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Beyond Agriculture: Engineered SynComs for Large-Scale Environmental Remediation

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Abstract Environmental pollution poses a serious threat to ecosystems and human health, while traditional remediation methods often have problems such as high cost, low efficiency and possible toxic byproducts. Therefore, the design and application of SynComs using innovative engineering methods provides a sustainable and efficient solution for environmental remediation. This study explores the pollutant degradation mechanism of SynComs based on biological pathways and methods to enhance its efficiency through genetic engineering. Through specific case studies, the application results, successful cases and lessons learned of SynComs are deeply analyzed, and the existing limitations and areas for improvement are pointed out. Technical difficulties, ecological and environmental considerations, economic scalability issues, and regulatory and safety issues are the main challenges that need to be overcome in the current application of SynComs. This paper also looks forward to the emerging trends and technologies of SynComs engineering and explores the potential of integrating SynComs into a wider range of environmental management practices. By exploring and optimizing the application of SynComs, this study hopes to make substantial contributions to solving global environmental pollution problems, restoring ecological balance and promoting sustainable development.

Keywords Environmental remediation; Engineered synComs; Pollutant degradation; Bioremediation; Sustainability

1 Introduction

Environmental pollution is a critical issue that poses significant threats to human health, ecosystems, and biodiversity. It is characterized by the contamination of the physical and biological components of the atmosphere, leading to harmful consequences for normal environmental processes (Baroudi et al., 2020). The rapid industrialization and modernization of agricultural systems have exacerbated the contamination of soil, water, and air, resulting in severe ecological and health impacts (Kumar et al., 2021a; 2021b). Traditional remediation techniques, while effective to some extent, often face challenges related to cost, efficacy, and the generation of toxic byproducts, making them unsustainable in the long term (Sabreena et al., 2022; Xiang et al., 2022). Therefore, there is an urgent need for innovative and sustainable approaches to mitigate environmental pollution and restore ecological balance.

Engineered synthetic communities (SynComs) represent a promising frontier in the field of environmental remediation. SynComs are designed microbial consortia that can be tailored to perform specific functions, such as the degradation of pollutants or the enhancement of soil health. While the application of SynComs has been extensively studied in agriculture, particularly in promoting plant growth and health (Xiang et al., 2022), their potential extends far beyond this domain. SynComs can be engineered to tackle a wide range of environmental pollutants, including heavy metals, organic contaminants, and persistent organic pollutants (POPs) (Ali et al., 2020; Rai and Singh, 2020; Bartlow et al., 2021). By leveraging the synergistic interactions between different microbial species, SynComs can enhance the efficiency and sustainability of bioremediation processes, offering a versatile tool for large-scale environmental remediation.

The primary objective of this systematic review is to explore the potential of engineered SynComs for large-scale environmental remediation, moving beyond their traditional applications in agriculture. This review aims to assess the current state of research on the use of SynComs in environmental remediation, highlighting key findings and advancements, identify the challenges and limitations associated with the deployment of SynComs in diverse environmental contexts and propose strategies and future directions for enhancing the efficacy and scalability of SynCom-based remediation technologies.

By synthesizing insights from multiple studies, this paper aims to provide a roadmap for future research and development in the field of SynCom-based environmental remediation, ultimately contributing to the sustainable management of polluted environments.

2 Engineered SynComs: An Overview

2.1 Definition and characteristics of engineered SynComs

Engineered Synthetic Microbial Communities (SynComs) are meticulously designed consortia of microorganisms that are assembled to perform specific functions within an ecosystem. These communities are constructed using a combination of microbial species selected for their complementary traits and interactions, which can be tailored to achieve desired outcomes in various environmental contexts (Souza et al., 2020; Marín et al., 2021; Martins et al., 2023). SynComs are characterized by their defined composition, stability, and the ability to be manipulated to enhance their functional capabilities (Pradhan et al., 2022; Leeuwen et al., 2023).

2.2 Methods for engineering SynComs

The engineering of SynComs involves several advanced methodologies, including synthetic biology and genetic modification. Synthetic biology allows for the design and construction of new biological parts, devices, and systems, or the re-design of existing, natural biological systems for useful purposes (Souza et al., 2020; Zhang et al., 2021). Genetic modification techniques are employed to enhance specific traits of microbial strains, such as their ability to degrade pollutants or resist environmental stressors (Sai et al., 2022; Martins et al., 2023). Additionally, computational methods, including machine learning and artificial intelligence, are increasingly used to predict and optimize the interactions within SynComs, ensuring their stability and functionality (Souza et al., 2020; Leeuwen et al., 2023).

