

MICROBIAL CONSORTIA: A SUSTAINABLE BIOTECHNOLOGICAL APPROACH TO WASTE MANAGEMENT AND RESOURCE RECOVERY

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ABSTRACT

The accelerating pace of industrialization, urbanization, and population growth has intensified the global waste crisis, exposing the structural limitations of conventional treatment technologies such as landfilling, incineration, and physicochemical treatment. These methods are frequently costly, energy-intensive, and prone to incomplete pollutant removal, often merely transferring contaminants between environmental compartments rather than eliminating them. Microbial consortia are cooperating assemblages of bacteria, fungi, archaea, and algae that have emerged as a biologically elegant and economically viable alternative capable of degrading complex, heterogeneous waste streams that defy treatment by single microbial strains. This review synthesizes current knowledge on the classification of microbial consortia into natural, synthetic, and engineered categories; the ecological and molecular mechanisms underpinning their function, including synergistic metabolism, cross-feeding, biofilm formation, and quorum sensing; and their demonstrated applications across solid waste management, plastic biodegradation, wastewater treatment, food waste valorization, and heavy metal remediation. Particular attention is given to the convergence of microbial consortia with advanced enabling technologies such as metagenomics, CRISPR-based genome editing, artificial intelligence and machine learning, biosensors, and bioelectrochemical systems which are transforming consortia from empirically assembled communities into rationally designed biological platforms. The review further examines the principal barriers to field-scale deployment, including consortium instability, inter-strain competition, scale-up difficulties, and regulatory uncertainty, before outlining future research priorities centred on smart bioreactors, AI-guided consortium design, and integration within circular bioeconomy frameworks. Collectively, the evidence indicates that microbial consortia represent one of the most promising avenues for achieving low-cost, low-emission, and resource-recovering waste management at a scale commensurate with the magnitude of the global waste challenge.

Keywords: Waste Management, Bioremediation, Quorum Sensing, Circular Bio economy, Metagenomics.

INTRODUCTION

A substantial and sustained increase in waste generation has accompanied the evolution of industrialization, urbanization, and world population growth over the past several decades. Waste arising from municipal, agricultural, and industrial sources, if disposed of improperly,

contributes to land, water, and air pollution, creating serious environmental, economic, and public health challenges that disproportionately burden developing economies. Conventional waste treatment methods including landfilling, incineration, composting, recycling, and various forms of biological treatment remain the

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support of municipal and industrial waste management worldwide. Landfilling and incineration primarily achieve volume reduction and disposal, while composting and biological treatment convert organic fractions into useful outputs such as compost and biogas, and recycling conserves raw materials by returning waste streams to the production cycle (Zhou, Y. *et al.*, 2025, Soni, P.K. *et al.* 2025). Despite their widespread adoption, these approaches share a common set of limitations, including greenhouse gas emissions, leachate generation, high capital and operating costs, and incomplete removal of hazardous or recalcitrant pollutants. Waste mismanagement is additionally a meaningful contributor to climate change through the emission of methane and carbon dioxide from decomposing organic matter, a problem that is especially acute where waste-management infrastructure struggles to keep pace with rapidly growing waste volumes. These pressures have elevated sustainable and efficient waste treatment strategies to a position of global policy priority.

Limitations of Conventional Waste Treatment

Conventional waste treatment technologies have been refined over decades of engineering practice, yet each carries intrinsic constraints that limit its suitability for the complex waste streams generated by modern economies. Landfilling: the most widely used disposal method

globally, but land-intensive and associated with soil and groundwater contamination through leachate, together with methane emissions that make landfills a significant source of greenhouse gases. Incineration: reduces waste volume and can recover energy, but entails high operational costs and risks releasing dioxins, furans, and particulate matter if emissions are not tightly controlled; the resulting toxic ash requires further disposal. Chemical and physical treatments: oxidation, precipitation, and adsorption are effective for specific waste streams but often depend on expensive reagents and energy inputs, and may generate secondary pollutants requiring additional treatment. Traditional composting: environmentally benign but generally effective only for readily biodegradable organic matter; it is slow, sensitive to environmental fluctuation, and largely ineffective against plastics, pesticides, dyes, pharmaceuticals, and other complex industrial chemicals. Incomplete degradation: many conventional methods transfer pollutants between environmental media rather than eliminating them outright, so persistent organic pollutants and emerging contaminants frequently remain untreated and pose long-term ecological risk. These shortcomings collectively underscore the need for innovative, cost-effective, and environmentally sustainable alternatives capable of handling diverse and chemically complex waste streams is a gap that biologically based, consortium-driven treatment is increasingly well positioned to fill (Prakash, A. *et al.* 2025, Qattan, S.Y. 2025).



Figure 1. Conceptual overview of waste sources, conventional disposal routes, and the environmental pressures that motivate biologically based alternatives. (Source: AI generated image).

The Rationale for Microbial Consortia

Microbial consortia refer to communities of different microorganisms such as bacteria, fungi, algae, and archaea that interact through synergistic ecological relationships to degrade, transform, or detoxify waste materials (Zhou, Y. *et al.*, 2025, Soni, P.K *et al.* 2025). Unlike single microbial strains, consortia possess a broader collective range of metabolic capabilities, enabling them to break down complex waste components more efficiently and completely. Enhanced degradation efficiency: Different species specialise in different compounds; one member may break a complex substance into intermediates that are subsequently degraded by other members, producing faster and more complete mineralization. Ability to treat complex waste: Modern waste streams contain mixtures of organic matter, plastics, hydrocarbons, dyes, pesticides, pharmaceuticals, and heavy metals that exceed the enzymatic repertoire of any single organism; consortia pool diverse enzymatic systems to target this heterogeneity collectively (Qattan, S.Y. 2025). Improved stability and resilience: Because temperature, pH, moisture, and nutrient availability fluctuate in real systems, consortia in which different members tolerate different conditions that tend to be more robust than pure cultures. Reduced treatment costs: Biological treatment with consortia typically requires less energy and fewer chemical inputs than conventional treatment, improving cost-effectiveness at scale. Resource recovery and circular economy: Beyond degradation, consortia facilitate recovery of biogas, biofertilizers, biohydrogen, organic acids, and industrial enzymes, directly supporting circular-economy objectives. Environmental sustainability: consortium-based treatment minimises secondary pollution and greenhouse gas emissions relative to thermal and chemical alternatives. For these reasons, microbial consortia have emerged as one of the most actively researched approaches to sustainable waste treatment and environmental remediation, and are the subject of this review.

Types of microbial consortia

Microbial consortia can be classified, according to their origin and the degree of human intervention involved in their assembly, into three broad categories: natural consortia, synthetic consortia, and engineered microbial communities (Zhou, Y. *et al.*, 2025, Soni, P.K *et al.* 2025).

