxygen, carbon dioxide and ammonia are typically employed as plasma gases.Through the use of plasma. Changes in physicochemical properties, such as surface free energy, hydrocarbon content and functional hydroxyl group content, have been examined. [6]

2. Quorum sensing manipulation

Targeted interference with the bacterial communication system is used in quorum sensing (QS) modification to enhance biofilm formation and encourage more effective and robust biofilm growth [34].

a. Quorum sensing induction

QS induction encourages bacterial cooperation and communication, which improves biofilm development. Utilizing artificial autoinducer analogues, such as acyl homoserine lactones or auto peptides, is one strategy. Even in the absence of the native bacteria, these analogues may activate bacterial Quorum sensing systems and promotes the production of more biofilm [31].

b. Quorum sensing manipulation by using CRISPR- Cas 9system

CRISPER-Cas9 system, which is well known for its ability to alter genes, may also be used to manipulate quorum sensing to improve biofilm development.Researchers can increase the production of sensing molecules by using CRISPER-Cas to target and alter the genes involved in the creation of autoinducers [32].

c. Quorum sensing manipulation through bioengineering

This technique focuses on manipulating bacteria to overexpress or downregulate essential quorum sensing genes, ultimately resulting in improved biofilm formation n.Bacterial cells manufacture additional signaling molecules and accelerate and widen the QS activation by upregulating the gene that make the autoinducers [33].

Industrial application of biofilms

1. Biofilm application in agriculture industry

- **Plant growth promoting**: According to several studies, inoculating seeds or roots with various microbial inoculants can increase plant growth and development and produce plant growth regulators. Barley plants growing under salt stress grew better after being inoculated with the rhizobacterium, which promotes the formation of biofilm in plants. Therefore, inaddition to its role in promoting growth, it may be used to help barley plant resist salt stress.
- **Biofertilizer:**beneficial microorganisms that are used to make biofertilizer include nitrogen-fixing bacteria, phosphorus(P)solubilizers, cellulolytic microorganisms, algae, azolla and mycorrhizal fungus. Biofilm biofertilizers can mobilise mineral from impassable forms, make atmospheric

nitrogen available to plants, solubilize phosphorus through increased carbon, microbial biomass carbon, control plant growth and suppress pathogens, under greenhouse and field conditions.

- **Biocontrol:** According to studies, the development of biofilm by Plant growth rhizobacteria is crucial cycle of nutrients as well as for the biocontrol of pests and diseases, which boosts agricultural output. For instance, *Paenibacilluspolymyxa*, a common soil bacterium, is thought to colonise plant roots, build biofilm like structures, and sheield the plants from root diseases.[7,8]

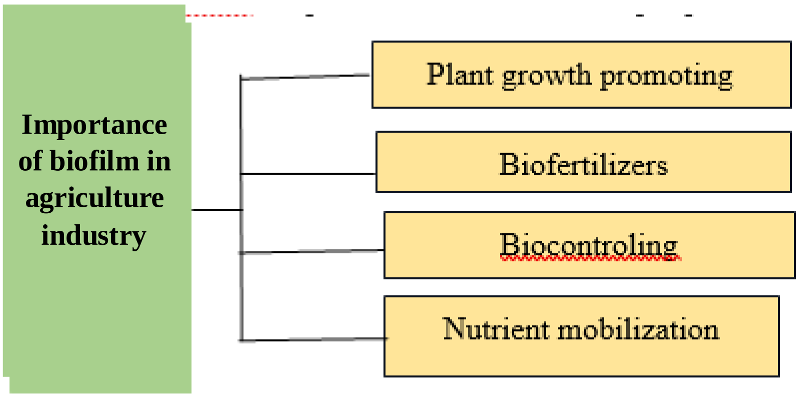

Fig 1: Importance of biofilms in agriculture industry

2. Biofilm application in energy production

The term "bioenergy" describes energy that comes from biological sources including microbes, biomass and organic waste.Applying biofilm, which are intricate colonies of bacteria enmeshed in a self-produced matrix of extracellular polymeric substances, is one viable strategy to improve bioenergy production.

