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Review Article

Biological interfaces in sustainable materials systems: Microbial exposure considerations for environmental technologies

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ABSTRACT

Sustainable materials and environmental technologies have been utilized for processing waste, managing air quality and wastewater management to address global environmental challenges. Such engineered systems function in biologically active environments where material-microbe interactions play an important role in the performance of the system and the impact on human exposure. While there has been considerable research into improving the efficiency of devices and materials, the biological processes taking place at interfaces of materials are relatively understudied within the realm of sustainability. This study emphasizes to investigate the microbial ecology in engineered environmental systems, through studying colonization of surfaces, formation of biofilms, and biotransformation that occurs at the interface of sustainable materials. Particular focus will be given on microbial adhesion mechanisms, metabolic activity and its effect on material strength, as well as bioaerosol formation and their contribution to exposure routes. Developments in the field of environmental microbiology from culture-dependent methods, through molecular analysis, and integrative exposure assessment approaches will be highlighted to show how microbial interactions can be analyzed in tandem with standard engineering data. Issues pertaining to microbial survival and spread will be evaluated in relation to occupational exposure, materials degradation, and reliability of system. By making microbial processes an intrinsic component of sustainable technologies, this paper shows the importance of combining microbiological knowledge into material properties, device design, and monitoring schemes. Biological insights on environmental technologies can help mitigate risks, increase system resilience, and ensure that any sustainability-related innovations address both ecological performance and human health aspects.

1. Introduction

Sustainable materials and environmental technologies have been recognized as essential tools for addressing various global challenges, such as pollution control, resource recovery, and climate resilience. Technologies such as wastewater treatment systems, air filtration systems, and solid waste processing systems are now often optimized for maximum efficiency, reduced environmental footprint, and support for circular economy principles [1, 2]. However, it is essential to note that such technologies do not function independently but within biologically active environments, where microbes play an essential role in defining system performance and environmental outcomes.

Microorganisms form an integral component of environmental systems, responsible for critical biochemical processes such as nutrient cycling, organic matter degradation, and contaminant transformation [3]. In engineered environments, microbial communities colonize material surfaces, forming complex and dynamic biofilms that

influence both functional efficiency and material integrity. These interfaces between microbes and engineered materials are now recognized as critical factors for defining system performances [4]. However, traditional approaches to designing sustainable technologies often overlook critical parameters such as microbes; instead those are primarily focused on physical and chemical parameters.

The idea of environmental technologies as microbial habitats emphasizes on the importance of understanding the role played by ecological factors in the structure and activity of microbial communities. Colonization by microorganisms starts with adhesion to surfaces, followed by the formation and eventual maturation of biofilms, which leads to the development of highly structured microbial communities with the capability to coordinate metabolic activity [5]. These processes can lead to positive system functionality, such as in biodegradation and bioremediation, but also to negative



consequences such as biofouling, degradation of materials, and the release of potentially hazardous bioaerosols [6].

The formation of bioaerosols represents a relatively new untapped area that connects engineered systems to human exposure. Processes such as aeration, agitation, and airflow can lead to the aerosolization of microorganisms, thereby facilitating the dispersion of microorganisms to the external environment [7]. This has significant implications for human exposure and environmental safety, particularly in relation to the potential for long-term exposure to microorganisms.

The advancements in environmental microbiology, including culture-dependent approaches and high-throughput molecular-based methods, have allowed for the more comprehensive characterization of microbial communities and their functional potential in engineered systems [8]. These approaches have provided significant insights into the diversity and function of microbes, as well as their interactions with material surfaces, thus aiding in the development of biological considerations in engineering approaches.

Keeping this in view, the present study has specifically addressed the aspect of microbial ecology in sustainable material systems, including the aspects of surface-microbe interaction, biofilm formation, microbial transformation processes, and bioaerosol formation. This study has attempted to focus on the importance of a biological perspective in addressing the issues of sustainability in material systems, including the potential for human exposure risk.