Natural consortia

Natural microbial consortia are communities that arise spontaneously in soils, sediments, compost heaps, wastewater treatment systems, marine environments, and the gastrointestinal tracts of animals, without deliberate human design. These assemblages evolve through ecological interactions such as mutualism, commensalism, and competition, and their members typically perform complementary functions in which some hydrolyzing complex organic compounds into simpler molecules and others fermenting these products into organic acids, methane, or carbon dioxide. Formed naturally through ecological evolution, with high microbial diversity.

Adapted to local environmental conditions and generally stable and resilient under changing conditions. Capable of degrading a wide range of organic and inorganic pollutants. Composting of agricultural and municipal waste; anaerobic digestion for biogas production. Wastewater treatment; bioremediation of contaminated soils and water bodies; nutrient cycling in natural ecosystems. The principal advantages of natural consortia are high stability, self-sustaining operation, and broad metabolic capability with minimal human intervention. They are offset by limitations in predictability: composition varies between environments, performance is difficult to forecast, and unwanted competing organisms may reduce treatment efficiency (Ahmad, R *et al.*, 2025).

Synthetic consortia

Synthetic microbial consortia are artificially assembled groups of microorganisms, deliberately selected and combined by researchers to exploit complementary metabolic activities for a specific function (Kumar, N *et al.*, 2023). Development typically begins with the selection of microorganisms exhibiting desirable traits including pollutant degradation, enzyme production, nutrient utilisation, or metabolite synthesis that are then cultivated together to achieve performance beyond that of any constituent strain alone. In a representative division-of-labour scheme, one bacterial species may degrade cellulose into sugars while a partner species converts those sugars into biofuels or valuable chemicals. Artificially constructed under controlled laboratory conditions, with composition tailored to specific objectives. Controlled interactions among members and greater predictability of behaviour than natural consortia.

Engineered microbial communities

Engineered microbial communities represent an advanced extension of synthetic consortia in which member organisms are genetically modified and strategically organised to perform highly specialised functions, drawing on principles of microbiology, genetic engineering, systems biology, and synthetic biology. Microorganisms within engineered communities can be modified to express specific enzymes, metabolic pathways, or signalling systems that enhance waste degradation, pollutant detoxification, and resource recovery; scientists can additionally design communication mechanisms between species using quorum sensing and other regulatory circuits to coordinate community-level behaviour. Degradation of recalcitrant pollutants and pharmaceutical or chemical waste; bioenergy production. Carbon capture and utilisation; biosensor development for environmental monitoring; industrial biotechnology processes. Engineered communities offer high treatment efficiency, precise targeting of specific contaminants, and enhanced bioproduct yields, but raise regulatory and biosafety concerns including the risk of horizontal gene transfer to indigenous microbiota together with higher development costs and the need for careful long-term monitoring of ecological impact.

Mechanism of Waste Degradation by Microbial Consortia

Microbial consortia degrade waste through complex interactions among their constituent members. Unlike individual strains, consortia exploit cooperative mechanisms that enhance the breakdown of organic and inorganic pollutants, improving degradation efficiency, ecological stability, and adaptability across diverse environmental conditions. The four principal mechanisms namely synergistic metabolism, cross-feeding, biofilm formation, and quorum sensing are discussed as follows.

Synergistic metabolism

Synergistic metabolism refers to the cooperative interaction between different microorganisms whose combined metabolic activities achieve more efficient degradation than any single species could accomplish alone. Many wastes contain complex compounds like cellulose, lignin, hydrocarbons, plastics, dyes, and pesticides that cannot be fully degraded by one organism. In synergistic metabolism, a primary degrader converts complex substrates into intermediate compounds, which other consortium members progressively metabolise into simpler molecules and, eventually, harmless end products such as carbon dioxide, water, methane, or biomass. A representative example is anaerobic digestion, in which hydrolytic bacteria convert organic matter into simple sugars and amino acids; fermentative bacteria convert these into volatile fatty acids; acetogenic bacteria produce acetate and hydrogen; and methanogenic archaea finally convert acetate and hydrogen into methane. This layered division of labour enhances degradation efficiency, extends treatment capability to complex waste streams, limits the accumulation of toxic intermediates, and improves overall process stability.

Cross feeding

Cross-feeding, or metabolic cooperation, occurs when one microorganism utilises the metabolic products of another as a nutrient or energy source, creating interconnected metabolic networks that facilitate efficient waste degradation. Cross-feeding is particularly important where degradation pathways involve multiple biochemical steps: by-products generated by one species become substrates for another, preventing intermediate accumulation and promoting complete degradation. Cross-feeding may be obligate, where partner species depend entirely on metabolites supplied by one another for survival, or facultative, where partners benefit from shared metabolites but remain independently viable. During cellulose degradation, for instance, cellulolytic bacteria break cellulose into glucose, fermentative bacteria convert glucose into organic acids, and methanogens subsequently utilise these acids and hydrogen to generate methane. Such sequential utilisation maximises resource use, enhances pollutant removal, increases microbial diversity and stability, and supports the degradation of otherwise recalcitrant compounds. In engineered PET-degrading

consortia, for example, one strain may be designed to consume terephthalic acid while a partner strain consumes ethylene glycol, with both cross-feeding essential nutrients or cofactors to sustain mutual growth.

Biofilm Formation

Biofilms are structured communities of microorganisms attached to surfaces and embedded within a self-produced matrix of extracellular polymeric substances (EPS), and represent one of the most important survival and degradation strategies used by microbial consortia. Within biofilms, microorganisms live in close proximity, allowing efficient exchange of nutrients, metabolites, enzymes, and genetic material, while the EPS matrix confers protection from environmental stress, toxic compounds, and predation.

Biofilm development proceeds through four broad stages:

Initial attachment, in which cells adhere to a surface via pili and flagella. Irreversible attachment, in which extracellular polymers strengthen adhesion. Biofilm maturation, in which populations grow into complex three-dimensional structures. Dispersion, in which some cells detach to colonise new environments. Biofilms concentrate microbial cells near waste substrates, facilitate enzyme retention and activity, enhance metabolic cooperation among species, and improve degradation of persistent contaminants properties that make biofilm reactors particularly effective in wastewater treatment systems, where microorganisms remain attached to surfaces and maintain high cell densities.