A promising future technology for variety of uses, including the production of sustainable power, is emerging: microbial fuel cell. The main actors in bio electrochemical systems involving microorganisms mediated electrocatalytic processes are electroactive biofilm produced by bacteria.The organisms extracellular polysaccharides contribute to the development of biofilms and transmission of electrons. A wide range of anaerobic and photosynthetic microorganisms have been used as electron donors and acceptors in microbial fuel cell. They include *Chlorella vulgaris, Phormidium sp. Sacchromycescerevisiae.*(35)

3. Biofilm application in food industry

Food items' biochemical quality, flavors and textural qualities could all be improved by biofilm formation, according to the food industry. Biofilm microbial interactions induced specific food processing. Desirable biofilm develops during the manufacturing of classic stretched cheeses as result of nonstarter lactic acid bacterial sticking to wooden vats or wooden planks. Due to the development of advantageous biofilms that operate as a biocontrol against pathogenic bacteria as an improvement in sensory quality. Cheese can ripen in wooden utensils (L. monocytogenes, Salmonella spp.). Production of black olives is another food process that benefited from biofilm.

L pentosus and p. membranifaciens attach to the surface of black olives during submerged fermentation to produce biofilm in the stomatal opening and on the olive epidermis.[7]

Conclusion

In conclusion, exploiting microbial biofilms for industrial application such as agriculture, bioenergy, food industry and biosensors provides several chances to revolutionise these industries with sustainable and efficient solutions. Adoption of biofilm based agricultural practices can result in a more ecologically friendly and economically feasible farming technique, providing food security for the world's rising population. Surface modification and quorum sensing modification methods that increase the capacity and performance of biofilm development offer significant potential for a wide variety of applications. These methods have the potential to improve the efficiency, functionality and specificity of biofilm-based processes in a variety of sectors and environmental environments. We can pave the road for new and sustainable solutions to real word difficulties by harnessing the power of biofilms and altering their behavior. Adopting these tactics would surely help to develop biotechnology, healthcare, environmental management and other fields, resulting in a more resilient and bio inspired future.

References

1. H. C. Flemming, J. Wingender, U. Szewzyk, P. Steinberg, S. A. Rice, and S. Kjelleberg, "Biofilms: An emergent form of bacterial life," *Nature Reviews Microbiology*, vol. 14, no. 9. Nature Publishing Group, pp. 563–575, Sep. 01, 2016. doi: 10.1038/nrmicro.2016.94
2. M. E. Davey and G. A. O'toole, "Microbial Biofilms: from Ecology to Molecular Genetics," *Microbiology and Molecular Biology Reviews*, vol. 64, no. 4, pp. 847–867, Dec. 2000, doi: 10.1128/mmbr.64.4.847-867.2000
3. G. Gebreyohannes, A. Nyerere, C. Bii, and D. B. Sbhatu, "Challenges of intervention, treatment, and antibiotic resistance of biofilm-forming microorganisms," *Heliyon*, vol. 5, no. 8. Elsevier Ltd, Aug. 01, 2019. doi: 10.1016/j.heliyon.2019.e02192.
4. J. N. Wilking, V. Zaburdaev, M. De Volder, R. Losick, M. P. Brenner, and D. A. Weitz, "Liquid transport facilitated by channels in Bacillus subtilis biofilms," *Proc Natl Acad Sci U S A*, vol. 110, no. 3, pp. 848–852, Jan. 2013, doi: 10.1073/pnas.1216376110.
5. E. Karatan and P. Watnick, "Signals, Regulatory Networks, and Materials That Build and Break Bacterial Biofilms," *Microbiology and Molecular Biology Reviews*, vol. 73, no. 2, pp. 310–347, Jun. 2009, doi: 10.1128/mmbr.00041-08
6. A. Sarjit, S. Mei Tan, and G. A. Dykes, "Surface modification of materials to encourage beneficial biofilm formation," *AIMS Bioeng*, vol. 2, no. 4, pp. 404–422, 2015, doi: 10.3934/bioeng.2015.4.404.
7. E. Ü. Turhan, Z. Erginkaya, M. Korukluoğlu, and G. Konuray, "Beneficial biofilm applications in food and agricultural industry," in *Health and Safety Aspects of Food Processing Technologies*, Springer International Publishing, 2019, pp. 445–469. doi: 10.1007/978-3-030-24903-8_15.
8. M. Ghiasian, "Microbial biofilms: Beneficial applications for sustainable agriculture," in *New and Future Developments in Microbial Biotechnology and Bioengineering: Trends of Microbial Biotechnology for Sustainable Agriculture and Biomedicine Systems: Diversity and Functional Perspectives*, Elsevier, 2020, pp. 145–155. doi: 10.1016/B978-0-12-820526-6.00009-9.
9. P. Stoodley, K. Sauer, D. G. Davies, and J. W. Costerton, "Biofilms as complex differentiated communities," *Annual Review of Microbiology*, vol. 56. pp. 187–209, 2002. doi: 10.1146/annurev.micro.56.012302.160705.
10. P. S. Stewart and M. J. Franklin, "Physiological heterogeneity in biofilms," *Nature Reviews Microbiology*, vol. 6, no. 3. pp. 199–210, Mar. 2008. doi: 10.1038/nrmicro1838.