2.3 Advantages of using engineered syncoms over traditional remediation methods

Engineered SynComs offer several advantages over traditional environmental remediation methods. Firstly, they provide a more sustainable and eco-friendly approach by leveraging natural microbial processes to degrade pollutants and restore ecosystems (Pradhan et al., 2022; Sai et al., 2022). Unlike chemical treatments, SynComs can be designed to target specific contaminants without causing harm to the surrounding environment. Secondly, SynComs can be tailored to function under diverse environmental conditions, making them versatile tools for remediation in various settings (Coker et al., 2022; Martins et al., 2023). Furthermore, the use of SynComs can enhance the efficiency and effectiveness of bioremediation efforts by ensuring the presence of microbial species that work synergistically to break down complex pollutants (Marín et al., 2021; Armanhi et al., 2021). Lastly, the ability to engineer and control SynComs allows for the development of reproducible and scalable remediation strategies, which are crucial for large-scale environmental applications (Leeuwen et al., 2023; Arnault et al., 2023).

3 Environmental Remediation: Challenges and Opportunities

3.1 Environmental pollutants and impact

Environmental pollution is a pervasive issue affecting various ecosystems globally. The contamination of soil, water, and air with organic pollutants, heavy metals, and other toxic substances poses significant threats to both human health and biodiversity. For instance, the contamination of soil with organic pollutants due to agricultural and industrial activities has accelerated, posing a major threat to global ecosystems and human health (Xiang et al., 2022). Similarly, the increasing contamination of freshwater systems with industrial and natural chemical compounds, even at low concentrations, raises considerable toxicological concerns, particularly when these compounds are part of complex mixtures (Schwarzenbach et al., 2006). The complexity of environmental pollution is further highlighted in regions like Africa, where artisanal activities and technical failures at exploration sites have led to significant ecological impacts (Odoh et al., 2019).

3.2 Remediation techniques and limitations

Various remediation techniques have been developed to address environmental pollution, including chemical, physical, and biological methods. However, each of these techniques has its limitations. Chemical and physical remediation methods often face challenges related to cost, efficacy, and the production of toxic byproducts, which limit their sustainability (Xiang et al., 2022). In-situ remediation techniques, although preferred for their minimal site disturbance and cost-effectiveness, often struggle with the heterogeneous distribution of contaminants in the subsurface, which can significantly impede their effectiveness (Reddy, 2010). Traditional bioremediation approaches, while environmentally friendly, also have limitations, such as the need for specific microbial interactions and the challenges posed by high concentrations of secondary toxins and nutrient limitations (Mishra et al., 2020). Moreover, the complexity of pollutant composition often necessitates the use of combined remediation techniques to achieve efficient and economical environmental remediation (Ugrina and Jurić, 2023).

3.3 SynComs in addressing challenges

Engineered Synthetic Communities (SynComs) offer a promising solution to the challenges faced by traditional remediation techniques. SynComs can be designed to enhance the efficiency of bioremediation by leveraging the synergistic interactions between different microbial species. For example, the integration of biochar, plant growth-promoting bacteria (PGPB), and plants has shown potential in overcoming several barriers to the remediation of organic pollutants in soil, such as the lack of suitable sinks for toxins and nutrient limitations (Xiang et al., 2022). Additionally, advancements in microbial electrochemical technologies have been identified as effective approaches for the remediation of pollutants, providing environmentally sound strategies (Mishra et al., 2020). Myco-remediation, which utilizes fungi for the degradation and removal of pollutants, also presents a green and economical alternative to conventional remediation technologies, with the potential to address a wide range of contaminants, including heavy metals and persistent organic pollutants (Akhtar and Mannan, 2020; Kumar et al., 2021a). The application of SynComs in environmental remediation thus represents a significant opportunity to enhance the sustainability and effectiveness of remediation efforts, addressing the limitations of existing techniques and contributing to the protection of global ecosystems.

4 Mechanisms of SynCom-Based Remediation

4.1 Biological pathways utilized by SynComs for degradation of pollutants

SynComs employ a variety of biological pathways to degrade pollutants, including enzymatic degradation, microbial metabolism, and electrochemical processes. Microbial enzymes such as hydrolases, oxidoreductases, dehalogenases, oxygenases, and transferases play a crucial role in breaking down toxic pollutants into non-toxic forms (Saravanan et al., 2021). For instance, the bio-electrokinetic (BIO-EK) remediation process combines microbial metabolism and electrochemical oxidation to degrade pyrene and its intermediate products more efficiently than traditional bioremediation methods (Fan et al, 2021). Additionally, the Fe_2^+/O_2/Tripolyphosphate system demonstrates how reactive oxygen species (ROS) can be regulated to degrade pollutants like p-nitrophenol through oxidation and reduction pathways (Zhang et al., 2022).

4.2 Genetic engineering approaches to enhance SynCom efficiency

Genetic engineering techniques have been developed to enhance the efficiency of SynComs in pollutant degradation. These techniques include the immobilization of enzymes and the modification of microbial strains to increase their degradation capabilities. For example, the construction of a novel AgI/BiSbO4 heterojunction enhances the generation of hydroxyl and superoxide radicals, thereby boosting the degradation of organic pollutants under visible light (Zhao et al., 2022). Similarly, the development of enzyme-releasing self-propelled motors demonstrates how the Marangoni effect can be utilized to disperse enzymes rapidly into contaminated solutions, significantly improving the biocatalytic degradation of pollutants (Orozco et al., 2014). Furthermore, microbial engineering techniques have been employed to create proficient microorganisms capable of degrading synthetic pollutants through combined and co-metabolic activities (Bhatt et al., 2020).

