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Synthetic Microbial Consortia for Bioremediation and Circular Bioeconomy: A Review

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ABSTRACT

The integration of synthetic microbial consortia (SMC) into bioremediation and the circular bioeconomy has emerged as a transformative approach to mitigate environmental pollution while promoting sustainable resource recovery. This review explores recent developments (2023–2025) in the design, engineering, and application of synthetic microbial consortia for bioremediation of pollutants including heavy metals, hydrocarbons, and plastics. We also delve into the role of SMC in facilitating circular bioeconomic processes such as nutrient cycling, bioenergy production, and valorisation of waste into high-value products. Key strategies for designing stable and functional consortia, including genome editing tools, quorum sensing manipulation, and computational modelling, are critically examined. Finally, the challenges, risks, and future directions for deploying SMC in real-world applications are discussed, emphasizing regulatory, ecological, and scalability considerations.

Introduction

Synthetic microbial consortia (SMC) embody a novel and dynamic strategy in microbial biotechnology, marking a significant departure from traditional monoculture-based approaches to environmental remediation.

Unlike monocultures, which rely on a single microbial species, SMC are composed of multiple, deliberately assembled microbial strains, each contributing unique enzymatic capabilities and metabolic functions. This multiplicity allows SMC to exhibit enhanced functional redundancy, metabolic versatility, and ecological resilience, making them well-suited for addressing the complexity of environmental pollutants and the multifaceted challenges of sustainable waste management (Liu *et al.,* 2023).

The rationale behind SMC lies in the principle of synergistic collaboration, where microbial partners engage in cross-feeding, syntrophic interactions, and division of labor to efficiently degrade pollutants or convert waste into value-added products. Such cooperative networks can be tailored to specific environmental or industrial contexts, thereby improving both degradation efficiency and process robustness (Kumar *et al.,* 2023).

Their significance becomes even more apparent in the context of the circular bioeconomy, an economic model focused on resource conservation, waste minimization, and closed-loop material flows. The circular bioeconomy aims to transition from a linear "take-make-dispose" model to one where biological resource are reused and regenerated.

Here, SMC act as biological engines that not only detoxify pollutants but also recycle carbon, nitrogen, phosphorus, and other nutrients into bio-based materials, fuels, and bioplastics. This dual capability—bioremediation coupled with biotransformation places SMC at the intersection of ecological health and industrial innovation (Rana *et al.,* 2025).

The global shift towards sustainability, driven by climate change mitigation, resource scarcity, and regulatory pressure, has further accelerated interest in microbial platforms that can operate under diverse environmental conditions and integrate into existing waste streams. These synthetic consortia offer an advantage over naturally occurring microbial communities by providing controlled, reproducible, and modular systems that can be fine-tuned for specific environmental applications.

This has led to a surge in research focusing on the construction, optimization, and deployment of synthetic consortia tailored for tasks such as plastic degradation, heavy metal detoxification, and bioenergy generation (Nguyen *et al.,* 2024).

This review aims to provide a comprehensive synthesis of the recent progress made between 2023 and 2025 in the field of synthetic microbial consortia. It explores the scientific foundations underpinning SMC design, including functional genomics, metabolic pathway integration, and the role of interspecies communication.

The biotechnological tools employed such as CRISPR-based genome editing, quorum sensing systems, and AI-assisted modelling are discussed with a focus on their applications in constructing robust and efficient microbial systems. Real-world applications in bioremediation and circular bioeconomy are examined through recent case studies and pilot-scale implementations. Furthermore, the review critically assesses the ecological, economic, and regulatory hurdles that must be overcome for widespread adoption, while also highlighting future opportunities and emerging trends in this rapidly evolving field.

Design and Engineering of Synthetic Microbial Consortia

Synthetic microbial consortia are constructed by intentionally combining microbial species with complementary metabolic functions. The foundation of designing an effective consortium lies in understanding metabolic interactions, division of labour, and communication mechanisms like quorum sensing. Modular metabolic engineering enables the division of a complex task among specialized strains, improving efficiency and reducing metabolic burden on individual members (Kumar *et al.,* 2023).

Recent advances have made it possible to engineer these consortia with precision using CRISPR/Cas systems, synthetic promoters, and biosensors. Computational modelling platforms like BioDesign Suite are facilitating predictive simulations of microbial interactions, thereby accelerating the design-to-deployment pipeline (Nguyen *et al.,* 2024).

Applications in Bioremediation

In the domain of bioremediation, SMC are revolutionizing pollutant degradation by enabling metabolic cooperation among diverse microbial species. In heavy metal detoxification, consortia employ mechanisms such as biosorption and bioaccumulation, facilitated by exopolysaccharide (EPS) production and redox-active proteins (Chen *et al.,* 2023).