Quorum Sensing

Quorum sensing (QS) is a cell-to-cell communication mechanism that allows microorganisms to coordinate behaviour according to population density. Microbial cells produce and release diffusible signalling molecules, or autoinducers, whose concentration rises with population size; once a threshold concentration is reached, cells detect the accumulated signal and activate genes that regulate collective behaviours such as enzyme production, biofilm formation, nutrient utilisation, and pollutant degradation. Certain hydrocarbon-degrading bacteria, for example, produce quorum-sensing signals that trigger the synthesis of enzymes required for petroleum breakdown only once a sufficient population density has been reached, thereby conserving resources until degradation is energetically worthwhile. Beyond enzyme regulation, QS coordinates biofilm development, optimises nutrient utilisation, enhances degradation pathways, and helps maintain community stability under stress; recent work has further shown that exogenous autoinducers can improve pollutant removal and EPS secretion in activated-sludge and biofilm reactor systems, including under heavy-metal and antibiotic stress. Engineered QS circuits, in which regulatory promoters are tuned to control multiple genes from a single signal, are increasingly used to programme predictable, coordinated behaviour in synthetic consortia.

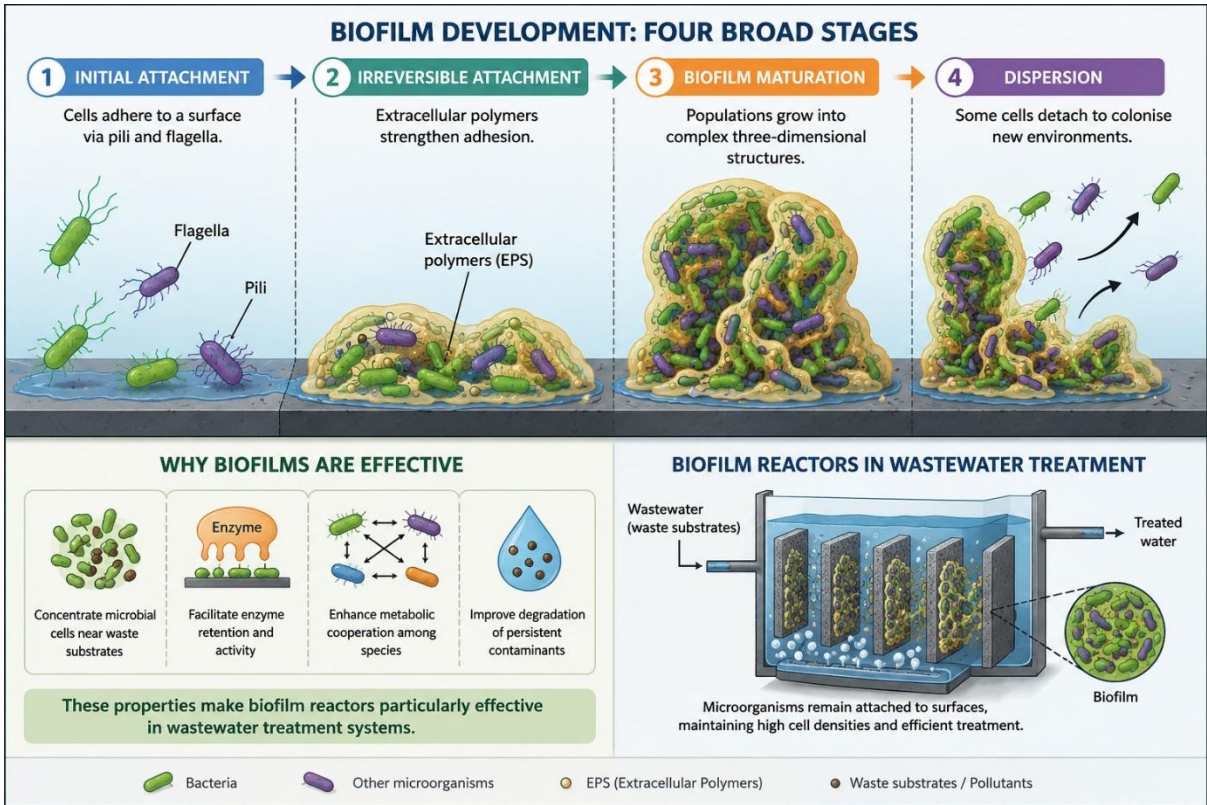


Figure 2. Biofilm development proceeds through four broad stages. (Source: AI generated image).

Table 1. The overall effectiveness of microbial consortia in waste degradation.

Synergistic metabolism	Cooperative, stepwise degradation pathways	Complete breakdown of complex waste
Cross-feeding	Exchange of metabolic intermediates	Efficient utilisation of by-products
Biofilm formation	Structured, protected microbial communities	Increased stability and stress resistance
Quorum sensing	Density-dependent cell-to-cell communication	Coordinated, resource-efficient degradation

Integrated role of these mechanisms

The overall effectiveness of microbial consortia in waste degradation arises from the combined, often interdependent, action of these four mechanisms summarised in Table 1. Quorum sensing, for instance, can regulate the production of cross-fed metabolites, while the metabolic state of individual cells can, in turn, influence signal production, creating feedback loops that stabilise community function over time.

Application of Microbial consortia in waste management

Microbial consortia have become powerful tools in environmental biotechnology owing to their ability to

efficiently degrade complex waste materials, detoxify pollutants, and recover valuable resources. Their diverse metabolic capabilities and cooperative interactions make them effective across solid waste treatment, plastic degradation, wastewater purification, food waste valorisation, and heavy-metal remediation.

Solid waste management

The rising generation of municipal solid waste (MSW) poses significant challenges worldwide, while conventional disposal practices such as landfilling and incineration can contribute to environmental pollution, greenhouse-gas emissions, and loss of potentially recoverable resources. Microbial consortia offer an eco-friendly and biologically driven alternative by accelerating the decomposition and

stabilisation of organic waste. Communities comprising bacteria, fungi, and actinomycetes act synergistically through the production of extracellular enzymes capable of degrading complex substrates such as cellulose, hemicellulose, proteins, lipids, and lignin into simpler compounds, ultimately facilitating their conversion into nutrient-rich compost or biogas (Kavya *et al.*, 2024). Composting of food scraps, yard waste, crop residues, straw, and animal manure can be enhanced through the application of selected microbial consortia. Such consortia promote the degradation of complex organic substrates, accelerate organic-matter stabilization, and improve the quality of the final compost (Kavya *et al.*, 2024; Zhang *et al.*, 2025). Similarly, anaerobic digestion employs diverse microbial communities to sequentially degrade organic substrates under oxygen-free conditions, producing methane-rich biogas that can be recovered as a renewable energy source (Kavya *et al.*, 2024). These biological approaches can reduce the quantity of organic waste entering landfills while facilitating nutrient recycling, energy recovery, and more sustainable waste management.