4.3 Case studies of SynComs engineered for specific pollutants

Several case studies highlight the successful application of engineered SynComs for the degradation of specific pollutants. For instance, the synchronous regulation of γ-hexachlorocyclohexane (γ-HCH) reduction and methane production in a microbial electrolysis cell demonstrates how bioelectrostimulation can promote redox reactions and construct mature biofilms for efficient pollutant removal (Cheng et al., 2021). Microbial electrolysis cell technology is used to treat a specific persistent organochlorine pesticide—γ-hexachlorocyclohexane (γ-HCH). Through bioelectrostimulation, which uses electric current as an external energy source, specific microbial communities are activated, promoting the reduction of γ-HCH and the production of methane. This synchronized regulation not only enhances treatment efficiency but also utilizes the generated methane as an energy source, achieving dual goals of pollution control and energy recovery. Mature biofilms play a crucial role in this process, providing a stable environment for microbes and enhancing the system's overall degradation capacity and stability. The application of this technology may face challenges in microbial selection and biofilm management, but its suitability and efficiency in complex environments demonstrate broad application prospects.

Another study on the co-degradation of methylparaben and amlodipine in enzyme-mediator systems illustrates how synthetic redox mediators can extend the types of enzyme-catalyzed substrates, providing an efficient method for the degradation of co-existing pollutants (Gong et al., 2021). By designing specific media, this system not only enhances the efficiency of enzymes in acting on various pollutants but also demonstrates potential in treating environments contaminated with complex pharmaceutical residues. This study highlights the need to consider chemical compatibility and the optimization of biodegradation pathways in the design of synthetic media, thereby ensuring efficient and environmentally friendly pollutant treatment. This method is particularly valuable in pharmaceutical wastewater treatment and environmental remediation, with potential challenges including enzyme stability and cost-effectiveness.

Additionally, the construction of iodine vacancy-rich BiOI/Ag@AgI Z-scheme heterojunction photocatalysts shows enhanced photocatalytic efficiency for the degradation of tetracycline, a refractory antibiotic, under visible light irradiation (Yang et al., 2018).The design of this photocatalyst fully utilizes the efficient charge separation capabilities and broad light absorption range provided by its heterostructure, enabling efficient photocatalytic processes even under ambient light conditions. This technology demonstrates that through material engineering, the activity and stability of photocatalysts can be optimized, offering a promising solution for treating recalcitrant organic pollutants. However, the large-scale application of photocatalysts may require further process optimization and cost evaluation.

In conclusion, the integration of biological pathways, genetic engineering approaches, and specific case studies demonstrates the potential of engineered SynComs for large-scale environmental remediation. These advancements highlight the importance of continued research and development in this field to address the growing challenges of environmental pollution.

5 Field Applications and Performance Evaluation

5.1 Field application methodologies

Field application of synthetic microbial communities (SynComs) for environmental remediation involves several methodologies to ensure effective deployment and optimal performance. Site Assessment and Preparation: Initial assessment of the contaminated site is crucial. This involves sampling and analyzing soil, water, and air to determine the types and concentrations of pollutants present (Wang et al., 2021). Site preparation may include adjusting pH, moisture levels, and nutrient content to create favorable conditions for microbial activity (Chen et al., 2020). Designing SynComs tailored to the specific contaminants and environmental conditions of the site is essential. This involves selecting microbial strains with complementary metabolic capabilities to degrade a wide range of pollutants (Liang et al., 2022). Techniques such as metabolic modeling and high-throughput screening can aid in identifying optimal microbial combinations (Kehe et al., 2019).

Methods for introducing SynComs to contaminated sites include soil injection, surface application, and mixing with soil amendments (Brune and Bayer, 2012). For groundwater contamination, permeable reactive barriers (PRBs) can be used to deliver SynComs directly into the aquifer (Wang et al., 2021). Continuous monitoring of microbial activity and pollutant degradation is necessary to evaluate the effectiveness of the SynComs. Parameters such as microbial population dynamics, pollutant concentrations, and environmental factors (e.g., pH, temperature) should be regularly measured. Maintenance may involve periodic re-inoculation and nutrient supplementation to sustain microbial activity (Kim et al., 2011).

5.2 Key field trials and large-scale applications

Several field trials and large-scale applications have demonstrated the effectiveness of SynComs in environmental remediation. Permeable Reactive Barriers (PRBs) utilizing systems containing zero-valent iron (ZVI) have significantly reduced hexavalent chromium (Cr(VI)) contamination in groundwater in a large-scale study (Figure 1). The key to this technology lies in the reductive action of zero-valent iron, which transforms toxic hexavalent chromium into the less toxic trivalent chromium. During this process, significant changes occurred in the native microbial communities, reflecting not only their adaptation to the new environment but also their active role in the pollutant transformation process. This successful on-site application highlights the practical value and environmental adaptability of PRBs in the treatment of persistent organic pollutants (Wang et al., 2021).