2. Microbial Ecology of Engineered Environmental Systems

2.1 Microbial diversity associated with waste, air, and water technologies

The engineered systems, which include wastewater treatment plants, air purification units, and solid waste processing facilities, are dynamic microbial ecosystems in which microorganisms interact with their physical and chemical environment. These systems are rich in nutrients and sometimes selective, allowing for the growth and survival of microorganisms such as bacteria, fungi, archaea, and many others. The microbial ecology in these systems is crucial in order to optimize the performance, stability, and minimize the risks associated with exposure to microorganisms.

The diversity of microorganisms in engineered systems varies depending on the specific environmental application. For example, in wastewater treatment systems, the diversity of microorganisms is usually high, including heterotrophic and autotrophic microorganisms that takes part in various biological processes such as the degradation of organic matter, nitrification, and denitrification [9]. In air handling systems, high diversity of thriving microorganisms sustained low in nutrients, including spore-forming microorganisms such as fungi and bacteria, which are usually adapted to dry environments [7]. In solid waste management systems, the microbial diversity participating in organic matter degradation is usually high, sustaining in both aerobic and anaerobic environments, producing methane as a by-product [1].

2.2 Ecological drivers shaping community structure

Apart from nutrient availability, different ecological factors, including nutrient gradients, moisture content, temperature, pH, oxygen availability, and physico-chemical properties of materials that affects the diversity and abundance

of these communities. These factors, in turn, acts as selection pressures in the environment, affecting the types of microorganisms that can survive in these environments. For instance, activated sludge systems, where high oxygen availability and high nutrient concentrations are prevalent, in return support the survival of heterotrophic bacteria that grows rapidly. Similarly, in anaerobic digestion systems, methanogenic archaea are prevalent, for their ability to survive in environments where oxygen is depleted [2].

2.3 Environmental selection pressures

The selection pressures in the environment further influence the functional specialization in these communities. Microorganisms in these environments develop adaptations that sustain their survival in different environments, thus developing cooperative and competitive relationships that improve the efficiency of these environments. These relationships include syntrophic relationships, quorum sensing, and cross-feeding, all of which influence efficiency in pollutant degradation and resource recovery [5].

Adaptations in these environments may; however, be a challenge in managing these environments, as opportunistic pathogens may develop, thus affecting the efficiency of these environments.

Temporal variability in natural phenomena, organism densities and level of pollutants, also increases the complexity in microbial ecology. Changes in parameters, such as flow rates and substrate composition, can cause changes in microbial communities thereby causing problems in terms of performance. Therefore, it is essential to monitor microbial communities in engineered systems.

There have been tremendous advances in environmental microbiology that have greatly improved our understanding of microbial ecology. This is because various techniques, such as culture-dependent and culture-independent methods like 16S rRNA gene sequencing, metagenomics, and meta-transcriptomics, can help us understand microbial ecology. These techniques can help us understand how microbial communities respond to environmental changes and how they interact with engineered materials. This can help us develop predictive models for containment of microbial communities.

It is therefore important that we understand that engineered environmental systems are not only physical and chemical systems. Rather, they are also microbial ecosystems. This is because microbial ecology is a crucial part of engineered environmental systems. Therefore, we can improve the performance of engineered environmental systems using ecological principles. This can help us reduce unintended impacts related to microbial exposure and system degradation.

3. Surface-microbe interactions on sustainable materials

3.1 Adhesion mechanisms

The first step for microbial interaction to environmental system is through colonisation that initiates the biofilm formation a key for adhesion to any surface [10]. Biofilm is a microbial aggregation pattern that is gradually formed by the microbes starting with the adhesion to a surface followed by the secretion of extracellular polymeric substance (EPS). Biofilms are harmful for both the living and industrial processes as biofilms are a major risk associated to infections.

Bacterial adherence starts with their extracellular layer i.e. the glycocalyx surrounding their cell wall. It is a viscous or jelly-like layer that is formed of polymers and peptides which acts as an important bridge, between the bacterium and its environment in its survival as well as its pathogenicity.

