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Posted Date: 19 January 2024

doi: 10.20944/preprints202401.1451.v1

Keywords: Biofilm Life Cycle; Extracellular Polymeric Substances (EPS); Environmental Science; Industrial Applications; Bibliographic Analysis; VOSviewer



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Article

# A Bibliography Study of Biofilm Life Cycle

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**Abstract:** This study explores the pivotal biofilm life cycle, essential for comprehending intricate processes in biofilm formation and dispersal. With profound implications for medicine, environmental science, and industrial applications, the life cycle involves initial attachment, irreversible attachment, maturation, and dispersion. Employing bibliographic analysis, the paper unravels critical aspects, unveiling key keywords, prominent research countries/regions, and significant research organizations. This comprehensive approach provides insights into the current biofilm research landscape, identifying gaps for future exploration. Biofilm's influence extends to medical conditions, environmental ecosystems, and industrial challenges, accentuating the urgency of understanding its life cycle. The study also delves into global research distribution and influential organizations, guiding collaborative efforts. As a forward-looking initiative, it proposes future research opportunities, aiming to steer advancements and address challenges in biofilm science. Ultimately, this analysis contributes to the ongoing progress of biofilm research, fostering interdisciplinary collaboration and inspiring future initiatives.

**Keywords:** biofilm life cycle; extracellular polymeric substances (EPS); environmental science; industrial applications; bibliographic analysis; VOSviewer

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## 1. Introduction

The study of the biofilm life cycle is of paramount importance in understanding the intricate processes involved in the formation and dispersal of biofilms, fundamental to various fields such as medicine, environmental science, and industrial applications [1]. The biofilm life cycle typically encompasses several key stages, including initial attachment, irreversible attachment, maturation, and dispersion [2]. These stages collectively contribute to the dynamic and complex life cycle of biofilms, influencing their structure, function, and impact on diverse ecosystems [3].

Recognizing the significance of comprehending the biofilm life cycle, this paper employs the methodology of bibliographic analysis [4] to delve into the most critical aspects of this field. By conducting an extensive review of existing literature, the study aims to unravel the key keywords, prominent research countries/regions, and noteworthy research organizations associated with the biofilm life cycle. This comprehensive bibliographic analysis provides a foundation for understanding the current landscape of biofilm research and identifying gaps in knowledge that warrant further exploration.

The initial stages of the biofilm life cycle begin with the process of initial attachment, where microorganisms adhere to a surface [5]. This phase is crucial as it sets the foundation for subsequent events in the biofilm development [6]. Irreversible attachment follows [7], involving the establishment of a stable bond between microbial cells and the substrate, leading to the formation of a more structured and cohesive biofilm. Maturation is characterized by the growth and development of the biofilm structure, with the formation of extracellular polymeric substances (EPS) contributing to the stability and resilience of the biofilm community [7]. Finally, dispersion marks the release of individual cells or clusters from the biofilm into the surrounding environment, facilitating the colonization of new surfaces and the initiation of biofilm formation in different locations [8].

The importance of understanding the biofilm life cycle extends beyond academic curiosity, as biofilms play significant roles in various industries and have implications for public health [9,10]. Medical conditions such as bacterial infections, dental plaque formation, and chronic wounds are

linked to biofilm development [11]. In environmental science, biofilms influence nutrient cycling and microbial ecology in aquatic ecosystems [12]. Moreover, biofilms pose challenges in industrial settings, causing biofouling in pipelines, equipment, and surfaces [13].

The bibliographic analysis conducted in this study aims to reveal the most important keywords associated with the biofilm life cycle [14]. These keywords serve as indicators of the predominant themes and research areas within the field [15]. By identifying the most frequently used terms in scholarly literature, researchers can gain insights into the key aspects and nuances of biofilm research [16].

Furthermore, the analysis explores the geographical distribution of biofilm research by identifying the most important research countries/regions [17]. Understanding the global distribution of research efforts provides valuable insights into regional priorities, challenges, and collaborative opportunities in biofilm research. Countries and regions that emerge as prominent contributors may showcase distinct approaches or unique environmental factors that influence biofilm dynamics.

