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Yuanzhao Ding *

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

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A Bibliography Study of Biofilm Life Cycle

Yuanzhao Ding

School of Geography and the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, UK; armstrongding@163.com; ORCID: 0000-0003-0116-3648

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].

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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*.

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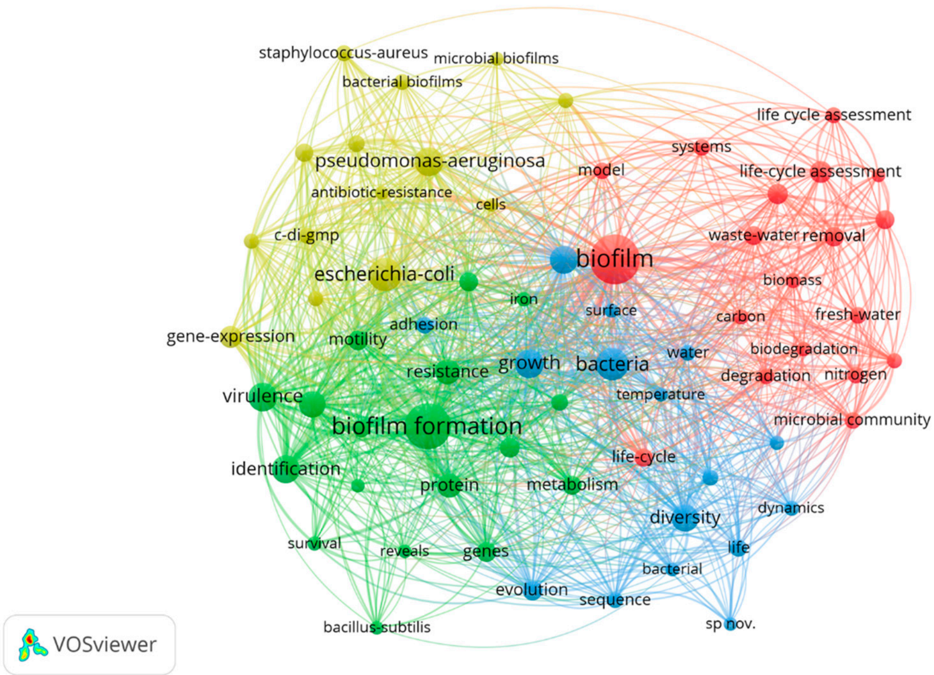

Figure 1. VOSviewer visualization of keywords obtained during the search for "biofilm life cycle" in Web of Science.

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.

Furthermore, the inclusion of keywords related to bacterial behavior adds another layer of complexity to the visualization. Terms such as adhesion, motility, resistance, growth, virulence, and survival underscore the multifaceted nature of biofilm formation and the dynamic interactions between bacterial communities and their environment. This nuanced representation in Figure 1 serves as a valuable resource for researchers seeking to explore and comprehend the intricate dynamics of biofilm life cycles.

Figure 2 offers a thorough and expansive portrayal of the key players on the global stage driving research in the realm of biofilm life cycles. Among these prominent contributors, the United States, China, and the United Kingdom emerge as central pillars, wielding significant influence and occupying pivotal positions in the advancement of this field. Their steadfast dedication and innovative pursuits have propelled the understanding of biofilm life cycles to new heights, setting benchmarks for others to follow suit.

Moreover, the landscape of biofilm life cycle research is enriched by the vibrant engagement and substantial contributions from a multitude of countries and regions across the globe. Nations such as South Korea, Singapore, India, Denmark, Poland, Brazil, Italy, France, Spain, Portugal, Austria, the Netherlands, Germany, Switzerland, Belgium, Finland, and Canada are actively involved in this domain, each bringing its unique perspective and expertise to the table. This collective effort underscores a global commitment to unraveling the intricacies of biofilm life cycles and underscores the interconnectedness of scientific endeavors worldwide.

The collaborative spirit witnessed among these diverse nations underscores the significance of unified action in driving progress and maximizing research efficacy. Through shared initiatives and cooperative ventures, researchers from around the world are pooling their resources, knowledge, and skills to delve deeper into the complexities of biofilm life cycles. This collaborative ethos reflects the evolving landscape of global research, where collective endeavors are essential for unlocking new frontiers and addressing pressing challenges in the field of microbiology.