Glycocalyx whether formed in natural or in controlled environment owing to its pathogenicity, leads to formation of micro-colonies which eventually forms of thick slimy layer on the surface, known as biofilms [11]. Bacteria capable of forming glycocalyx, develop it in such a way that their daughter cells after the division gets trapped which leads to formation of microcolonies resulting in morphologically identical cells that forms a strong bond with the surface and adheres to it firmly. This formation benefits the bacteria by trapping the soluble nutrients and is thus sustained into an environment that favours their growth, provides protection against the antibacterial agents like antibiotics, chemical compounds, surfactants etc. Bacteria forming glycocalyx tends to concentrate and grow at the solid-water interfaces due to nutrient accumulation. The adherent bacteria form fibrous glycocalyx materials that help to glue themselves to the surface in such a way that their reversible adsorption becomes irreversible adhesion [11, 12, 13].

Other studies have also shown that microbes that adhere onto the metal surfaces forms biofilm to cause undesirable changes in the metal surface by the process of bio-corrosion or microbially influenced corrosion (MIC). Biofilm production onto metal surfaces involves the microbes to cause redox reactions and the EPS mediates the initial cell adhesion to the surface followed by constitution of the biofilm matrix though the exact mechanism is yet to be known [14].

3.2 Biofilm development and maturation

Biofilm plays an important role in the life-cycle of a microbe. It consists of layers of morphologically identical cells rooted into hydrated matrix [11, 13]. It not only helps the bacteria to capture and retain organic nutrients but also protects it from the physical forces as well as chemical compounds including the antibiotics and surfactants and these microbes are capable of evading phagocytosis once inside the living cell system [15]. In case of *in vitro* biofilm formation, the development of a 3D structure termed as 'maturation' which is attained by several stages becomes the benchmark for the biofilm formation. Maturation leads to formation of strong and compact biofilm structure including the formation of EPS. The research also suggested that the DNA from the microbes were involved into the formation of biofilm and acts as an initiator during the initial stages of the biofilm formation.

The first stage depicts the development of an irreversible attachment from the reversible bond onto the surface using flagella and type I pilli. After the firm attachment, cells are divided and trapped into a hydrated matrix that traps organic nutrients and leads to clump formation or micro-colonies. These micro-colonies secrete a substance called EPS that glues them together to the surface. Colonic acid is shown to be essential for the thick and mature 3D structure formation which has been proved by the report, where the *E.coli* mutants considered for the study were unable to produce thick biofilm and produced a thin and flatter layer unlike the wild-type strain of *E.coli* that was able to produce a robust and thick biofilm layer. This eventually matures to form a complete 3D structure that contains water channels that permits the flow of nutrients in and waste products out of the cell [15].

4. Microbial transformation processes

4.1 Biodegradation and metabolic activity

Transformation by the microbes depicts the functional core of sustainable environmental technologies, where the metabolic diversity of the microbes increases to neutralize anthropogenic pollutants. This process involves the biochemical modification of chemical compounds, ranging from the complete mineralization of organic matter to the targeted biotransformation of complex xenobiotics.

The biofilm producing microbes are capable of degradation of polycyclic aromatic hydrocarbons (PAHs). Initiation of the rapid biodegradation of the PAHs and several physiochemical parameters that are involved in the biodegradation is mediated by the 3D structure of biofilm [16].

4.2 Functional roles in pollutant transformation

The catabolic processes of indigenous microbial communities enable biodegradation. Microorganisms use specialized enzymatic suites to utilize a vast array of organic compounds as carbon and energy sources. Recalcitrant compounds that cannot be degraded through natural processes often demands for the concerted action of multiple species within a biofilm or sludge community. The metabolic efficiency of these clustered microbes is governed by enzymatic kinetics and the presence of specific catabolic operons. The degradation of aromatic hydrocarbons typically initiated with the action of dioxygenase enzymes enables the incorporation of molecular oxygen into the aromatic ring, for breakdown.

Genus like *Burkholderia* and *Rhodococcus* are often recognised as primary degraders in contaminated environments due to their expansive genomes and metabolic plasticity. *Rhodococcus* species, in particular, have numerous oxygenases and hydrolases that enables them to breakdown into high-molecular-weight hydrocarbons and heterocyclic compounds persisting in the environment. The activity of these organisms is often tested through respirometry or resazurin-based assays, which provides a constant stream of information of the metabolic state of the community during the degradation process [17].