Recent experimental studies have provided further evidence for the effectiveness of microbial consortia in organic-waste management. A 2025 study reported that a consortium of *Pseudomonas* strains possessing cellulolytic, pectinolytic, proteolytic, and lipolytic activities enhanced the biodegradation potential of urban organic waste and simultaneously exhibited plant-growth-promoting properties, demonstrating its potential for sustainable composting and agricultural applications (Exploring different *Pseudomonads* strains, 2025). Similarly, Zhang *et al.* (2025) optimized a bacterial–fungal consortium for oily food-waste composting and demonstrated improved degradation of oil-containing organic waste compared with uninoculated treatment. Lignocellulolytic fungal consortia have also demonstrated potential for improving leaf-litter composting and producing quality compost enriched with beneficial nutrients (Application of compatible lignocellulolytic fungal consortia, 2024). Thus, microbial consortia represent an important biological strategy for converting municipal and agricultural organic wastes into useful products while simultaneously supporting waste reduction, nutrient recovery, soil health, and circular bioeconomy approaches.

Plastic waste degradation

Plastic pollution has emerged as one of the most persistent environmental challenges because of the extensive production and consumption of synthetic polymers, their chemical stability, and their resistance to natural degradation. Conventional disposal practices, including landfilling, open dumping, and incineration, may result in long-term environmental contamination and contribute to the accumulation of macroplastics and microplastics in terrestrial and aquatic ecosystems. Consequently, microbial biodegradation has received increasing attention as a biologically based approach for reducing plastic persistence and recovering useful carbon resources. Bacteria and fungi can colonize plastic surfaces, form biofilms, initiate

polymer deterioration, and produce extracellular enzymes capable of modifying or hydrolysing polymer structures. Enzymes such as laccases, peroxidases, cutinases, lipases, esterases, and specialized hydrolases have been associated with the degradation of different synthetic polymers, although their efficiency varies considerably according to polymer structure and environmental conditions (Kumar *et al.*, 2023; Zhang *et al.*, 2025). Recent reviews emphasize that microbial degradation is particularly promising when biological treatment is combined with physicochemical pretreatment, enzyme engineering, or synthetic microbial-consortium approaches (Matsakas *et al.*, 2025; Antonopoulou *et al.*, 2025). Polyethylene terephthalate (PET) has received particular attention because of its extensive use in beverage bottles, food packaging, textiles, and other consumer products, together with its relatively high chemical stability and crystallinity. The discovery of *Ideonella sakaiensis* and its PET-degrading enzyme system provided an important foundation for biological PET depolymerization. The bacterium produces PETase (IsPETase), which hydrolyses PET and generates predominantly mono(2-hydroxyethyl) terephthalate (MHET), together with smaller amounts of bis(2-hydroxyethyl) terephthalate (BHET) and terephthalic acid (TPA). MHETase subsequently hydrolyses MHET to TPA and ethylene glycol (EG), enabling the resulting products to enter microbial metabolic pathways (Son *et al.*, 2023; Ahmed *et al.*, 2025).

Recent studies have focused on improving the catalytic efficiency, thermostability, substrate specificity, and industrial applicability of PET-degrading enzymes through protein engineering, enzyme immobilization, and metabolic engineering (Son *et al.*, 2023; Ahmed *et al.*, 2025). Microbial consortia provide an additional advantage because different microorganisms can perform complementary metabolic functions during polymer degradation. Rather than relying on a single microorganism, consortium members may collectively contribute to surface colonization, polymer oxidation or hydrolysis, assimilation of degradation intermediates, and subsequent mineralization. A five-member bacterial consortium investigated through pangenomic and transcriptomic approaches demonstrated synergistic PET-degradation potential and revealed a diverse repertoire of genes associated with plastic and plasticizer degradation. The study also identified EstB, a novel PETase capable of hydrolysing both the PET oligomer BHET and PET polymer, highlighting the value of community-level approaches for discovering previously unrecognized plastic-degrading enzymes (Tanasupawat *et al.*, 2022). More recent research has further emphasized the development of engineered and synthetic microbial consortia in which different members are assigned complementary roles, potentially improving the conversion of complex polymers and degradation intermediates (Matsakas *et al.*, 2025; Jeyachandran *et al.*, 2025). Beyond PET, considerable research has investigated microbial degradation of polyethylene (PE), polypropylene (PP), polystyrene (PS), polyurethane (PU), and other synthetic or

biodegradable polymers. Polyethylene remains particularly challenging because of its hydrophobicity, high molecular weight, and strong carbon-carbon backbone. Recent reviews indicate that microbial PE degradation generally involves surface colonization and biofilm formation, oxidative modification of the polymer, fragmentation, assimilation of smaller molecules, and, in favourable conditions, partial mineralization. Extracellular oxidative enzymes such as laccases and peroxidases have been implicated in these processes, although degradation rates remain relatively low compared with those observed for more hydrolysable polymers such as PET (Zhang *et al.*, 2025; Antonopoulou *et al.*, 2025). The development of synthetic microbial consortia containing complementary polymer-degrading capabilities is therefore being explored as a strategy to overcome the limitations of individual strains (Matsakas *et al.*, 2025). The major advantages of microbial-consortium-based plastic biodegradation include reduction of persistent plastic accumulation, lower dependence on conventional disposal methods, recovery of potentially valuable degradation products, and compatibility with circular-bioeconomy approaches. Nevertheless, several limitations remain, including the slow degradation of highly crystalline and hydrophobic polymers, limited enzyme accessibility to polymer surfaces, dependence on temperature and pH, differences in polymer composition and additives, and difficulties in maintaining stable microbial-community interactions under large-scale conditions. Therefore, future research should focus on the isolation of novel plastic-degrading microorganisms, metagenomic and pangenomic screening, enzyme engineering, synthetic-consortium design, appropriate physicochemical pretreatment, and development of controlled bioreactor systems to improve degradation efficiency and facilitate practical application (Matsakas *et al.*, 2025; Jeyachandran *et al.*, 2025).