In addition to geographical considerations, the analysis delves into the organizations that play a pivotal role in advancing biofilm research [18]. Recognizing the institutions at the forefront of this field allows for a deeper understanding of the collaborative networks, resources, and expertise that contribute to the progress of biofilm studies.

As a forward-looking endeavor, the study not only aims to summarize the current state of biofilm research but also proposes future research opportunities and methodologies. Identifying gaps in the existing literature and suggesting areas for further investigation can guide researchers and policymakers in prioritizing research efforts and addressing critical challenges in biofilm science.

In conclusion, the biofilm life cycle is a complex and dynamic process that holds implications for various fields. This paper's bibliographic analysis provides a comprehensive overview of the current state of biofilm research, highlighting key keywords, influential research countries/regions, and prominent research organizations. By shedding light on the existing knowledge landscape, the study aims to inspire future research initiatives, foster interdisciplinary collaboration, and contribute to the ongoing advancement of biofilm science.

## 2. Materials and methods

The bibliographic analysis is following previous study with slightly modifications [19,20]. In 2024, the complete dataset was retrieved from the Web of Science, encompassing a substantial total of 883 articles, with the search centered around the keywords "biofilm life cycle." Upon acquiring the dataset, we employed the advanced data visualization tool, VOSviewer, for comprehensive analysis and presentation [21,22]. This sophisticated software facilitates the exploration of intricate relationships within datasets and allows for the creation of meaningful visualizations [22-24].

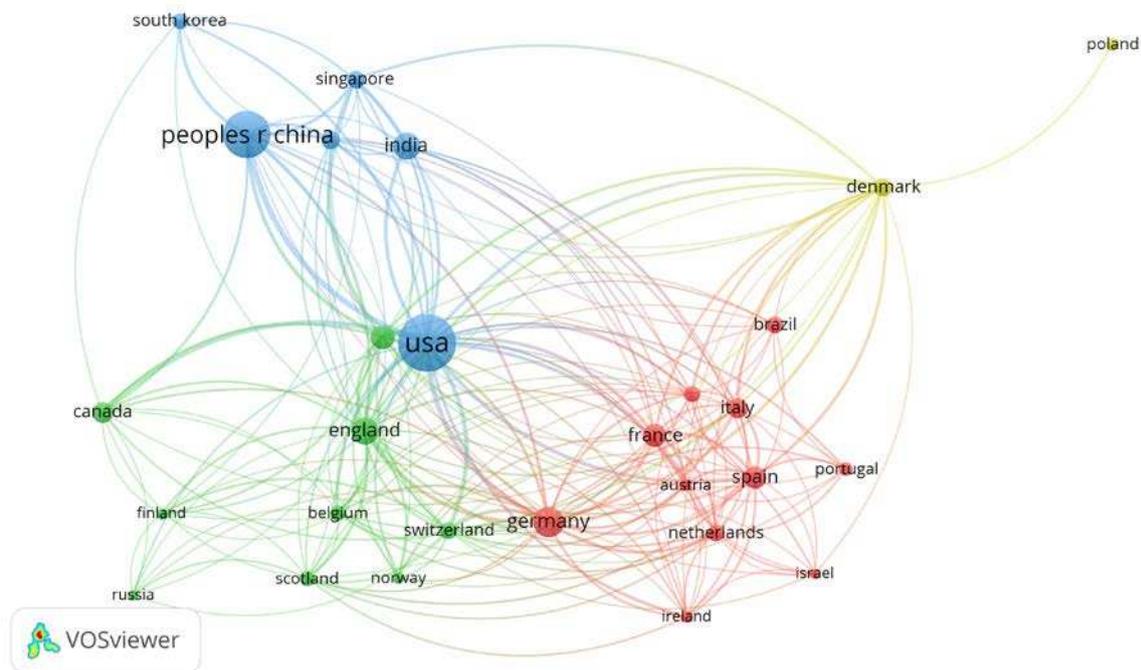
In the keyword analysis, we set a minimum occurrence threshold of 15 for keywords, ensuring a focus on prominent and frequently appearing terms. Similarly, in the country/region-based analysis, a minimum of 10 documents was established as a criterion for inclusion. Additionally, for organization-based analysis, a minimum of 5 documents from a specific organization were considered. These carefully chosen thresholds were implemented to ensure a robust and meaningful analysis, refining the scope and relevance of the findings to uncover significant insights into the biofilm life cycle domain.