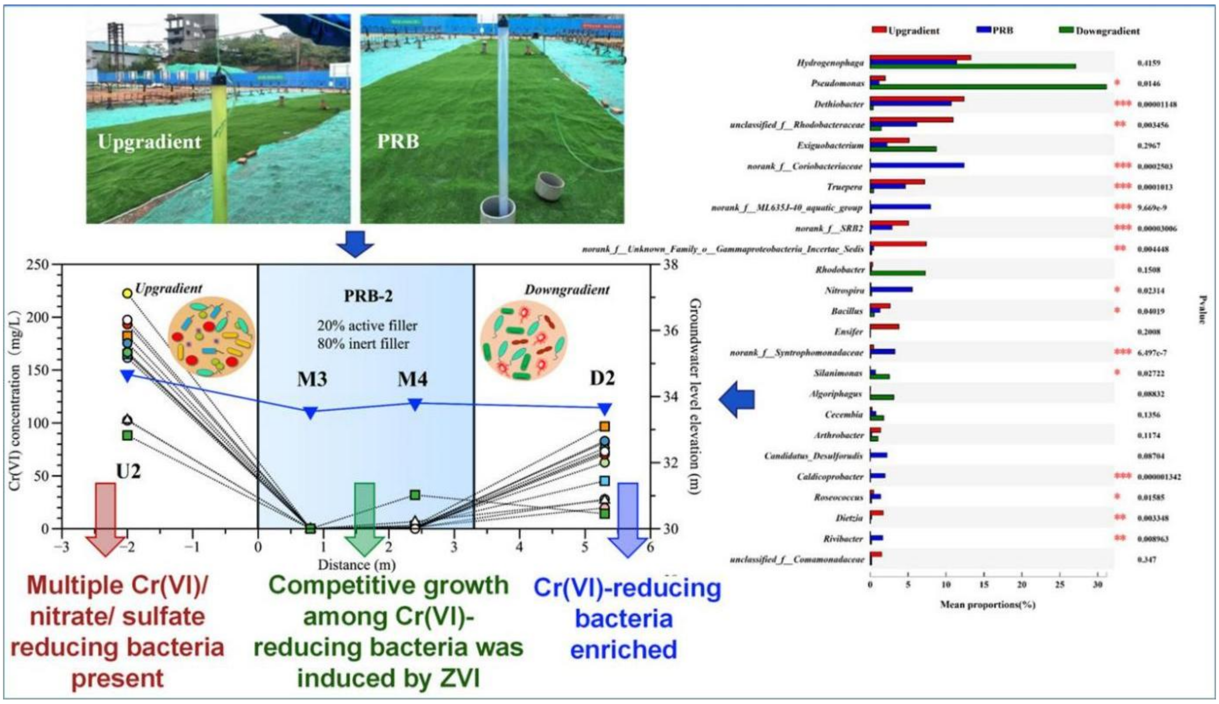

Figure 1 In situ remediation of Cr(VI) contaminated groundwater by ZVI-PRB and the corresponding indigenous microbial community responses (Adopted from Wang et al., 2021)

Image caption: The PRB segment with 20% active reaction medium (ZVI) was able to successfully reduce Cr(VI) via chemical reduction from 27.29-242.65 mg/L to below the clean-up goal of 0.1 mg/L, and can be scaled-up under field conditions. The ZVI induced significant changes in the indigenous microbial community structure and compositions in the area of the PRB and those areas downgradient. The competitive growth among Cr(VI)-reducing bacteria (the reduced abundance of *Hydrogenophaga*, Pseudomonas, *Exiguobacterium* and *Rhodobacter*, along with the enrichment of *Rivibacter* and *Candidatus_Desulforudis*) were observed in PRB (Adopted from Wang et al., 2021).

At an abandoned oil shale chemical site in Estonia, a long-term field experiment combining bioaugmentation and phytoremediation techniques demonstrated the effectiveness of this integrated approach. Specifically introduced Pseudomonas strains were not only able to stably exist in the contaminated soil but also continued to degrade phenolic compounds over several years. The success of this strategy highlights the efficacy of using specific microbes for targeted pollutant degradation and also showcases the feasibility and durability of bioremediation techniques in treating industrial waste sites (Juhanson et al., 2009).

In a small-scale passive treatment system at an abandoned coal mine, SynComs enriched with iron-oxidizing and iron-reducing bacteria significantly removed soluble iron from AMD and improved water quality. This system not only highlighted the crucial role of microbes in heavy metal removal but also demonstrated the importance of environmental factors such as pH and redox potential in influencing the structure and function of microbial communities. Furthermore, this study provides valuable insights into how to optimize microbial consortia to enhance remediation effectiveness (Chen et al., 2020).