The microbes are capable of performing two primary types of transformations: mineralization and biotransformation:

- **Mineralization:** The complete degradation or decomposition of organic pollutants into their inorganic components, e.g., CO₂, H₂O, and salt [18]. This is the best strategy for wastewater treatment, where the pollutant is permanently removed from the environment.
- **Biotransformation:** This is the change of an organic pollutant from a complex molecule to a simpler, often less toxic molecule. In some instances, however, the process can result in activation where the new molecule is more mobile or toxic than the original [1, 18, 19].

5. Bioaerosol generation and microbial dispersion

5.1 Mechanisms of aerosolization

Bioaerosols are produced by different biological and physical processes that facilitate microorganisms to become airborne. In human-associated environments, respiratory activities such as coughing, sneezing, and speaking generate

droplets through fluid film rupture and shear forces within the respiratory tract. These droplets are different in size and can get evaporated and form smaller droplets, that remain suspended in the air for longer durations [20]. Processes like soil/dust re-suspension, sea spray, and mechanical disturbances can play a vital role in releasing microorganisms into the environment [21].

The factors that affect the efficiency of aerosolization are mainly surface tension, speed of airflow and environmental conditions. The small particles remain in suspension while the larger droplets tend to settle quickly due to gravitational forces. Additionally, physicochemical changes, particularly evaporation, influence particle size and composition, affect their persistence and potential for transmission.

5.2 Particle association and survival dynamics

Microorganisms either exist as individual cells or remain in association with particulate matter like dust, organic debris or liquid droplets after being aerosolized. Attachment to particulate matter is an important criterion that determines the survival of microbes since it offers resistance to stress factors such as UV irradiation and drying, among others [22]. In addition, particulates may serve as sources of nutrients, thereby improving microbial stability.

The survival efficacy of bioaerosols is controlled by prevalent environmental conditions viz., relative humidity, temperature, and radiation exposure. Increase in the relative humidity level favours microbial survival by reducing desiccation stress, whereas low humidity can lead to rapid water loss and decreased viability. The evaporation process causes an increase in the concentration of the solutes within the droplet, leading to osmotic pressure, which can be harmful to microbial cells [20]. The interaction between particle composition and environmental conditions results in a complex survival pattern that varies across microbial species. Understanding these dynamics is essential for assessing the persistence of airborne pathogens and potential health impacts.

5.3 Environmental transport behaviour

The transportation of bioaerosols at various spatial scales is achieved, from local-scale indoor environments to long-range transportation in the atmosphere. At a micro-scale, factors including airflow patterns, ventilation systems, and turbulence affect the distribution of airborne particles in indoor environments. At a larger scale, wind currents play significant role in the transportation of bioaerosols [23].

The environment influences the effectiveness of bioaerosol movement and microbial survival. An example of an environmental effect on movement includes stability of the atmosphere that favors transport and turbulence that facilitates diffusion. Bioaerosols can also interact with atmospheric processes by acting as cloud condensation nuclei and ice-nucleating particles, thereby influencing cloud formation and climate dynamics [24].

Overall, the bioaerosol transportation is governed by a combination of physical forces and environmental conditions which marks their importance in both public health and atmospheric science.

6. Exposure pathways, indicators, and occupational relevance of bioaerosols

6.1 Inhalation and contact exposure routes

Inhalation is considered as the primary route of bioaerosols exposure. Airborne particles vary among different sizes that can penetrate the respiratory tract and colonise at different regions. Larger particles of over 10 μm are usually found in the upper respiratory system, whereas smaller particles of less than 2.5 μm can reach the lower respiratory system, particularly the alveolar region, which can cause infection or inflammatory reactions [25]. The level of inhalation exposure is affected by different parameters, including size, concentration, and duration.

Apart from inhalation, dermal exposure is another mode of exposure. Bioaerosols that gets deposited on skin, mucous membranes and surfaces indirectly results in transmission through hand-to-face contact or ingestion. Reported studies suggest that dermal exposure is common when contaminated surfaces act as a source of infection. Studies have shown that exposure to bioaerosols-contaminated surfaces can lead to increased infection, especially when hygiene practices are poor [26]. Inhalation along with the contact exposure contributes to the overall exposure determining the outcome.