For organic pollutants like hydrocarbons, engineered consortia can degrade both aliphatic and aromatic compounds through coordinated catabolic pathways. For instance, *Pseudomonas putida* and *Acinetobacter baylyi* exhibit synergistic degradation of polycyclic aromatic hydrocarbons (PAHs) (Zhang *et al.,* 2024). Synthetic microbial consortia have also demonstrated promising results in breaking down complex pollutants such as pharmaceuticals and plastics. Thermophilic co-cultures combining *Ideonella sakaiensis* and *Bacillus coagulans* have been effective in degrading polyethylene terephthalate (PET), offering a sustainable alternative to chemical recycling (Patel *et al.,* 2024).

Integration in Circular Bioeconomy

The circular bioeconomy emphasizes resource efficiency and sustainable material cycles. Synthetic microbial consortia play a pivotal role by transforming waste streams into value-added products. For instance, co-cultures of *Escherichia coli* and *Cupriavidus necator* have been employed to convert lignocellulosic biomass into polyhydroxyalkanoates (PHAs), a class of biodegradable plastics (Rana *et al.,* 2025).

In bioenergy sectors, SMC enhance the anaerobic digestion process by enabling syntrophic interactions that improve the yield of hydrogen and methane. Pilot-scale setups using *Clostridium butyricum* and methanogens have achieved remarkable efficiency in simultaneous H2 and CH4 production (Ali *et al.,* 2023).

These consortia are also being used for nutrient recovery from wastewater. For example, *Bacillus megaterium* and *Microthrix parvicella* have been shown to recover phosphate in the form of struvite, a slow-release fertilizer (Desai *et al.,* 2024).

Challenges and Future Perspectives

While synthetic microbial consortia offer immense potential, their widespread application is hindered by several challenges. Ecological safety remains a concern due to the potential for horizontal gene transfer and persistence of engineered strains in natural environments.

Regulatory barriers also impede field-scale deployment, as there is a lack of harmonized international protocols for evaluating and approving the release of synthetic consortia (OECD, 2025).

Economic scalability is another critical factor. Although promising results have been achieved at the laboratory scale, transitioning to industrial applications requires cost-effective feedstocks, modular reactor designs, and efficient downstream processing (Rana *et al.,* 2025).

Emerging technologies such as artificial intelligence and digital twins are being explored to optimize SMC configurations. Tools like AI-assisted metabolic modelling and in situ biosensors may help in stabilizing consortia and enhancing process yields (Singh *et al.,* 2025).

Synthetic microbial consortia represent a powerful frontier in environmental biotechnology, offering robust and adaptive solutions for tackling some of the most persistent environmental challenges.

Their capacity to combine complementary metabolic activities across multiple species makes them uniquely suited for degrading complex pollutants and valorising waste materials, aligning closely with the goals of bioremediation and the circular bioeconomy. From 2023 to 2025, the field has witnessed substantial advancements in microbial consortia design, including modular genetic engineering, synthetic ecology frameworks, and the incorporation of computational and AI-based tools for pathway prediction and dynamic modelling.

These developments have not only enhanced the functional efficiency of SMC but have also facilitated their application in increasingly diverse and extreme environmental contexts. Yet, despite their growing promise, translating laboratory-scale success into real-world deployment remains a significant challenge.

Biosafety concerns, ecological uncertainties, and the need for standardized regulatory frameworks continue to impede commercialization and widespread use. Moreover, the economic feasibility of scaling up these biotechnological platforms depends heavily on reducing production costs, optimizing bioprocesses, and integrating them seamlessly into existing waste management infrastructures.

Future progress in the field will likely be driven by cross-disciplinary collaborations that bring together synthetic biology, systems ecology, machine learning, and environmental engineering.

Approaches such as adaptive laboratory evolution, automated high-throughput screening, and in situ biosensing may help in developing more resilient and responsive consortia.

In particular, the convergence of artificial intelligence with synthetic ecology holds tremendous potential to design microbial systems that are not only efficient but also self-regulating and environmentally benign.

Ultimately, synthetic microbial consortia have the potential to redefine how we approach pollution, resource scarcity, and industrial sustainability. Their evolution into next-generation platforms could pave the way for a future where waste is a resource, pollutants are feedstocks, and microbial communities are central to global environmental health.