## 3. Results

Figure 1 provides a comprehensive overview of the most noteworthy keywords identified in the context of the search term "biofilm life cycle." The displayed keywords span a diverse range of categories, notably highlighting various bacterial species integral to biofilm studies, such as *Bacillus subtilis*, *Escherichia coli*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*.

Beyond bacterial taxonomy, the keywords extend into the realm of biochemical processes, shedding light on critical aspects like biodegradation, waste-water removal, dynamics, evolution, and metabolism. This broadens the scope of the analysis, offering insights into the intricate biochemical mechanisms associated with biofilm life cycles.

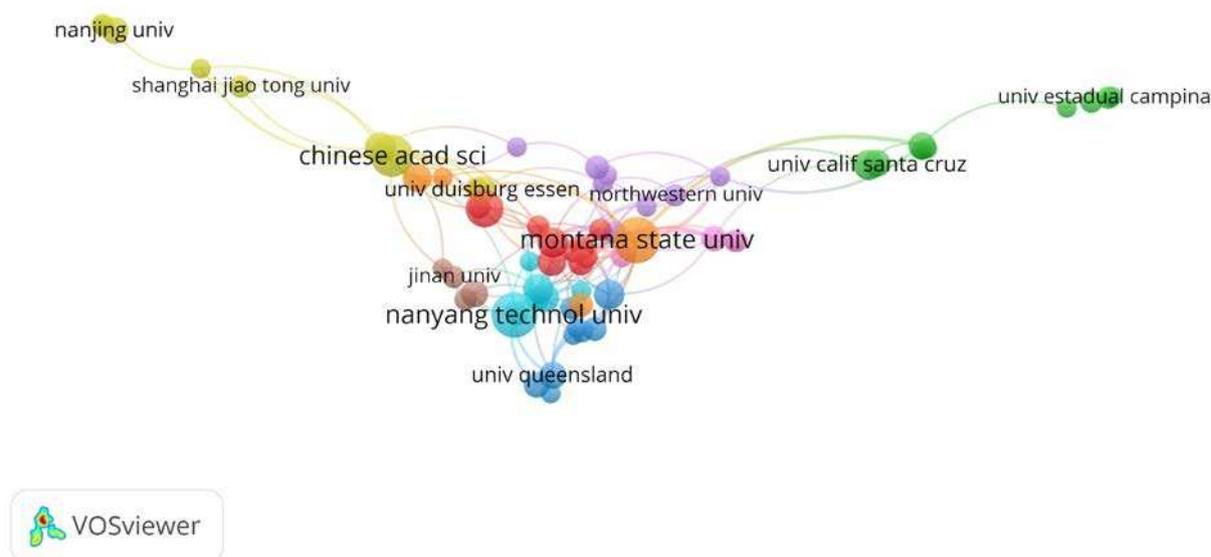




**Figure 2.** VOSviewer visualization of countries/regions obtained during the search for "biofilm life cycle" in Web of Science. The line suggests the research collaboration.

Figure 3 provides a comprehensive overview of the prominent organizations that spearhead biofilm life cycle research, with distinguished roles held by esteemed institutions such as Montana State University, Nanyang Technological University, and the Chinese Academy of Sciences. Beyond these notable contributors, substantial impacts are evident from a range of institutions, including Nanjing University, Shanghai Jiao Tong University, University of Duisburg-Essen, Northwestern University, University of California Santa Cruz, Universidade Estadual de Campinas, Jinan University, University of Queensland, and several others.