Wastewater treatment

Wastewater generated from domestic, agricultural, and industrial activities contains complex and heterogeneous mixtures of organic matter, nitrogen and phosphorus compounds, suspended solids, pathogens, dyes, pharmaceuticals, heavy metals, and other potentially toxic contaminants. Conventional wastewater-treatment processes can effectively reduce many pollutants; however, increasing pollutant diversity and the emergence of persistent and trace contaminants have stimulated interest in biologically based and resource-recovery-oriented treatment technologies. Microbial consortia are particularly important in biological wastewater treatment because different microorganisms perform complementary metabolic functions, enabling simultaneous organic-matter degradation, nutrient transformation, pollutant detoxification, and biomass production. Such microbial communities operate in activated sludge, biofilm reactors, constructed wetlands, anaerobic digesters, membrane-associated systems, and algal-bacterial treatment platforms (Li *et al.*, 2024; Liu *et al.*, 2024). Organic-matter removal is primarily mediated by heterotrophic microorganisms that

utilize dissolved and particulate organic compounds as carbon and energy sources, converting them into biomass and inorganic end products such as carbon dioxide and water under aerobic conditions. In anaerobic systems, diverse microbial guilds cooperate through hydrolysis, acidogenesis, acetogenesis, and methanogenesis, ultimately converting complex organic substrates into methane-rich biogas. The functional diversity of microbial consortia is therefore particularly important because the degradation of complex wastewater matrices generally requires several sequential metabolic reactions rather than the activity of a single microorganism. Such metabolic cooperation also contributes to process stability when wastewater composition fluctuates (Liu *et al.*, 2024). Nutrient removal represents another major function of microbial consortia in wastewater treatment. During nitrification, ammonia-oxidizing microorganisms convert ammonia into nitrite, followed by the oxidation of nitrite to nitrate by nitrite-oxidizing microorganisms. Denitrifying microorganisms subsequently reduce nitrate and nitrite to gaseous nitrogen under oxygen-limited or anoxic conditions, thereby facilitating biological nitrogen removal. Phosphorus can be removed through microbial assimilation and enhanced biological phosphorus removal, in which specialized microorganisms accumulate phosphorus intracellularly. The integration of these microbial processes enables simultaneous removal and transformation of carbon, nitrogen, and phosphorus and can contribute to nutrient recovery rather than simply transferring pollutants from one phase to another.

Microalgae-bacterial consortia have attracted considerable attention as an alternative biological treatment system because of their complementary metabolic interactions. Microalgae produce oxygen through photosynthesis, which can support bacterial oxidation of organic matter, while bacterial respiration releases carbon dioxide that can subsequently be utilized by microalgae. Microalgae can additionally assimilate nitrogen and phosphorus and accumulate biomass that may have potential for subsequent recovery as biofertilizer, bioenergy feedstock, or other value-added products (Li *et al.*, 2024; Liu *et al.*, 2024). Recent studies and reviews have reported the application of microalgal-bacterial consortia to municipal, agricultural, pharmaceutical, textile, aquaculture, and industrial wastewaters, demonstrating their potential for simultaneous pollutant removal and biomass production (Li *et al.*, 2024; Wu *et al.*, 2025). Recent research has further emphasized the importance of microbial interactions and consortium configuration in determining wastewater-treatment performance. Microalgal-bacterial consortia can occur as suspended flocs, attached biofilms, or granular structures, and their performance is influenced by wastewater characteristics, microbial composition, light availability, pH, temperature, dissolved oxygen, hydraulic retention time, organic loading, and nutrient availability (Liu *et al.*, 2024; Zhang *et al.*, 2026). A 2026 review highlighted that attached microalgal-bacterial consortia can provide particularly high pollutant-removal capacities, especially for organic matter

and phosphorus, whereas the performance of suspended floc systems is strongly influenced by operational conditions and wastewater organic loading (Zhang *et al.*, 2026). These findings demonstrate that consortium architecture and process conditions are critical determinants of treatment efficiency.

Microbial consortia are also being explored for the removal of recalcitrant and emerging contaminants. Microalgae–bacterial systems have demonstrated potential for the degradation or transformation of organic pollutants, pharmaceutical compounds, dyes, and other contaminants that may be difficult to remove through conventional biological treatment alone. Recent evidence indicates that multi-omics approaches, including metagenomics, transcriptomics, and metabolomics, can help elucidate microbial interactions and identify metabolic pathways responsible for pollutant transformation, thereby providing opportunities for rational consortium design and process optimization (Chaiwong *et al.*, 2024). Similarly, bacterial–microalgal consortia have been investigated for textile wastewater treatment, where complementary microbial activities can contribute to dye degradation, nutrient removal, detoxification, and resource recovery (Rathour *et al.*, 2024). An important emerging direction is the transition from pollutant removal toward integrated resource recovery. Microbial consortia can facilitate the recovery of carbon, nitrogen, phosphorus, biomass, and energy from wastewater, thereby linking biological treatment with circular-bioeconomy principles. Microalgal–bacterial systems can simultaneously remove nutrients and generate biomass, while anaerobic microbial consortia can convert organic residues into methane-rich biogas. Recent reviews have therefore emphasized the potential of consortium-based wastewater treatment to combine pollution control, carbon management, biomass production, and resource recovery within integrated treatment systems (Liu *et al.*, 2024; Wu *et al.*, 2025; Zhang *et al.*, 2026). Despite these advantages, several challenges limit the large-scale implementation of microbial consortia.

Maintaining a stable and reproducible microbial community under fluctuating wastewater composition remains difficult, while variations in temperature, pH, dissolved oxygen, light intensity, nutrient ratios, hydraulic loading, and contaminant concentrations can substantially affect consortium performance. Scale-up, biomass harvesting, reactor design, contamination control, and long-term community stability also require further investigation. Consequently, future research should integrate microbial ecology, metagenomics, synthetic-community design, process engineering, artificial intelligence-assisted monitoring, and resource-recovery technologies to develop robust microbial consortia capable of treating complex wastewater matrices under real-world conditions (Wu *et al.*, 2025; Zhang *et al.*, 2026).

Food waste Valorization

Food waste represents a substantial fraction of the global organic-waste stream and contains considerable amounts of

carbohydrates, proteins, lipids, minerals, and other biodegradable compounds that can be recovered through biological processing. When disposed of through landfilling or other conventional routes, these resources are lost and may contribute to greenhouse-gas emissions and environmental pollution. Consequently, microbial food-waste valorisation has emerged as an important component of circular-bioeconomy strategies, in which microorganisms are employed to convert heterogeneous food residues into energy, chemicals, biomaterials, nutrients, and other value-added products. Microbial consortia are particularly suitable for this purpose because food waste contains chemically diverse substrates requiring sequential and complementary metabolic activities. Through coordinated hydrolysis, fermentation, acidogenesis, acetogenesis, and methanogenesis, microbial communities can convert complex organic matter into biogas, volatile fatty acids (VFAs), organic acids, biofuels, single-cell protein, biofertilizers, and other useful products (Soon *et al.*, 2025; Kaur *et al.*, 2025). Anaerobic digestion (AD) represents one of the most established consortium-based approaches for food-waste valorisation. In this process, hydrolytic and fermentative microorganisms initially break down complex carbohydrates, proteins, and lipids into soluble compounds, which are subsequently converted into organic acids and other intermediates. Acetogenic microorganisms further transform these products into acetate, hydrogen, and carbon dioxide, while syntrophic bacteria and methanogenic archaea convert the resulting intermediates into methane-rich biogas. The stability and efficiency of anaerobic digestion therefore depend strongly on interactions among multiple microbial populations rather than the activity of a single organism. Recent research has highlighted the importance of syntrophic relationships and microbial-community structure in maintaining reactor stability and improving energy recovery from food waste (Mancini *et al.*, 2024; Assis *et al.*, 2022). A recent comprehensive review further emphasized that temperature, pH, organic loading rate, retention time, ammonia concentration, volatile fatty acid accumulation, substrate characteristics, and pretreatment are major determinants of methane production and process stability (Zhang *et al.*, 2026).