6.2 Indicator organisms and biomarkers

Indicator organisms are found to be useful for the assessment of bioaerosol contamination and potential health risks. These organisms serve as the indication of the presence of pathogenic or environmentally important microbes. Some common bacterial indicators are *Bacillus* and *Staphylococcus*, while *Aspergillus* and *Penicillium* are some common indicator fungi in air samples [22]. Their presence can reflect environmental conditions and levels of microbial contamination.

The biomarkers are used to have more understanding of the exposure and the biological effects. Endotoxins that form part of the cell wall of gram-negative bacteria are common examples of the biomarkers due to their association with respiratory tract inflammation and immune responses. Fungal β -glucans are also used as biomarkers because of their association with allergic and inflammatory responses [26]. Molecular techniques such as PCR-based detection of specific genes help to confirm the microbial signature in bioaerosols. The application of both indicator species and biomarkers helps to have a better knowledge of the exposure.

6.3 Relevance to occupational settings

Bioaerosol exposure is highly significant in occupational environments since workers usually come across high levels of bioaerosols in the air. Some industries such as agriculture, waste management, wastewater treatment, and healthcare facilities pose higher risks for workers due to the presence of organic matter and microbial growth. Workers in such environments are more likely to suffer from respiratory illness, allergies and infections [27].

Exposure of workers to bioaerosols is influenced by factors such as ventilation, work practices and environmental conditions. For instance, workers involved while composting and animal rearing are likely to be exposed to high concentrations of bioaerosols, as organic materials can release high amounts of bioaerosols when disturbed. In healthcare settings, aerosol-generating procedures increase the risk of airborne transmission of pathogens. Bioaerosol monitoring by using indicator microorganisms and biomarkers is a prerequisite for assessing the risks and developing mitigation strategies.

Effective mitigation measures include improved ventilation, use of personal protective equipment (PPE), and implementation of hygiene protocols. The exposure of workers to bioaerosols and the associated risks need to be understood for improving worker safety.

7. Analytical approaches in environmental microbiology

7.1 Culture-based characterization

The standard method used in microbiology to isolate, identify and describe the microorganisms based on their outer as well as microscopic characterisation is growing them onto nutrient based media in controlled laboratory environment. Unlike the molecular methods that checks for the genotypic characterisation like the DNA and RNA sequencing, this method relies on the phenotypic characterisation of the microbes which acts as a first line of health risk potential. Though the newer genomic techniques are fast and much more reliable, culture-based methods remain essential because they prove the micro-organism is viable (alive and active) or not and provide a physical map for further experimentation.

It involves the isolation of microbes from different environmental samples like soil, water and air. Isolation of microbes onto different nutrient media including basal media like nutrient agar and potato dextrose agar, that allows the growth of most of the microbes; enriched media that contains some specific nutrient type like Blood agar, Jensen media etc; selective media that consists of some nutrients that selects specific microbes against other like *Klebsiella* selective agar and Mannitol salt agar that selects for *Klebsiella* sp. and *Staphylococcus aureus* respectively while inhibiting the others. Other media like indicator media, transport and storage media are also used for isolation of microbes and other purposes.

Culture based method is useful to determine the biochemical reactions (catalase, oxidase etc.), check for haemolysis on agar and also to determine the minimal inhibitory concentration (MIC). This measures exactly how much of an antibiotic is needed to stop the growth of a specific strain. This is vital because a microbe might possess a resistance gene whose expression has been repressed or not been fully expressed due to lack of nutrients. Culturing the microbes onto provided conditions might induce the expression of the repressed gene that molecular probes cannot design beforehand.

7.2 Molecular and sequencing methods

Though culture-based technique holds significant importance in microbiology but it should be accompanied by the molecular and sequencing methods as only about 1% of the microbes are culturable or known to be culturable while the rest 99% are non-culturable or are difficult to culture. For capturing the information about those microbes, molecular approaches are essential. Molecular and sequencing-based methods are essential for capturing the true diversity and functional potential of microbial ecosystems.