These organizations, strategically positioned as leaders in the biofilm life cycle research landscape, play a pivotal role in advancing our collective understanding of the intricate dynamics within this domain. Their collaborative efforts, extending across global borders, form an interconnected network that amplifies the efficiency and impact of scientific research. This collaborative spirit signifies a shared commitment among institutions worldwide to unravel the complexities inherent in biofilm life cycles, contributing to the broader scientific knowledge and facilitating breakthroughs in this critical area of study.



**Figure 3.** VOSviewer visualization of organization obtained during the search for "biofilm life cycle" in Web of Science. The line suggests the research collaboration.

## 4. Discussion

### 4.1. Biofilm Life Cycle: A Pivotal Framework for Multifaceted Understanding

The investigation into biofilm proves to be of paramount importance due to its profound influence on bacterial adhesion to surfaces and the subsequent production of EPS. Biofilm, metaphorically referred to as a "bacterial house," [25] plays a significant role in human life, presenting a spectrum of challenges and opportunities. The adverse effects of detrimental biofilms, such as contributing to urinary tract infections [26-28], underscore the critical medical implications of biofilm research. Conversely, the positive attributes of biofilms open avenues for diverse applications, notably in the development of biofilm reactors with immobilizing heavy metals [29,30], which are found in the waterway and detrimental to water quality [31,32].

The biofilm life cycle, encompassing key stages like initial attachment, irreversible attachment, maturation, and dispersion, provides a comprehensive framework for understanding the dynamic and complex nature of biofilm development [33]. Innovative strategies employed during the initial attachment phase, such as the incorporation of Graphene-Based  $\text{TiO}_2$  into cement materials, showcase the potential for creating self-sterilizing surfaces [34,35]. This groundbreaking intervention seeks to inhibit bacterial attachment during the crucial early stages of biofilm formation, paving the way for the realization of advanced self-sterilization technologies [36,37].

The irreversible attachment stage represents a pivotal point in the biofilm life cycle, signifying the commitment of bacteria to settle and proliferate in specific locations. The maturation phase witnesses successful bacterial reproduction, leading to the generation of numerous offspring. This period is marked by the emergence of biofilm-based reactors [38], contributing to various engineering domains, including pollution treatment [29,30], microbial fuel cells [39-41], and self-healing concrete [42-44]. These applications leverage the biofilm's unique ability to immobilize heavy metal pollutants in water sources [30], offering solutions for environmental remediation and clean water initiatives.

The dispersion stage, marking the culmination of the biofilm life cycle, involves the disintegration of the biofilm structure [45]. Some bacteria participate in breaking down the biofilm house, dispersing and seeking new environments [46,47]. This final phase underscores the dynamic

nature of biofilms and their adaptability to changing conditions, adding a layer of complexity to their life cycle [48,49].

In conclusion, biofilm research is not only pivotal but also multifaceted, offering profound insights into the challenges and opportunities presented by these bacterial communities [50]. Understanding the intricacies of the biofilm life cycle empowers researchers to develop targeted interventions, mitigating the negative impacts of detrimental biofilms [51,52] and harnessing their positive aspects for a myriad of applications [53]. From medical treatments to environmental and engineering solutions, the multifaceted nature of biofilm research underscores its significance in addressing complex challenges across various scientific disciplines, highlighting its potential to shape the future of diverse fields [54].

#### 4.2. Future Direction: Machine Learning Insights into Biofilm Life Cycle Dynamics

The future development directions stemming from the exploration of the biofilm life cycle present several promising avenues for research. One particularly impactful trajectory involves integrating the realms of big data, machine learning, and biofilm life cycle studies. Previous research has demonstrated the widespread applications of big data and machine learning in areas such as facial recognition [55], autonomous driving [56,57], species distribution prediction [58], and educational program plan [59,60]. However, the immense potential of big data and machine learning in the context of the biofilm life cycle remains largely untapped.