Beyond methane production, controlled microbial fermentation can redirect food-waste carbon toward short-chain volatile fatty acids and other platform chemicals. VFAs such as acetate, propionate and butyrate have applications as carbon sources, chemical precursors, and intermediates for the production of higher-value biochemicals and materials. Recent studies demonstrate that anaerobic fermentation of food waste can generate specialized microbial communities enriched for VFA production, and that process conditions such as pH, temperature, substrate concentration, and hydraulic retention time strongly influence both VFA yield and product distribution (Martínez *et al.*, 2025). At demonstration scale, anaerobic fermentation of food waste has also been shown to maintain VFA production while microbial communities become progressively specialized for acidogenic metabolism, supporting the feasibility of

scaling biological food-waste valorisation beyond laboratory systems (2025). Microbial consortia can additionally facilitate the production of organic acids and other fermentation products from carbohydrate-rich food residues. Fruit and vegetable wastes are particularly attractive substrates because they contain readily biodegradable sugars and polysaccharides that can be converted into lactic, acetic, succinic, citric, and other organic acids by suitable microbial communities. The use of mixed microbial populations can broaden substrate utilization and provide complementary metabolic pathways, while synthetic biology and metabolic engineering can be employed to redirect carbon flux toward specific target products. Recent research has identified microbial fermentation as a promising green approach for transforming heterogeneous food waste into energy, valuable chemicals, biomaterials, and other products, while also emphasizing the importance of substrate characterization, process control, metabolic engineering, and biorefinery integration (Soon *et al.*, 2025). Food waste can also serve as a substrate for microbial biomass and single-cell protein (SCP) production. Anaerobic digestion generates carbon-rich intermediates and biogas that can potentially be integrated with microbial biomass production, thereby increasing the overall value recovered from the original waste stream. A recent review identified numerous bacterial, archaeal, and fungal genera capable of contributing to microbial upcycling of food waste and highlighted the potential integration of anaerobic digestion with SCP production as a route for simultaneous energy recovery and biomass generation (Mancini *et al.*, 2024). Such integrated systems may contribute to reducing dependence on conventional feed resources while recovering nutrients and carbon from discarded food materials.

An important development in this field is the engineering of synthetic microbial consortia with defined functional roles. Instead of relying entirely on naturally occurring mixed communities, microbial community engineering can deliberately combine microorganisms with complementary hydrolytic, fermentative, acidogenic, or product-forming capabilities. Recent reviews indicate that synthetic biology, metagenomics, metabolic engineering, and electro-fermentation can be used to improve substrate conversion, product selectivity, and resource recovery from food waste (Kaur *et al.*, 2025). Functional division of labour within a consortium may allow one population to hydrolyse complex polymers while other members consume the resulting intermediates and channel carbon toward desired products. However, the performance of engineered consortia remains dependent on microbial compatibility, competition, substrate heterogeneity, environmental conditions, and long-term community stability. Therefore, rational consortium design should be considered a complementary strategy rather than a universally superior alternative to naturally enriched microbial communities.

Composting represents another important biological route for food-waste management, in which microbial communities transform organic residues into stabilized,

humified material that can potentially be used as a soil amendment or biofertilizer. During composting, successive microbial populations participate in the degradation of readily available organic compounds followed by more resistant components, with changes in temperature, moisture, oxygen availability, pH, and substrate composition influencing microbial succession and decomposition. Integrating food-waste composting with microbial inoculation or other biological treatments may accelerate stabilization and improve the quality of the final compost, although the effectiveness of inoculants depends on their ability to establish and remain active within the indigenous microbial community. Overall, microbial consortia provide a versatile biological platform for food-waste valorisation by enabling simultaneous waste stabilization and recovery of energy, nutrients, chemicals, and microbial biomass. Anaerobic digestion can produce methane-rich biogas and nutrient-containing digestate, controlled fermentation can generate VFAs and organic acids, while microbial biomass production and composting provide additional routes for resource recovery. Nevertheless, feedstock heterogeneity, inhibition by ammonia and accumulated VFAs, variability in microbial community composition, process instability, scale-up, product separation, economic feasibility, and biosafety remain important challenges. Future research should therefore integrate metagenomics, synthetic-community engineering, metabolic modelling, real-time process monitoring, artificial intelligence, and biorefinery concepts to develop stable and scalable microbial-consortium systems for high-efficiency food-waste valorisation (Soon *et al.*, 2025; Kaur *et al.*, 2025; Zhang *et al.*, 2026).

Heavy metal remediation

Heavy metals and metalloids such as lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), arsenic (As), nickel (Ni), and copper (Cu) are persistent environmental contaminants released through mining, industrial activities, agriculture, and improper waste disposal. Unlike organic pollutants, metals cannot be biologically degraded and may persist, bioaccumulate, and pose long-term ecological and health risks. Microbial consortia provide a sustainable approach to heavy-metal remediation through complementary mechanisms including biosorption, bioaccumulation, biotransformation, biomineralization, and redox transformation. Cell-wall functional groups and extracellular polymeric substances can bind metal ions, while microbial metabolism can alter metal speciation, mobility, and toxicity. Consortium-based systems may provide greater metabolic versatility and environmental adaptability than individual strains, particularly in complex or multi-metal contaminated environments (Zhang *et al.*, 2024; Khan *et al.*, 2025). Microbial consortia have therefore been investigated for the treatment of mining wastewater, industrial effluents, contaminated soils, and groundwater, with recent research emphasizing their potential for simultaneous metal immobilization and ecological restoration (Zhang *et al.*, 2024; Mallick *et al.*,

2025). Microalgae–bacterial consortia represent another promising strategy because algal biomass provides abundant metal-binding functional groups, while bacterial partners can contribute complementary transformation and detoxification processes. Biosorption, ion exchange, complexation, precipitation, and bioaccumulation can collectively contribute to metal removal, although efficiency is strongly influenced by pH, metal speciation, biomass characteristics, temperature, and competing ions (Machado *et al.*, 2024). Recent studies also emphasize the potential of microbial consortia in arsenic-contaminated agricultural soils, where microbial interactions can influence arsenic oxidation–reduction, methylation, immobilization, and bioavailability (Zhang *et al.*, 2024). Despite these advantages, high metal concentrations may inhibit microbial activity, while environmental variability, competition among consortium members, metal remobilization, and difficulties in maintaining long-term community stability can limit field performance. Consequently, metagenomics, microbial-network analysis, engineered consortia, and site-specific bioaugmentation strategies are increasingly being explored to develop stable and predictable heavy-metal bioremediation systems (Khan *et al.*, 2025; Zhang *et al.*, 2026).