11. H. Wu, C. Moser, H. Z. Wang, N. Høiby, and Z. J. Song, "Strategies for combating bacterial biofilm infections," *International Journal of Oral Science*, vol. 7. Sichuan University Press, pp. 1–7, Mar. 23, 2015. doi: 10.1038/ijos.2014.65
12. V. P. P. Alonso, A. M. M. Harada, and D. Y. Kabuki, "Competitive and/or Cooperative Interactions of Listeria monocytogenes With Bacillus cereus in Dual-Species Biofilm Formation," *Front Microbiol*, vol. 11, Feb. 2020, doi: 10.3389/fmicb.2020.00177.
13. S. Atkinson and P. Williams, "Quorum sensing and social networking in the microbial world," *Journal of the Royal Society Interface*, vol. 6, no. 40. Royal Society, pp. 959–978, 2009. doi: 10.1098/rsif.2009.0203.
14. D. Kour *et al.*, "Microbial biofilms: Functional annotation and potential applications in agriculture and allied sectors," in *New and Future Developments in Microbial Biotechnology and Bioengineering: Microbial Biofilms Current Research and Future Trends in Microbial Biofilms*, Elsevier, 2019, pp. 283–301. doi: 10.1016/B978-0-444-64279-0.00018-9.
15. M. P. Singh, P. Singh, H. B. Li, Q. Q. Song, and R. K. Singh, "Microbial biofilms: Development, structure, and their social assemblage for beneficial applications," in *New and Future Developments in Microbial Biotechnology and Bioengineering: Microbial Biofilms Current Research and Future Trends in Microbial Biofilms*, Elsevier, 2019, pp. 125–138. doi: 10.1016/B978-0-444-64279-0.00010-4.
16. A. V. Samrot*et al.*, "Mechanisms and impact of biofilms and targeting of biofilms using bioactive compounds—a review," *Medicina (Lithuania)*, vol. 57, no. 8. MDPI AG, Aug. 01, 2021. doi: 10.3390/medicina57080839
17. D. Dufour, V. Leung, and C. M. Lévesque, "Bacterial biofilm: structure, function, and antimicrobial resistance." ."*Endodontic topics,*vol 22, 2-16, 23 nov 2023.
18. R. Van Houdt and C. W. Michiels, "Role of bacterial cell surface structures in Escherichia coli biofilm formation," *Research in Microbiology*, vol. 156, no. 5–6. pp. 626–633, Jun. 2005. doi: 10.1016/j.resmic.2005.02.005
19. K. Velmourougane, R. Prasanna, and A. K. Saxena, "Agriculturally important microbial biofilms: Present status and future prospects," *Journal of Basic Microbiology*, vol. 57, no. 7. Wiley-VCH Verlag, pp. 548–573, Jul. 01, 2017. doi: 10.1002/jobm.201700046
20. R. M. Donlan and J. W. Costerton, "Biofilms: Survival mechanisms of clinically relevant microorganisms," *Clinical Microbiology Reviews*, vol. 15, no. 2. pp. 167–193, 2002. doi: 10.1128/CMR.15.2.167-193.2002.
21. H. C. Flemming, T. R. Neu, and D. J. Wozniak, "The EPS matrix: The 'House of Biofilm Cells,'" *Journal of Bacteriology*, vol. 189, no. 22. pp. 7945–7947, Nov. 2007. doi: 10.1128/JB.00858-07
22. S. L. Chua *et al.*, "Dispersed cells represent a distinct stage in the transition from bacterial biofilm to planktonic lifestyles," *Nat Commun*, vol. 5, Jul. 2014, doi: 10.1038/ncomms5462.
23. P. S. Stewart, "Diffusion in biofilms," *Journal of Bacteriology*, vol. 185, no. 5. pp. 1485–1491, Mar. 2003. doi: 10.1128/JB.185.5.1485-1491.2003
24. H. C. Flemming and J. Wingender, "The biofilm matrix," *Nature Reviews Microbiology*, vol. 8, no. 9. pp. 623–633, Sep. 2010. doi: 10.1038/nrmicro2415
25. D. M. Cornforth and K. R. Foster, "Competition sensing: The social side of bacterial stress responses," *Nature Reviews Microbiology*, vol. 11, no. 4. pp. 285–293, Apr. 2013. doi: 10.1038/nrmicro2977