An avenue with substantial potential lies in establishing a comprehensive database for the biofilm life cycle, incorporating variables such as temperature, humidity, species composition, media chemical composition, surface properties, durations of initial attachment, irreversible attachment, maturation, and dispersion. By leveraging machine learning models, it becomes possible to predict the environmental conditions conducive to rapid biofilm growth and those hindering such growth. This approach facilitates a deeper understanding of the biofilm life cycle, offering insights that can be effectively applied to medical and engineering research fields [61].

Specifically, the creation of a large-scale biofilm life cycle database allows for the systematic collection and organization of multifaceted environmental factors. Machine learning models can then analyze these datasets to discern patterns and correlations, ultimately enabling predictions about optimal and suboptimal conditions for biofilm development. This predictive capability holds the potential to revolutionize our comprehension of biofilm dynamics, offering valuable information for medical treatments, engineering applications, and beyond [62].

In essence, the integration of big data and machine learning into biofilm life cycle studies not only expands the scope of our understanding but also provides practical applications for healthcare and engineering research [63]. As technology continues to advance, this interdisciplinary approach promises to unlock new insights, driving innovation and advancements in the field of biofilm research [64,65].

#### Reference

1. Sauer, K.; Stoodley, P.; Goeres, D.M.; Hall-Stoodley, L.; Burmølle, M.; Stewart, P.S.; Bjarnsholt, T. The biofilm life cycle: Expanding the conceptual model of biofilm formation. *Nature Reviews Microbiology* **2022**, *20*, 608-620.
2. Tilahun, A.; Haddis, S.; Teshale, A.; Hadush, T. Review on biofilm and microbial adhesion. *Int J Microbiol Res* **2016**, *7*, 63-73.
3. McDougald, D.; Rice, S.A.; Barraud, N.; Steinberg, P.D.; Kjelleberg, S. Should we stay or should we go: mechanisms and ecological consequences for biofilm dispersal. *Nature Reviews Microbiology* **2012**, *10*, 39-50.
4. Zhu, Y.; Li, J.J.; Reng, J.; Wang, S.; Zhang, R.; Wang, B. Global trends of *Pseudomonas aeruginosa* biofilm research in the past two decades: A bibliometric study. *MicrobiologyOpen* **2020**, *9*, 1102-1112.
5. Crouzet, M.; Le Senechal, C.; Brözel, V.S.; Costaglioli, P.; Barthe, C.; Bonneu, M.; Garbay, B.; Vilain, S. Exploring early steps in biofilm formation: set-up of an experimental system for molecular studies. *BMC microbiology* **2014**, *14*, 1-12.
6. Armbruster, C.R.; Parsek, M.R. New insight into the early stages of biofilm formation. *Proceedings of the National Academy of Sciences* **2018**, *115*, 4317-4319.