Advanced Technologies in Microbial Consortia for Waste Management

Recent advances in biotechnology, molecular biology, and computational science have significantly deepened the understanding and expanded the application of microbial consortia in waste management. Traditional microbiological techniques often fail to capture the full complexity of microbial communities and their interactions; metagenomics, CRISPR-based genome engineering, artificial intelligence and machine learning, biosensors, and bio electrochemical systems have collectively transformed the design, monitoring, and optimisation of microbial consortia, enhancing degradation efficiency, resource recovery, and environmental sustainability.

Metagenomics

Recent advances in metagenomics, genome engineering, and artificial intelligence (AI) are transforming the design and optimization of microbial consortia for sustainable waste management. Metagenomic and genome-resolved approaches enable culture-independent identification of microorganisms, functional genes, metabolic pathways, and interspecies interactions within complex communities, providing valuable information for optimizing anaerobic digestion, composting, biodegradation, and resource recovery (Kim *et al.*, 2022; Ghiotto *et al.*, 2024; Ostos *et al.*, 2024). CRISPR-based genome engineering further enables precise modification of microbial strains to enhance pollutant-degradation pathways, enzyme production, stress

tolerance, and conversion of recalcitrant substrates such as PET, thereby facilitating the development of more functional synthetic microbial consortia (Jourdain & Gu, 2025; Zhou *et al.*, 2024). In parallel, AI and machine-learning approaches can integrate metagenomic, physicochemical, and real-time process data to predict microbial community dynamics, identify influential operational parameters, optimize consortium composition, and improve process stability and treatment efficiency (Gupta *et al.*, 2024; Chen *et al.*, 2025). The integration of multi-omics, CRISPR engineering, and AI therefore provides a promising framework for developing precision microbial consortia capable of targeted waste degradation and resource recovery. However, challenges including genetic stability, horizontal gene transfer, ecological uncertainty, data quality, model interpretability, biosafety, and regulatory requirements must be addressed before widespread field-scale application (Jourdain & Gu, 2025; Chen *et al.*, 2025). Biosensors are analytical devices that integrate biological recognition elements with physicochemical or electrochemical transducers for rapid detection of environmental contaminants and process parameters. In microbial-consortium-based waste treatment, microbial and bioelectrochemical biosensors can be used for monitoring heavy metals, toxic pollutants, biochemical oxygen demand (BOD), and microbial activity, thereby providing rapid indications of changes in treatment performance and contamination levels. Recent advances in microbial bioelectronic sensors have improved the sensitivity, selectivity, and potential for continuous environmental monitoring, while electrochemical BOD biosensors provide faster and potentially real-time alternatives to conventional BOD measurements (Velusamy *et al.*, 2022; Li *et al.*, 2025; 2024). Thus, biosensors can complement microbial treatment systems by enabling early detection of pollutants and supporting process monitoring and control. Bioelectrochemical systems (BESs) integrate microbial metabolism with electrochemical processes to simultaneously treat wastes and recover energy or other valuable resources.

Microbial fuel cells (MFCs) convert organic substrates into electricity through extracellular electron transfer, whereas microbial electrolysis cells (MECs) use an external electrical input to facilitate hydrogen production; microbial desalination cells (MDCs) additionally combine wastewater treatment with desalination (Radeef & Najim, 2024; Adepitan *et al.*, 2025). MFCs have demonstrated potential for wastewater treatment, biosensing, heavy-metal remediation, and bioenergy recovery, while advances in electrode materials, reactor design, and microbial engineering are improving their performance (Suleiman *et al.*, 2026). Despite these advantages, high electrode and membrane costs, biofouling, low power density, operational stability, and difficulties in scaling up from laboratory systems remain important challenges. Continued integration of BESs with microbial consortium engineering

and data-driven optimization may further improve their recovery. applicability for sustainable waste treatment and resource