A spatially structured SynCom, including chlorophenol-degrading Pseudomonas and Ralstonia metal-resistant strains, was successfully used to degrade PCP and reduce the concentration of mercury (II) at a contaminated site. This structured microbial consortium not only protected sensitive microbial populations but also significantly enhanced the overall pollutant removal effectiveness. This indicates that considering spatial structuring in the design of microbial treatment systems can effectively improve the survival and activity of specific sensitive microbes, thereby enhancing the restoration capabilities of the entire system (Kim et al., 2011).

5.3 Evaluating the performance of SynComs in remediation efforts

Evaluating the performance of synthetic microbial communities (SynComs) in environmental remediation involves multiple key indicators and methods. First and foremost, pollutant degradation efficiency is a major evaluation metric, primarily measured using chemical analysis techniques such as gas chromatography-mass spectrometry (GC-MS) and high-performance liquid chromatography (HPLC) to monitor the reduction in pollutant concentrations (Tran et al., 2021).

Additionally, monitoring the activity and viability of the microbes is crucial, utilizing methods like quantitative PCR (qPCR), next-generation sequencing (NGS), and community-level physiological profiles (CLPP) to gain deep insights into the dynamics and viability of SynComs (Liang et al., 2022).

The assessment of environmental impact is equally important, including monitoring changes in soil and water quality, such as pH levels, nutrient content, and redox potential, to determine the broad environmental effects of SynCom applications. Bioindicators and ecological assessments are also used to evaluate the health of ecosystems. Furthermore, assessing the long-term stability and adaptability of SynComs is essential, which involves tracking their persistence and functional capabilities over time, as well as their ability to adapt to environmental fluctuations and maintain pollutant degradation efficiency (Juhanson et al., 2009).

Analyzing the cost-effectiveness of SynCom applications compared to traditional remediation methods is critical, especially when considering large-scale implementation. This involves calculating the costs associated with microbial production, inoculation, monitoring, and maintenance. Engineered SynComs have demonstrated high efficiency in pollutant degradation and adaptability to various conditions in environmental remediation. Ongoing evaluation and optimization of these microbial communities are crucial to maximize their potential and achieve sustainable environmental restoration (Eng and Borenstein, 2019).

6 Case Studies

6.1 Detailed analysis of specific field trials and outcomes

Field trials have been instrumental in validating the effectiveness of various engineered SynComs (Synthetic Communities) for environmental remediation. One notable study involved the remediation of subsurface systems contaminated with light non-aqueous phase liquids (LNAPLs). This study employed a multi-phase remediation approach, including LNAPL skimming and vacuum-enhanced skimming, over a 78-day period. The trials successfully extracted over 5 m^3 of LNAPL, and the results were validated using a multi-component simulation framework. This framework accurately predicted LNAPL mass removal rates and compositional changes, demonstrating its potential for long-term remediation planning (Figure 2) (Lari et al., 2018).

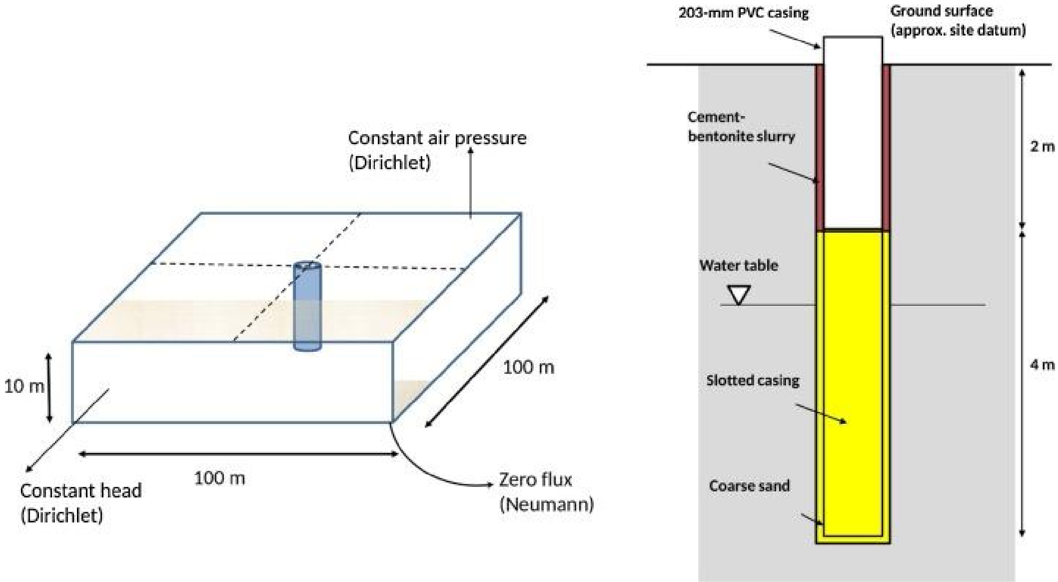

Figure 2 Location of multi-phase recovery well (Adopted from Lari et al., 2018)

Image caption: Left: The simulation domain and the boundary conditions; Right: The recovery well (at the site) configuration (Adopted from Lari et al., 2018)

The setup shown in the diagram is typical for environmental engineering and hydrogeological studies, where monitoring and recovery of pollutants such as Light Non-Aqueous Phase Liquids (LNAPL) are required. The site's hydrogeology—primarily consisting of sand, with some discontinuities and partially cemented areas—presents specific challenges for pollutant recovery. The high permeability of the sand generally facilitates the movement of contaminants, making it crucial to precisely locate recovery wells like the one depicted in the diagram.