7. Caiazza, N.C.; O'Toole, G.A. SadB is required for the transition from reversible to irreversible attachment during biofilm formation by *Pseudomonas aeruginosa* PA14. **2004**.
8. Rumbaugh, K.P.; Sauer, K. Biofilm dispersion. *Nature Reviews Microbiology* **2020**, *18*, 571-586.
9. Mahami, T.; Adu-Gyamfi, A. Biofilm-associated infections: public health implications. *International Research Journal of Microbiology (IRJM)(ISSN: 2141-5463) Vol* **2011**, *2*, 375-381.
10. Ren, Y.; Jongsma, M.A.; Mei, L.; van der Mei, H.C.; Busscher, H.J. Orthodontic treatment with fixed appliances and biofilm formation—a potential public health threat? *Clinical oral investigations* **2014**, *18*, 1711-1718.
11. Omar, A.; Wright, J.B.; Schultz, G.; Burrell, R.; Nadworny, P. Microbial biofilms and chronic wounds. *Microorganisms* **2017**, *5*, 9.
12. Battin, T.J.; Besemer, K.; Bengtsson, M.M.; Romani, A.M.; Packmann, A.I. The ecology and biogeochemistry of stream biofilms. *Nature Reviews Microbiology* **2016**, *14*, 251-263.
13. Barton, F.; Spencer, B.F.; Tartèse, R.; Graham, J.; Shaw, S.; Morris, K.; Lloyd, J.R. The potential role of biofilms in promoting fouling formation in radioactive discharge pipelines. *Biofouling* **2023**, *39*, 785-799.
14. Jain, A.; Gupta, Y.; Agrawal, R.; Jain, S.K.; Khare, P. Biofilms—a microbial life perspective: a critical review. *Critical Reviews™ in Therapeutic Drug Carrier Systems* **2007**, *24*.
15. Coenye, T.; Kjellerup, B.; Stoodley, P.; Bjarnsholt, T. The future of biofilm research—Report on the '2019 Biofilm Bash'. *Biofilm* **2020**, *2*, 100012.
16. Costerton, J.W. Overview of microbial biofilms. *Journal of Industrial Microbiology and Biotechnology* **1995**, *15*, 137-140.
17. Khudzari, J.M.; Kurian, J.; Tartakovsky, B.; Raghavan, G.S.V. Bibliometric analysis of global research trends on microbial fuel cells using Scopus database. *Biochemical engineering journal* **2018**, *136*, 51-60.
18. Jiang, Y.; Xia, W.; Zhao, R.; Wang, M.; Tang, J.; Wei, Y. Insight into the interaction between microplastics and microorganisms based on a bibliometric and visualized analysis. *Bulletin of Environmental Contamination and Toxicology* **2021**, 1-12.
19. Chen, S.; Ding, Y. Tackling Heavy Metal Pollution: Evaluating Governance Models and Frameworks. *Sustainability* **2023**, *15*, 15863.
20. Chen, S.; Ding, Y. A bibliography study of *Shewanella oneidensis* biofilm. *FEMS Microbiology Ecology* **2023**, *99*, fiad124.
21. Van Eck, N.; Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *scientometrics* **2010**, *84*, 523-538.
22. Van Eck, N.J.; Waltman, L. Citation-based clustering of publications using CitNetExplorer and VOSviewer. *Scientometrics* **2017**, *111*, 1053-1070.
23. Wong, D. VOSviewer. *Technical Services Quarterly* **2018**, *35*, 219-220.
24. Huang, Y.-J.; Cheng, S.; Yang, F.-Q.; Chen, C. Analysis and visualization of research on resilient cities and communities based on VOSviewer. *International Journal of Environmental Research and Public Health* **2022**, *19*, 7068.
25. Flemming, H.-C.; Neu, T.R.; Wozniak, D.J. The EPS matrix: the "house of biofilm cells". *Journal of bacteriology* **2007**, *189*, 7945-7947.
26. Trautner, B.W.; Darouiche, R.O. Role of biofilm in catheter-associated urinary tract infection. *American journal of infection control* **2004**, *32*, 177-183.
27. Tenke, P.; Köves, B.; Nagy, K.; Hultgren, S.J.; Mendling, W.; Wullt, B.; Grabe, M.; Wagenlehner, F.M.E.; Cek, M.; Pickard, R. Update on biofilm infections in the urinary tract. *World journal of urology* **2012**, *30*, 51-57.
28. Saint, S.; Chenoweth, C.E. Biofilms and catheter-associated urinary tract infections. *Infectious Disease Clinics* **2003**, *17*, 411-432.
29. Ding, Y.; Zhou, Y.; Yao, J.; Szymanski, C.; Fredrickson, J.; Shi, L.; Cao, B.; Zhu, Z.; Yu, X.-Y. In situ molecular imaging of the biofilm and its matrix. *Analytical chemistry* **2016**, *88*, 11244-11252.
30. Ding, Y.; Peng, N.; Du, Y.; Ji, L.; Cao, B. Disruption of putrescine biosynthesis in *Shewanella oneidensis* enhances biofilm cohesiveness and performance in Cr (VI) immobilization. *Applied and environmental microbiology* **2014**, *80*, 1498-1506.
31. Ding, Y. Heavy metal pollution and transboundary issues in ASEAN countries. *Water Policy* **2019**, *21*, 1096-1106.
32. Ding, Y.; Zhou, Y.; Yao, J.; Xiong, Y.; Zhu, Z.; Yu, X.-Y. Molecular evidence of a toxic effect on a biofilm and its matrix. *Analyst* **2019**, *144*, 2498-2503.
33. Petrova, O.E.; Sauer, K. Escaping the biofilm in more than one way: desorption, detachment or dispersion. *Current opinion in microbiology* **2016**, *30*, 67-78.
34. Hamdany, A.H.; Ding, Y.; Qian, S. Graphene-Based TiO<sub>2</sub> Cement Composites to Enhance the Antibacterial Effect of Self-Disinfecting Surfaces. *Catalysts* **2023**, *13*, 1313.