Table.1 Engineering Strategies for Synthetic Microbial Consortia (2023–2025)

Strategy	Description	Example Organisms Used	References
Quorum sensing rewiring	Synthetic signalling pathways for communication	*E. coli*, *P. putida*	Kumar *et al.,* (2023)
CRISPR-based gene editing	Targeted metabolic enhancement	*B. subtilis*, *R. eutropha*	Liu *et al.,* (2023)
Modular plasmid systems	Functional gene module integration	*E. coli*, *S. cerevisiae*	Singh *et al.,* (2025)
Metabolic flux modeling	Pathway optimization and resource allocation	Mixed consortia	Nguyen *et al.,* (2024)

Table.2 Case Studies of Bioremediation by Synthetic Consortia (2023–2025)

Pollutant Type	Consortium Composition	Mode of Action	Efficiency (%)	References
Heavy metals	*B. subtilis* + *P. aeruginosa*	Bioaccumulation + EPS	85	Chen *et al.,* (2023)
Hydrocarbons	*P. putida* + *A. baylyi*	Aliphatic/aromatic degradation	92	Zhang *et al.,* (2024)
Pharmaceuticals	*E. coli* + *S. oneidensis*	Reductive breakdown	78	Ahmad *et al.,* (2025)
PET plastics	*I. sakaiensis* + *B. coagulans*	Enzymatic hydrolysis	67	Patel *et al.,* (2024)

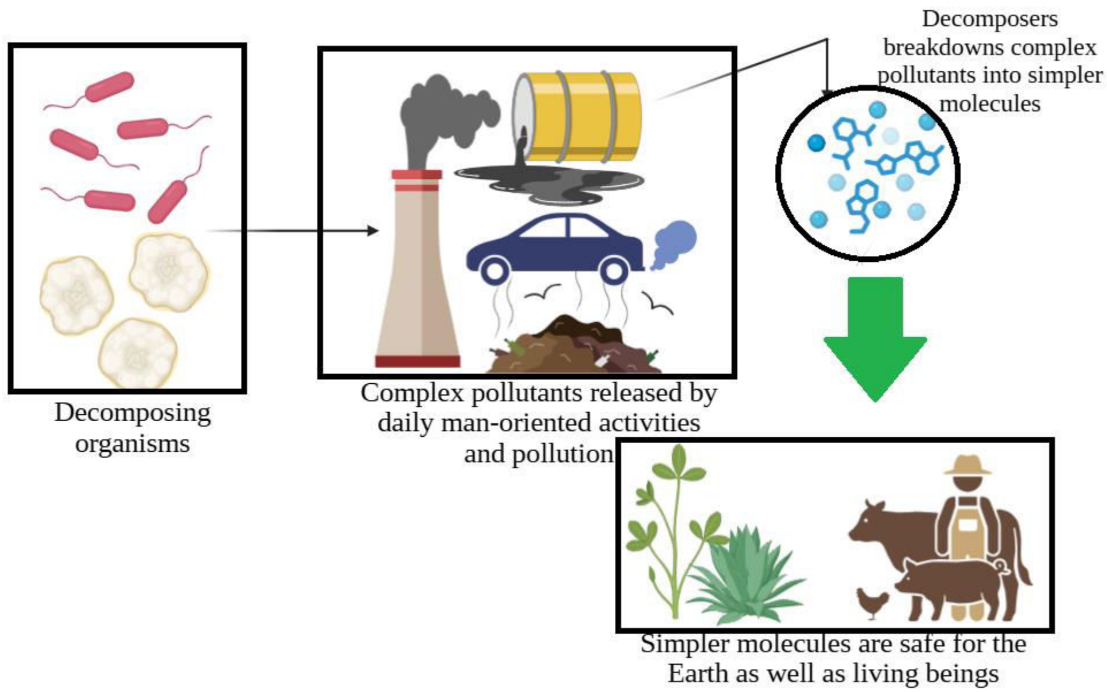
Table.3 Roles of SMC in Circular Bioeconomy

Application Domain	SMC Members Involved	Output Product	Scale	References
Biohydrogen production	*C. butyricum* + methanogens	H2 + CH4	Pilot plant	Ali *et al.,* (2023)
Phosphorus recovery	*B. megaterium* + *M. parvicella*	Struvite	Lab scale	Desai *et al.,* (2024)
Bioplastic synthesis	*E. coli* + *C. necator*	PHA	Industrial	Rana *et al.,* (2025)
Waste VFAs	*Clostridium spp.* + *Lactobacillus*	VFAs	Bench scale	Verma *et al.,* (2024)

Table.4 Challenges and Emerging Trends in SMC Applications

Challenge	Description	Proposed Solution	References
Biosafety	Environmental persistence of engineered strains	Containment circuits	OECD (2025)
Stability	Drift in microbial ratios over time	Feedback regulation	Singh *et al.,* (2025)
Economic scalability	High operational cost	Low-cost feedstocks + modular design	Rana *et al.,* (2025)
Regulatory barriers	Absence of global guidelines	International SMC protocols	Desai *et al.,* (2024)

Figure.1 Role of microorganism in bioremediation. They acts as natural decomposers of complex and toxic molecules by converting them into simpler molecules which are safe for the Earth and its biotic components.



Author Contributions

Priyanshu Kumar Soni: Investigation, formal analysis, writing—original draft. Kumar Anand: Validation, methodology, writing—reviewing. Medha Mishra:—Formal analysis, writing—review and editing. Archita Sarkar: Investigation, writing—reviewing.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

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