Another significant field trial involved the use of bilayer tubular micromotors for simultaneous environmental monitoring and remediation. These micromotors, composed of mesoporous silica-coated titania (TiO_2@$mSiO_2$) with platinum and magnetic Fe_3O_4 nanoparticles, showed a remarkable ability to adsorb and degrade pollutants (Figure 3). The micromotors achieved up to 98% degradation of the model pollutant rhodamine 6G within 30 minutes, highlighting their efficiency and potential for large-scale environmental applications (Liang et al., 2018).

Integrating advanced materials such as TiO_2, $mSiO_2$, platinum, and Fe_3O_4 nanoparticles into a single micromotor, combined with precise magnetic field control, marks a significant technological advancement in the field of environmental science. As demonstrated by this study, this technology can effectively and rapidly adsorb and degrade pollutants, opening new frontiers for environmental remediation, especially in areas where traditional methods are ineffective or too cumbersome. The visual evidence from these setups not only shows the functional efficiency of the micromotors but also illustrates the practical aspects of operating such systems under real-world conditions.

6.2 Success stories and lessons learned

The success of these field trials underscores the potential of engineered SynComs in environmental remediation. The LNAPL remediation study demonstrated that a well-validated computational framework could significantly enhance the predictability and efficiency of remediation efforts. The ability to simulate various remediation techniques and predict their outcomes allows for better planning and optimization of field operations (Lari et al., 2018).

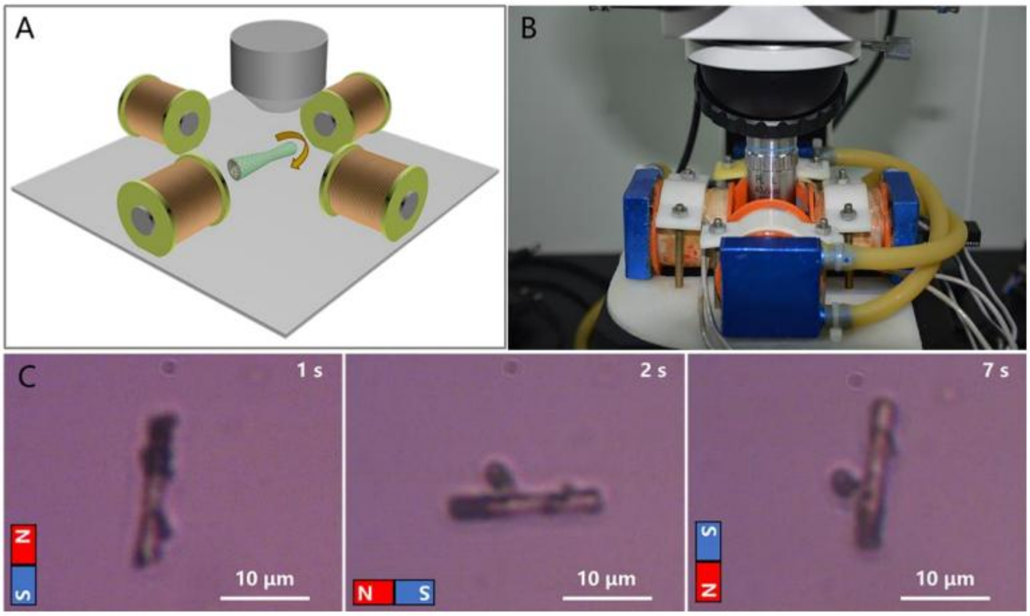

Figure 3 Use of bilayer tubular micromotors for simultaneous environmental monitoring and remediation (Adopted from Liang et al., 2018)

Image caption: (A) Schematic illustrating the rotation of TiO_2@mSiO_2 bilayer tubular motor under uniform magnetic field, (B) Picture of magnetic control platform; (C)Optical image of the TiO_2@mSiO_2 bilayer tubular motor rotated under the uniform magnetic field (Adopted from Liang et al., 2018)

The bilayer tubular micromotors study showcased the dual functionality of these devices in both monitoring and remediation. The high adsorption capacity and rapid degradation rates of the micromotors illustrate their effectiveness in addressing complex environmental pollutants. This success story highlights the importance of integrating multiple functionalities into a single remediation tool to achieve comprehensive environmental governance (Liang et al., 2018).