35. Hamdany, A.H.; Ding, Y.; Qian, S. Visible light antibacterial potential of graphene-TiO<sub>2</sub> cementitious composites for self-sterilization surface. *Journal of Sustainable Cement-Based Materials* **2023**, *12*, 972-982.
36. Hamdany, A.H.; Ding, Y.; Qian, S. Cementitious Composite Materials for Self-Sterilization Surfaces. *ACI Materials Journal* **2022**, *119*, 197-210.
37. Hamdany, A.H.; Ding, Y.; Qian, S. Mechanical and antibacterial behavior of photocatalytic lightweight engineered cementitious composites. *Journal of Materials in Civil Engineering* **2021**, *33*, 04021262.
38. Gunes, B. A critical review on biofilm-based reactor systems for enhanced syngas fermentation processes. *Renewable and Sustainable Energy Reviews* **2021**, *143*, 110950.
39. Zhao, C.e.; Wu, J.; Ding, Y.; Wang, V.B.; Zhang, Y.; Kjelleberg, S.; Loo, J.S.C.; Cao, B.; Zhang, Q. Hybrid conducting biofilm with built-in bacteria for high-performance microbial fuel cells. *ChemElectroChem* **2015**, *2*, 654-658.
40. Zhao, C.-e.; Chen, J.; Ding, Y.; Wang, V.B.; Bao, B.; Kjelleberg, S.; Cao, B.; Loo, S.C.J.; Wang, L.; Huang, W. Chemically functionalized conjugated oligoelectrolyte nanoparticles for enhancement of current generation in microbial fuel cells. *ACS Applied Materials & Interfaces* **2015**, *7*, 14501-14505.
41. Yang, Y.; Ding, Y.; Hu, Y.; Cao, B.; Rice, S.A.; Kjelleberg, S.; Song, H. Enhancing bidirectional electron transfer of *Shewanella oneidensis* by a synthetic flavin pathway. *ACS synthetic biology* **2015**, *4*, 815-823.
42. Zhang, Z.; Ding, Y.; Qian, S. Influence of bacterial incorporation on mechanical properties of engineered cementitious composites (ECC). *Construction and Building Materials* **2019**, *196*, 195-203.
43. Zhang, Z.; Weng, Y.; Ding, Y.; Qian, S. Use of genetically modified bacteria to repair cracks in concrete. *Materials* **2019**, *12*, 3912.
44. Zhang, Z.; Liu, D.; Ding, Y.; Wang, S. Mechanical performance of strain-hardening cementitious composites (SHCC) with bacterial addition. *Journal of Infrastructure Preservation and Resilience* **2022**, *3*, 1-11.
45. Guilhen, C.; Forestier, C.; Balestrino, D. Biofilm dispersal: multiple elaborate strategies for dissemination of bacteria with unique properties. *Molecular microbiology* **2017**, *105*, 188-210.
46. Kaplan, J.á. Biofilm dispersal: mechanisms, clinical implications, and potential therapeutic uses. *Journal of dental research* **2010**, *89*, 205-218.
47. Landini, P.; Antoniani, D.; Burgess, J.G.; Nijland, R. Molecular mechanisms of compounds affecting bacterial biofilm formation and dispersal. *Applied microbiology and biotechnology* **2010**, *86*, 813-823.
48. Wood, T.K.; Hong, S.H.; Ma, Q. Engineering biofilm formation and dispersal. *Trends in biotechnology* **2011**, *29*, 87-94.
49. Nijland, R.; Hall, M.J.; Burgess, J.G. Dispersal of biofilms by secreted, matrix degrading, bacterial DNase. *PloS one* **2010**, *5*, e15668.