Various tools used for molecular approaches are genomics, proteomics, transcriptomics, metabolomics, phenomics and metagenomics [28]. Polymerase Chain Reaction (PCR), in particular, continues and is considered to be the gold standard in environmental monitoring based on its specificity and sensitivity. Conventional PCR is used in the presence/absence method, while quantitative PCR (qPCR) and

digital PCR (dPCR) enable the accurate quantification of particular genetic markers, including antimicrobial resistance genes (ARGs) and functional genes in nitrogen cycling processes. It enables the detection of pathogens in wastewater, tracking fecal sources, and quantifying genes in soil or dust samples. 16S rRNA sequencing acts as a marker for studying the microbes at genetic level in case of bacteria whereas 18S rRNA sequencing acts as a marker for studying fungal genome sequencing. The conserved marker genes are used to profile thousands of taxa simultaneously. The latest versions of the technology, such as the Oxford Nanopore R10.4.1, provide full-length 16S sequencing, enabling species-level resolution, which was not previously possible with short-read technologies [29].

Unlike the amplicons, shotgun approaches are used for the sequencing of all genomic DNA in a sample providing a blueprint of the community's functional potential, allowing for the reconstruction of metabolic pathways and the discovery of novel enzymes or resistance mechanisms without prior sequence knowledge.

7.3 Quantitative microbial risk frameworks

Quantitative microbial risk assessment (QMRA) is a tool that helps to study the risk assessment and evaluate the microbial safety of drinking water and acts as a framework to understand the respiratory pathogen transmission and inform policy on infection control allowing for the quantitative expression of risk in terms of infection, illness or mortality from microbial pathogens and includes four main steps: hazard identification, exposure assessment, dose response and risk characterisation [30].

Although QMRA has traditionally relied on culture-based counts (CFUs), it is now in the process of developing into the new and exciting area of "next-generation" QMRA (ngQMRA), which incorporates molecular biology and the application of machine learning [31].

Another major area of QMRA is in the evaluation of the risks of transmission of AMR in environmental settings, such as aquatic systems or indoors. The latest frameworks have also included the Horizontal Gene Transfer (HGT) rates in the dose-response section of the QMRA, which considers the fact that the risk is not only from the microorganism but also from the potential of the resistance genes to be transferred to the commensal microbiota of the host [32].

8. Microbial impacts on sustainability and materials integrity

Bio-deterioration is defined as an undesirable change in the properties of materials resulting from the vital activities of living organisms. It is generally considered to be the sum of two processes, which are bio-fouling (surface overgrowth) and microbiologically influenced corrosion (MIC). The influence of microorganisms such as sulphate-reducing bacteria (SRB) and acid-producing bacteria (APB) results in corrosive micro-environments. Recent investigations have divided these into metabolite MIC (MMIC), which is influenced by protons and organic acids, and electrical MIC (EMIC), in which microbes extract electrons from the metal surface [33].

Bio-deterioration of non-metals includes the influence of microorganisms which is not restricted to metals alone but also affects the durability of concrete and synthetic polymers. The influence of microbial dark matter' in environmental biofilms

is also reported to degrade complex plastic additives, which results in the embrittlement of marine and industrial infrastructure [34].

Microbial colonization results in a negative feedback loop that reduces the operational efficiency of engineered systems, resulting in a rise in energy consumption and carbon footprint. In engineered cooling systems and heat transfer equipment, the formation of 3D structure of a biofilm, or a slime layer, behaves as a potent insulator. A thin biofilm, i.e., less than 100 μm , may result in a reduction of thermal conductivity that surpasses that of calcium carbonate scaling, causing the system to operate less efficiently and consume more energy [35].

In the field of maritime sustainability, the presence of biofilms on ship hulls enhances the roughness of the ship's surface, causing friction. This may result in a 40% to 80% increase in fuel consumption and the resulting CO₂ footprint [36]. Biofilms affect the sensitivity of electrochemical sensors and the efficiency of bio-electro-chemical devices, such as microbial fuel cells, by acting as a barrier that restricts the diffusion of substrates to the electrode surface [37].