6.3 Limitations and areas for improvement

Despite the promising outcomes, there are several limitations and areas for improvement in the application of engineered SynComs for environmental remediation. The LNAPL remediation study, while successful, relied heavily on advanced computational resources, such as a Cray supercomputer and a cluster, which may not be readily available in all remediation scenarios. Additionally, the study focused on a specific type of contaminant, and further research is needed to assess the framework's applicability to other pollutants (Lari et al., 2018).

The bilayer tubular micromotors, although highly effective, face challenges related to scalability and practical deployment in diverse environmental settings. The recovery and reuse of micromotors, as well as their long-term stability and potential ecological impacts, require further investigation. Moreover, the integration of these micromotors into existing environmental monitoring and remediation systems needs to be streamlined to facilitate widespread adoption (Liang et al., 2018).

In conclusion, while engineered SynComs have shown great promise in field trials, ongoing research and development are essential to address their limitations and enhance their applicability for large-scale environmental remediation. Future studies should focus on improving the efficiency, scalability, and ecological safety of these innovative technologies.

7 Challenges and Limitations

7.1 Technical challenges in engineering and deploying SynComs for environmental remediation

Engineering and deploying synthetic microbial communities (SynComs) for environmental remediation face several technical challenges. One significant issue is ensuring the stability and functionality of these communities in diverse and often harsh environmental conditions. For instance, microbial biofilm formation and the production of secondary metabolites are critical for the success of SynComs, but these processes can be inconsistent and difficult to control in natural settings (Martins et al., 2023). Additionally, the horizontal gene transfer and retained mutations within the SynComs can lead to changes in microbial composition over time, potentially reducing their effectiveness (Martins et al., 2023). Another technical challenge is the development of cost-effective and low-maintenance systems for deploying these communities. For example, textile-based cyanobacteria biocomposites have shown promise, but their scalability and long-term viability remain uncertain (Hart et al., 2021).

7.2 Ecological and environmental considerations

The ecological and environmental impacts of deploying SynComs must be carefully considered. One major concern is the potential for genetically engineered microorganisms (GEMs) to exchange genetic material with native microbial populations, which could lead to unintended ecological consequences (Liu et al., 2019). Additionally, the introduction of SynComs into natural environments may disrupt existing microbial communities and ecological balances, potentially causing harm to local ecosystems (Pradhan et al., 2022). The risk of ecological disruption is particularly high when dealing with multi-functional genetic engineering microorganisms (MFGEMs) designed to tackle complex contaminants, as their interactions with native species are not fully understood (Wu et al., 2021). Therefore, a thorough ecological risk assessment is essential before deploying SynComs for environmental remediation.

7.3 Economic and scalability issues

Economic and scalability issues are significant barriers to the widespread adoption of SynComs for environmental remediation. The cost of developing and maintaining these engineered microbial communities can be prohibitively high, particularly when compared to traditional physicochemical remediation methods (Liu et al., 2019). Moreover, scaling up laboratory successes to field applications presents numerous challenges, including the need for large-scale production facilities and the logistics of deploying SynComs in diverse environmental settings (Hart et al., 2021). The economic feasibility of SynComs is further complicated by the need for ongoing monitoring and maintenance to ensure their effectiveness and stability over time (Martins et al., 2023). Addressing these economic and scalability issues is crucial for the practical implementation of SynComs in large-scale environmental remediation projects.

7.4 Regulatory and safety concerns

Regulatory and safety concerns are paramount when considering the deployment of SynComs for environmental remediation. The use of GEMs raises significant regulatory challenges, as these organisms must be carefully controlled to prevent unintended release and potential ecological harm (Wu et al., 2021). Regulatory frameworks must be established to oversee the development, testing, and deployment of SynComs, ensuring that they meet safety standards and do not pose risks to human health or the environment (Liu et al., 2019). Additionally, public perception and acceptance of GEMs and SynComs can influence regulatory decisions, necessitating transparent communication and engagement with stakeholders (Wu et al., 2021). Ensuring the safety and regulatory compliance of SynComs is essential for their successful and responsible use in environmental remediation.

8 Future Directions and Perspectives

8.1 Emerging trends and technologies in SynCom engineering

The field of synthetic microbial communities (SynComs) is rapidly evolving, driven by advancements in biotechnology and computational methods. One emerging trend is the integration of machine learning and artificial intelligence to design and optimize SynComs for specific environmental applications. These technologies enable the identification of microbial traits that contribute to desired phenotypes, such as enhanced plant health or pollutant degradation (Souza et al., 2020; Martins et al., 2023). Additionally, the use of omics approaches, including genomics, proteomics, and metabolomics, is becoming increasingly prevalent. These methods provide comprehensive insights into microbial interactions and functions, facilitating the creation of more effective and stable SynComs (Souza et al., 2020; Pradhan et al., 2022).