50. Wuertz, S.; Okabe, S.; Hausner, M. Microbial communities and their interactions in biofilm systems: an overview. *Water Science and Technology* **2004**, *49*, 327-336.
51. Scannapieco, F.A. Role of oral bacteria in respiratory infection. *Journal of periodontology* **1999**, *70*, 793-802.
52. Parsonnet, J. Bacterial infection as a cause of cancer. *Environmental health perspectives* **1995**, *103*, 263-268.
53. Strik, D.P.; Hamelers, H.V.M.; Snel, J.F.H.; Buisman, C.J.N. Green electricity production with living plants and bacteria in a fuel cell. *International Journal of Energy Research* **2008**, *32*, 870-876.
54. Highmore, C.J.; Melaugh, G.; Morris, R.J.; Parker, J.; Direito, S.O.L.; Romero, M.; Soukarieh, F.; Robertson, S.N.; Bamford, N.C. Translational challenges and opportunities in biofilm science: a BRIEF for the future. *npj Biofilms and Microbiomes* **2022**, *8*, 68.
55. Coe, J.; Atay, M. Evaluating impact of race in facial recognition across machine learning and deep learning algorithms. *Computers* **2021**, *10*, 113.
56. Huang, H.; Chang, J.; Zhang, D.; Zhang, J.; Wu, H.; Li, G. Machine learning-based automatic control of tunneling posture of shield machine. *Journal of Rock Mechanics and Geotechnical Engineering* **2022**, *14*, 1153-1164.
57. Skorucak, J.; Hertig-Godeschalk, A.; Schreier, D.R.; Malafeev, A.; Mathis, J.; Achermann, P. Automatic detection of microsleep episodes with feature-based machine learning. *Sleep* **2020**, *43*, zsz225.
58. Chen, S.; Ding, Y. Machine Learning and Its Applications in Studying the Geographical Distribution of Ants. *Diversity* **2022**, *14*, 706.
59. Chen, S.; Ding, Y. A Machine Learning Approach to Predicting Academic Performance in Pennsylvania's Schools. *Social Sciences* **2023**, *12*, 118.
60. Chen, S.; Ding, Y. Assessing the Psychometric Properties of STEAM Competence in Primary School Students: A Construct Measurement Study. *Journal of Psychoeducational Assessment* **2023**, *41*, 796-810.
61. Francolini, I.; Donelli, G. Prevention and control of biofilm-based medical-device-related infections. *FEMS Immunology & Medical Microbiology* **2010**, *59*, 227-238.
62. Philipp, L.-A.; Bühler, K.; Ulber, R.; Gescher, J. Beneficial applications of biofilms. *Nature Reviews Microbiology* **2023**, 1-15.

63. Cámara, M.; Green, W.; MacPhee, C.E.; Rakowska, P.D.; Raval, R.; Richardson, M.C.; Slater-Jefferies, J.; Steventon, K.; Webb, J.S. Economic significance of biofilms: a multidisciplinary and cross-sectoral challenge. *npj Biofilms and Microbiomes* **2022**, *8*, 42.
64. Wong, G.C.L.; O'Toole, G.A. All together now: Integrating biofilm research across disciplines. *Mrs Bulletin* **2011**, *36*, 339-342.
65. Dzianach, P.A.; Pérez-Reche, F.J.; Strachan, N.J.C.; Forbes, K.J.; Dykes, G.A. The Use of Interdisciplinary Approaches to Understand the Biology of *Campylobacter jejuni*. *Microorganisms* **2022**, *10*, 2498.

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