9. Integrating microbial knowledge into environmental technology design

9.1 Biologically informed material selection

Material selection has been found to be a key factor in the control of microbial colonization and the consequent formation of bioaerosols in engineered systems. Materials in indoor and industrial environments have been found to inhibit or enhance microbial growth depending on the physico-chemical properties. Materials with low surface roughness and porosity have been found to inhibit microbial growth by limiting the number of sites available for microbial colonization [38]. On the other hand, porous materials such as untreated woods and textiles have been found to retain moisture and organic matter, thus enhancing microbial growth.

Biologically inspired material design has been developed to reduce the microbial load by incorporating antimicrobial properties. For instance, metal surfaces such as copper and silver have been found to inhibit microbial growth. These surfaces have been attributed to the antimicrobial properties of metals such as copper and silver, which exert antimicrobial effects by creating oxidative stress and disrupting cell membranes [39]. Therefore, selecting materials that inhibit biofilm formation is critical, as biofilms are potential sources of bioaerosols when disturbed mechanically. Thus, incorporating microbiological aspects in material selection has the potential to reduce bioaerosol generation from the source.

9.2 Monitoring strategies

For the effective monitoring of bioaerosols, it is important to assess the level of exposure risks and the efficacy of the control mechanisms. Conventional monitoring techniques involve the use of culture-based monitoring, where it is possible to identify and quantify the microorganisms present in the air. However, the technique is limited in that it is not possible to monitor the non-culturable microorganisms and the total microbial diversity [40].

Advancements in molecular techniques have made it possible to monitor the levels of bioaerosols in the air. Methods like quantitative PCR (qPCR) and next-generation sequencing (NGS) helps us in detecting specific microbial genes present in the air. These methods are mainly useful for

identifying pathogens and antimicrobial resistance genes in airborne samples. Also, the use of biomarkers such as endotoxins and β -glucans is effective in the monitoring of the levels of biologically active components in the air [26].

Real-time monitoring technologies, such as optical particle counters and biosensors, have made it possible to measure the levels of aerosol concentration in the air. Using more than one monitoring techniques is useful for a comprehensive assessment of bioaerosol presence, viability and potential health risks.

9.3 Preventive engineering approaches

Preventive engineering strategies are crucial for controlling bioaerosol exposure in both indoor and occupational environments. The role of ventilation systems in controlling airborne particles is very crucial which involves diluting and removing airborne particles. High-efficiency particulate air (HEPA) filtration is widely used to filter airborne particles, including microorganisms, thereby reducing concentrations of bioaerosols [41].

Another important strategy used in controlling bioaerosol exposure is the management of airflow. Controlled airflow patterns, such as laminar flow systems, limit the spread of bioaerosols in sensitive environments such as healthcare facilities. Humidity plays a crucial role in controlling bioaerosol exposure as optimal relative humidity levels limit bioaerosol survival.

Source control measures, such as enclosing the emission points and reducing mechanical disturbances, further decrease bioaerosol generation. Personal protective equipment, such as masks and respirators, provides protection for individuals in bioaerosol-exposed environments. Therefore, the integration of engineering controls with environmental management strategies provides a comprehensive approach to controlling bioaerosol exposure and associated health risks.

10. Future directions in microbial-materials research

10.1 Systems biology perspectives

Systems biology is a science that provides an integrated approach to the understanding of bioaerosols by integrating data from various levels of biology. Unlike other approaches, which focus on the interaction of an individual population, this approach considers the interaction of populations of microbes and their reaction to environmental factors. With the help of high-throughput technologies such as metagenomics, transcriptomics, and metabolomics, the characterization of the microbial communities in the air has been extensively performed [42].

In the study of bioaerosols, systems biology has been applied in the identification of key biological processes in which microbes play a significant role in stress response, survival, and pathogenicity. This is because environmental factors such as UV light and desiccation induce changes in the expression of genes, which increase the survival potential of the microbes. This is because environmental factors, such as UV light or desiccation, induce gene expression changes that enhance the survival potential of microbes. This approach also enables scientists to identify interactions among different species of microbes and environmental factors using network analysis. This is important in understanding how bioaerosols behave as dynamic biological systems rather than behaving as individual entities.