26. J. B. Xavier and K. R. Foster, “Cooperation and conflict in microbial biofilms,” 2007. [Online]. Available: www.pnas.orgcgidoi10.1073pnas.0607651104
27. C. D. Nadell, K. Drescher, and K. R. Foster, “Spatial structure, cooperation and competition in biofilms,” *Nature Publishing Group*, vol. 14, 2016, doi: 10.1038/nrmicro2016.84
28. A. Luo, F. Wang, D. Sun, X. Liu, and B. Xin, “Formation, Development, and Cross-Species Interactions in Biofilms,” *Frontiers in Microbiology*, vol. 12. Frontiers Media S.A., Jan. 04, 2022. doi: 10.3389/fmicb.2021.757327.
29. A. Pier-Francesco, R. J. Adams, M. G. J. Waters, and D. W. Williams, “Titanium surface modification and its effect on the adherence of Porphyromonasgingivalis: An in vitro study,” *Clin Oral Implants Res*, vol. 17, no. 6, pp. 633–637, 2006, doi: 10.1111/j.1600-0501.2006.01274.x.
30. J. Wu and Y. Hong, “Enhancing cell infiltration of electrospun fibrous scaffolds in tissue regeneration,” *Bioactive Materials*, vol. 1, no. 1. KeAi Communications Co., pp. 56–64, Sep. 01, 2016. doi: 10.1016/j.bioactmat.2016.07.001.
31. K. B. Xavier and B. L. Bassler, “Interference with AI-2-mediated bacterial cell-cell communication,” *Nature*, vol. 437, no. 7059, pp. 750–753, Sep. 2005, doi: 10.1038/nature03960.
32. I. Yosef, M. Manor, R. Kiro, and U. Qimron, “Temperate and lytic bacteriophages programmed to sensitize and kill antibiotic-resistant bacteria,” *Proc Natl Acad Sci U S A*, vol. 112, no. 23, pp. 7267–7272, Jun. 2015, doi: 10.1073/pnas.1500107112.
33. K. Riedel *et al.*, “N-Acylhomoserine-lactone-mediated communication between Pseudomonas aeruginosa and Burkholderiacepacia in mixed biofilms,” 2001. [Online]. Available: www.sgmjournals.org
34. T. B. Rasmussen and M. Givskov, “Quorum-sensing inhibitors as anti-pathogenic drugs,” *International Journal of Medical Microbiology*, vol. 296, no. 2–3. Elsevier GmbH, pp. 149–161, Apr. 06, 2006. doi: 10.1016/j.ijmm.2006.02.005.
35. M. J. Angelaalincy, R. NavaniethaKrishnaraj, G. Shakambari, B. Ashokkumar, S. Kathiresan, and P. Varalakshmi, “Biofilm Engineering Approaches for Improving the Performance of Microbial Fuel Cells and Bioelectrochemical Systems,” *Frontiers in Energy Research*, vol. 6. Frontiers Media S.A., Jul. 05, 2018. doi: 10.3389/fenrg.2018.00063