Another significant trend is the development of genetically engineered bacteria with enhanced capabilities for environmental remediation. These engineered microbes can degrade a wide range of pollutants, including synthetic dyes, heavy metals, and petroleum hydrocarbons, offering a more viable and eco-friendly alternative to traditional physicochemical methods (Liu et al., 2019). Furthermore, advancements in synthetic biology and protein engineering are paving the way for the creation of novel biocatalytic and biosorptive materials, which can be used to degrade persistent organic contaminants and recover valuable metals from waste streams (Zhu et al., 2019).

8.2 Integration of SynComs into broader environmental management practices

The integration of SynComs into broader environmental management practices requires a multidisciplinary approach that combines microbiology, ecology, and engineering. One promising strategy is the use of SynComs for rhizosphere engineering to enhance plant resilience against biotic stresses. By manipulating the soil microbiome, it is possible to improve plant health and productivity in a sustainable manner (Pradhan et al., 2022). This approach not only benefits agriculture but also contributes to environmental sustainability by reducing the need for chemical inputs.

Moreover, the concept of Integrated Environmental Modeling (IEM) offers a holistic framework for incorporating SynComs into environmental management. IEM leverages modern technologies, such as cloud computing, the Internet of Things, and big data analytics, to create comprehensive models that predict the behavior of environmental systems under various stressors. This approach facilitates the development of cross-domain applications that can address complex environmental challenges, such as pollution and climate change (Laniak et al., 2013; Granell et al., 2016).

8.3 Potential breakthroughs and long-term vision for SynComs in large-scale environmental remediation

The long-term vision for SynComs in large-scale environmental remediation involves several potential breakthroughs. One key area is the development of stable and resilient SynComs that can maintain their functionality under diverse environmental conditions. This requires a deep understanding of microbial ecology and the factors that influence community stability, such as horizontal gene transfer and microbial interactions (Souza et al., 2020; Martins et al., 2023). Advances in computational methods and high-throughput screening techniques will play a crucial role in achieving this goal.

Another potential breakthrough is the creation of SynComs that can address emerging environmental contaminants, such as pharmaceuticals, nanomaterials, and flame retardants. These contaminants pose significant challenges due to their persistence and toxicity, but engineered SynComs with tailored degradation pathways could offer effective solutions (Richardson and Kimura, 2017). Additionally, the integration of SynComs with other environmental technologies, such as biocatalytic and biosorptive materials, could enhance their efficacy and broaden their application scope (Zhu et al., 2019).

In conclusion, the future of SynComs in environmental remediation is promising, with numerous emerging trends and technologies driving innovation. By integrating SynComs into broader environmental management practices and pursuing potential breakthroughs, it is possible to achieve a sustainable and resilient approach to addressing environmental challenges.

9 Concluding Remarks

The integration of engineered synthetic microbial communities (SynComs) into large-scale environmental remediation presents a promising frontier beyond traditional agricultural applications. The potential of SynComs to enhance nutrient acquisition, mitigate drought, and resist pathogens in crops underscores their broader applicability in environmental sustainability. However, the transition from agricultural to environmental applications necessitates a comprehensive understanding of SynCom interactions with diverse ecosystems and the development of robust frameworks to ensure their efficacy and safety.

SynComs have been identified as crucial for reducing dependency on chemical fertilizers, improving crop resilience, and enhancing growth on marginal soils. Engineered nanomaterials (ENMs) offer sustainable alternatives in agriculture, such as soil amendments, seed coatings, and foliar sprays, which can be adapted for environmental remediation. The holistic, systems-based approach in utilizing ENMs highlights the importance of considering the entire lifecycle and environmental impact, which is equally relevant for SynCom applications in environmental contexts. The development of ecology-based inoculants through SynComs can significantly augment nutrient acquisition and pathogen resistance, ensuring sustainability in various environmental settings.

The findings suggest that engineered SynComs can be pivotal in addressing large-scale environmental challenges. By leveraging the principles of sustainable agriculture, such as reducing chemical inputs and enhancing resilience, SynComs can be tailored for environmental remediation. This approach not only promotes ecological balance but also offers a scalable solution to mitigate environmental degradation. The successful application of SynComs in agriculture provides a blueprint for their deployment in broader environmental contexts, potentially transforming practices in waste management, soil restoration, and pollution control.

To fully realize the potential of SynComs in environmental remediation, further research is essential in the following areas:

Ecosystem Interactions: Investigate the interactions between SynComs and various ecosystems to understand their impact and optimize their functionality in different environmental conditions.

Safety and Efficacy: Develop robust frameworks to assess the safety and efficacy of SynComs in large-scale applications, ensuring they do not disrupt existing ecological balances.

Interdisciplinary Collaboration: Foster collaboration between microbiologists, ecologists, environmental scientists, and policymakers to create integrated strategies for SynCom deployment.

Field Trials and Case Studies: Conduct extensive field trials and document case studies to gather empirical data on the performance of SynComs in real-world environmental remediation scenarios.

By addressing these research areas, the scientific community can advance the development and application of SynComs, paving the way for innovative solutions to global environmental challenges.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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