10.2 Predictive microbiome modelling

Predictive microbiome modelling involves the use of various computational tools and mathematical models for predicting the behaviour, composition, and dynamics of microbial communities in aerosols. This type of predictive modelling includes various environmental factors such as temperature, humidity, and airflow rate as well as direction. Additionally, predictive microbiome modelling also includes various biological factors such as growth rate and survival mechanisms [43].

Recently, researchers have been applying various machine learning techniques to predict changes in bioaerosol composition under various environmental conditions. For instance, predictive microbiome modelling can predict changes in bioaerosol composition under various conditions such as changes in humidity levels or pollution levels. This type of predictive microbiome modelling can help researchers to predict the spread of airborne diseases or antimicrobial resistance in a specific environment.

There are various limitations to predictive microbiome modelling, such as a lack of standardized data sets and uncertainties regarding environmental parameters. Despite such limitations, predictive microbiome modelling has been improved significantly by recent advancements in data integration techniques.

10.3 Interdisciplinary integration

The study of bioaerosols is an interdisciplinary science that requires the integration of concepts from microbiology, environmental science, engineering, atmospheric physics, and public health. Each of these disciplines provides a unique perspective and set of methodologies that are essential in the understanding of the complex processes that govern the behaviour of bioaerosols. An example is the role that atmospheric physics plays in the understanding of transport and dispersion mechanisms, and the role that microbiology plays in the understanding of the identity and functions of microorganisms in the air.

The role of engineering in the design of control strategies such as ventilation and filtration in the reduction of exposure is also essential. At the same time, the role of public health frameworks in the understanding of the effects of bioaerosols on public health and the design of appropriate policies to mitigate the effects is also essential. The integration of all these disciplines is essential in the design of effective monitoring and intervention strategies.

Interdisciplinary collaboration in the study of bioaerosols and the sharing of data are essential in the integration of knowledge from all disciplines. This combined approach is critical for addressing complex challenges such as airborne disease transmission, environmental contamination, and climate-related impacts of bioaerosols.

11. Conclusions

This study demonstrates that sustainable environmental technologies are not physico-chemical systems, but rather biological interfaces that are governed by the dynamics of microbial communities. The results of this study demonstrates that microbial interactions, which include surface adhesions, biofilm formations, and various metabolic transformations, are of significant importance in governing system efficiencies as well as material longevity. Moreover, the biological interactions in such systems are of significant importance in

governing various dimensions of human exposure, particularly through the formation of bioaerosols.

One of the most significant findings of this study is that microbial interactions, such as colonization, are two-sided. On one hand, microbial consortia are of significant importance in governing various biological transformations, such as biodegradation, which is essential for pollutant removal. On the other hand, such interactions are also responsible for biofouling, biodeterioration, and various forms of microbiologically influenced corrosion, which can significantly reduce system efficiencies and increase operational costs. Moreover, the formation of bioaerosols can directly link such engineered systems to human exposure, which is of significant importance in developing integrated exposure assessment frameworks.

Significant improvements have been observed in analytics, such as culture-based approaches, high-throughput sequencing, and quantitative microbial risk assessment. However, as the study reveals, there is a need for a holistic and interdisciplinary approach that brings together microbiology, engineering, and environmental and public health sciences.

One of the most significant aspects of this study is that it promotes a biological approach to the design and management of environmental technologies. As such, there are strategies that can be used, such as the use of antimicrobial materials, the use of real-time bioaerosol monitoring, and the use of preventive engineering control strategies, such as ventilation optimization and filtration. The inclusion of microbial intelligence in sustainability strategies allows for the creation of technologies that are not only efficient but also safe and long-lasting.

As the field moves forward, there are new approaches that are being developed, such as systems biology and predictive microbiome modelling, as well as data-driven approaches for environmental monitoring. It is, therefore, possible to create a more balanced approach that brings together ecological performance, material integrity, and human health considerations.

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Authors' contributions

All authors contributed equally to the conception, design, experimental work, data analysis, interpretation of results, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript for publication.

Conflicts of interest

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No new data were created.

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