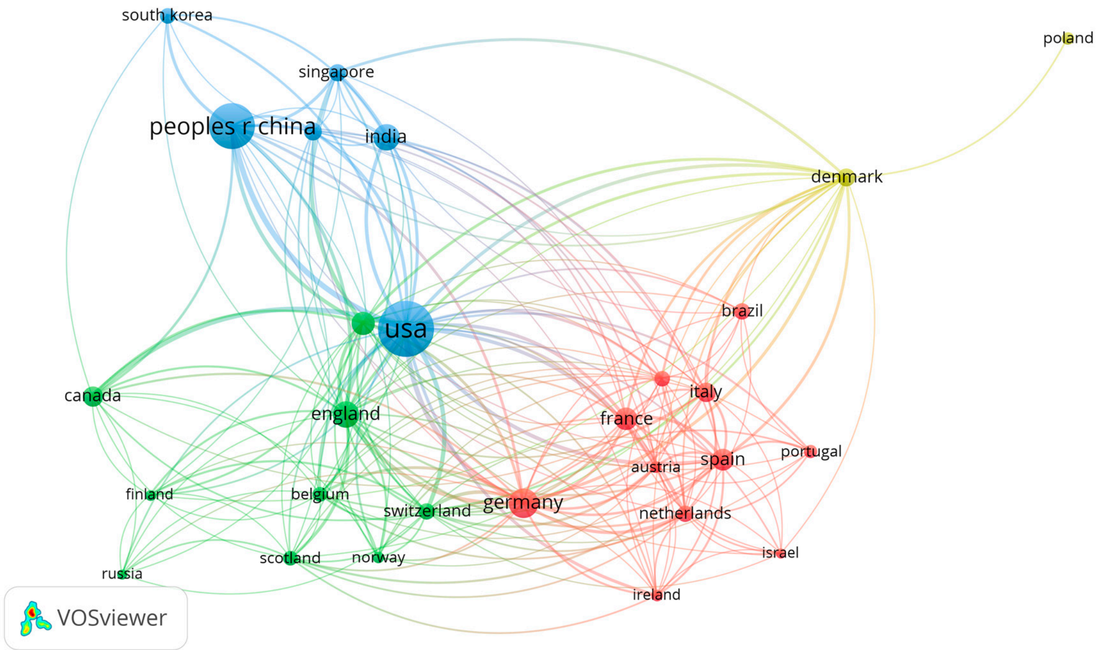

Figure 2. VOSviewer visualization of countries/regions obtained during the search for "biofilm life cycle" in Web of Science. The line suggests the research collaboration.

Figure 3 serves as an expansive canvas, offering a detailed portrayal of the illustrious organizations at the forefront of biofilm life cycle research. Within this tapestry of scientific inquiry, distinguished institutions such as Montana State University, Nanyang Technological University, and the Chinese Academy of Sciences occupy prominent positions, wielding their expertise and resources to push the boundaries of knowledge in this field. Yet, the landscape is not solely defined by these titans; a constellation of impactful organizations, 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 numerous others, embellishes the tableau with their significant contributions.

These organizations, strategically positioned as vanguards in biofilm life cycle research, serve as beacons of scientific excellence, illuminating pathways to deeper understanding and practical application. Their collective efforts transcend geographical boundaries, forming a nexus of collaboration that amplifies the efficacy and impact of scientific endeavors. This collaborative ethos underscores a shared commitment among institutions worldwide to unravel the intricacies inherent in biofilm life cycles, recognizing the collective pursuit of knowledge as a driving force for progress.

Through interdisciplinary collaboration and knowledge exchange, these organizations synergize their strengths, fostering an environment ripe for innovation and discovery. This collaborative spirit not only enriches the scientific community but also paves the way for transformative breakthroughs in addressing pressing challenges associated with biofilm-related issues. As these institutions continue to forge ahead in their research pursuits, their collective contributions promise to shape the trajectory of scientific inquiry, opening new vistas of understanding and offering solutions to real-world problems.

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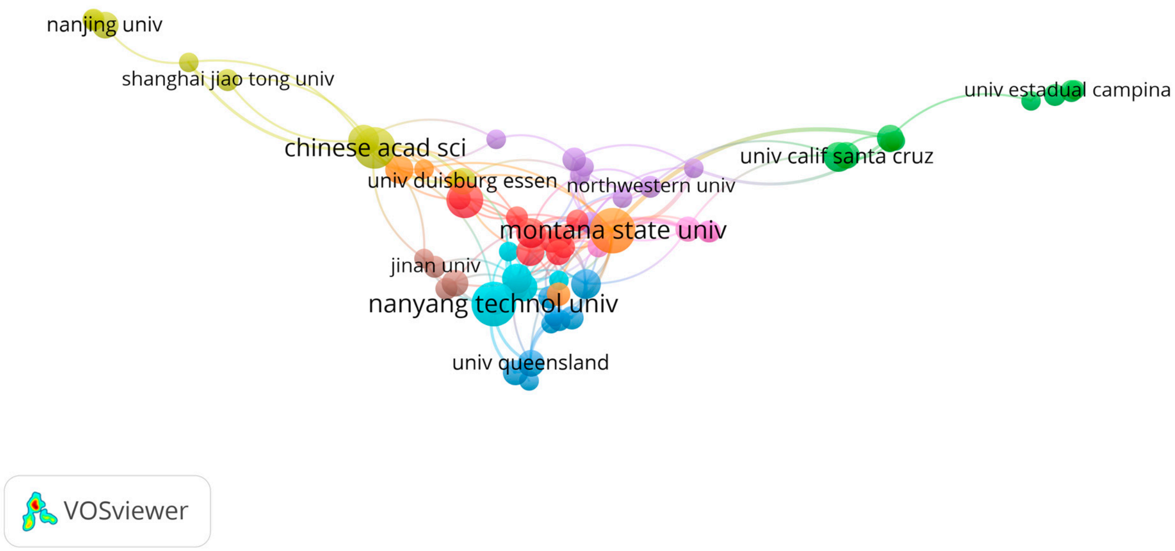

Figure 3. VOSviewer visualization of organization obtained during the search for "biofilm life cycle" in Web of Science. The line suggests the research collaboration.

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 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].

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