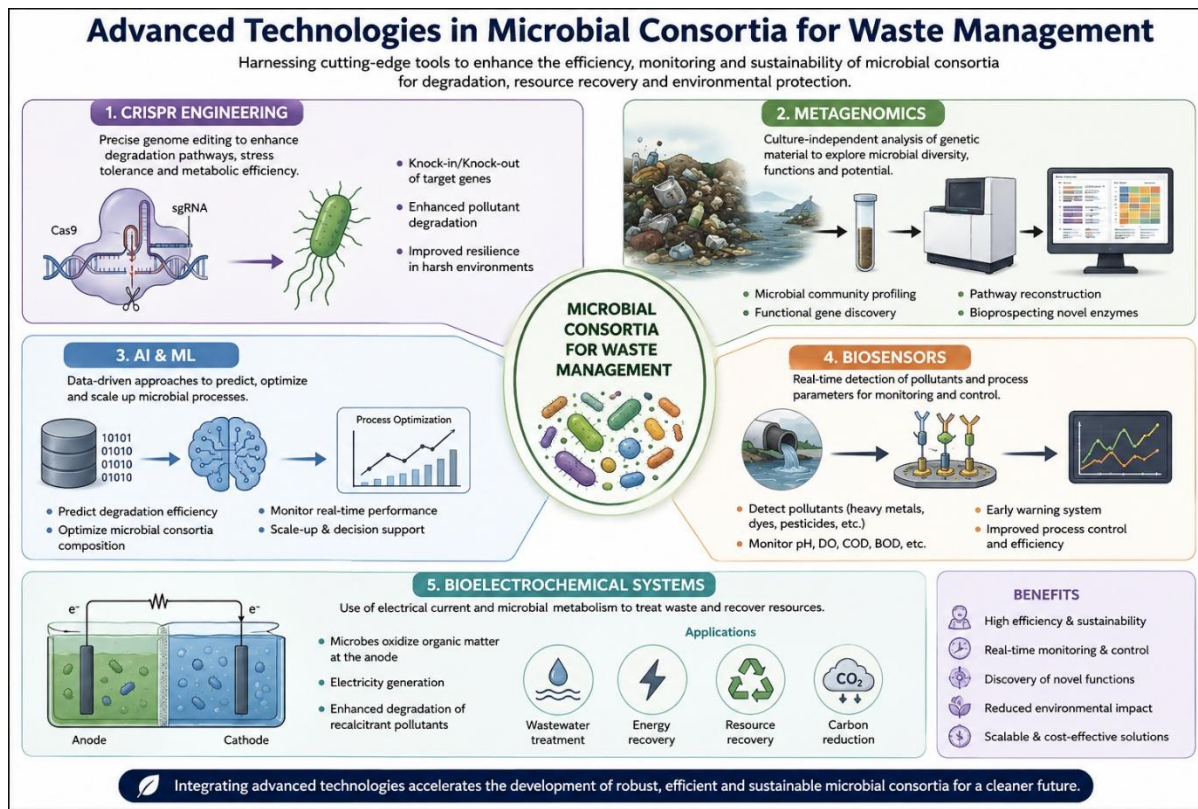


Figure 3. Integrating advance technologies in microbial consortia for waste management (Source: AI generated image).

CONCLUSION

Microbial consortia occupy a distinctive position among waste-management strategies: they combine the metabolic breadth needed to address chemically heterogeneous, real-world waste streams with a cost and emissions profile that compares favourably with landfilling, incineration, and chemical treatment. This review has traced that potential from its ecological foundations such as the classification of consortia into natural, synthetic, and engineered categories, and the synergistic metabolism, cross-feeding, biofilm formation, and quorum sensing mechanisms that underlie their function through to their demonstrated applications in solid waste management, plastic biodegradation, wastewater treatment, food waste valorisation, and heavy-metal remediation. The convergence of consortia with metagenomics, CRISPR-based genome engineering, artificial intelligence and machine learning, biosensors, and bioelectrochemical systems is now shifting the field from empirically assembled communities toward rationally designed biological platforms whose composition, interactions, and performance can be predicted and controlled with increasing precision. Nevertheless, meaningful barriers remain: consortium instability, inter-strain competition, scale-up difficulty, and an unsettled regulatory landscape for genetically engineered organisms

collectively constrain the pace at which laboratory successes translate into field-deployed systems. Addressing these barriers through smart, adaptively controlled bioreactors, AI-guided consortium design, and tighter integration with circular-bioeconomy value chains represents the clearest path toward realising the full potential of microbial consortia as a mainstream, sustainable pillar of global waste management.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declare that no AI and related tools are used to write the scientific content of this manuscript and Image generating Chat GPT used.

DATA AVAILABILITY

Data will be available on request

REFERENCES

- Adedayo, A., et al. (2025). Bioelectrochemical systems for waste treatment and valorization: A review of applications and benefits. *Biofuels, Bioproducts and Biorefining*, 19(6), 2700–2711. doi:10.1002/bbb.70035
- Ahmad, R., Malik, A., Khan, Z., & Rehman, A. (2025). Reductive biodegradation of pharmaceutical pollutants using synthetic microbial consortia. *Biotechnology Advances*, 66, 108045.
- Ahmed, S., et al. (2025). A mini-review on the role of PETase in polyethylene terephthalate degradation. Reviews in *Environmental Science and Bio/Technology*. doi:10.1007/s11157-025-09737-3
- Ali, M. I., Hassan, S., & Farooq, M. (2023). Biohydrogen and methane co-generation from organic waste using syntrophic microbial consortia. *Renewable Energy*, 214, 1023–1031.
- Antonopoulou, I., et al. (2025). Polyethylene biodegradation: A multifaceted approach. *Biotechnology Advances*. doi:10.1016/j.biotechadv.2025.108577
- Application of compatible lignocellulolytic fungal consortia for quality composting of leaf litter and assessment of the end products. (2024). *Bioresource Technology Reports*, 25, 101800. doi:10.1016/j.biteb.2024.101800
- Assis, T. I., Gonçalves, R. F., et al. (2022). Valorization of food waste by anaerobic digestion: A bibliometric and systematic review focusing on optimization. *Journal of Environmental Management*, 320, 115763. doi: 10.1016/j.jenvman.2022.115763
- Chaiwong, C., Danaee, S., & Vo, T. P. H. (2024). Microalgae-bacteria consortia for organic pollutants remediation from wastewater: A critical review. *Journal of Environmental Chemical Engineering*, 12(6), 114213. doi: 10.1016/j.jece.2024.114213
- Chen, J., Wang, X., Zhou, L., & Hu, Y. (2023). Bioremediation of heavy metals using engineered *Bacillus subtilis* and *Pseudomonas aeruginosa* consortia. *Environmental Science and Pollution Research*, 30, 40012–40025.
- Chen, X., Lei, Z., Chang, J.-S., & Lee, D.-J. (2025). Navigating future wastewater treatment plants with artificial intelligence: Applications, challenges, and innovations. *Journal of Cleaner Production*, 504, 145467. doi: 10.1016/j.jclepro.2025.145467
- Desai, T., Sharma, S., & Patel, R. (2024). Recovery of phosphorus from wastewater using synthetic microbial consortia. *Journal of Environmental Management*, 342, 118278.
- Exploring different *Pseudomonads* strains with efficient cellulolytic, pectinolytic, proteolytic, and lipolytic activity in consortia for bioaugmentation of sustainable urban organic waste composting. (2025). *Cleaner Waste Systems*, 12, 100405. doi: 10.1016/j.clwas.2025.100405.
- Ghiotto, G., et al. (2024). Current status and future developments of assessing microbiome composition and dynamics in anaerobic digestion systems using metagenomic approaches. *Heliyon*, 10(6), e28221. doi: 10.1016/j.heliyon. 2024.e28221.
- Gupta, R., Hajabdollahi Ouderji, Z., Uzma, Yu, Z., Sloan, W. T., & You, S. (2024). Machine learning for sustainable organic waste treatment: A critical review. *NPJ Materials Sustainability*, 2, 5. doi:10.1038/s44296-024-00009-9
- Jeyachandran, S., et al. (2025). Microbial consortium-mediated degradation of polyethylene terephthalate in orthodontic aligners: A comprehensive review. *International Journal of Microbiology*. 2, 5. doi:10.1033/s44296-024-00009-8.
- Jourdain, L., & Gu, W. (2025). Designing synthetic microbial communities for enhanced anaerobic waste treatment. *Applied and Environmental Microbiology*. doi:10.1128/aem.00404-25
- Kaur, A., et al. (2025). Innovative approaches in microbial community engineering for food waste management: A comprehensive review. *Journal of Environmental Management*, 393, 127000. doi: 10.1016/j.jenvman.2025.127000
- Kavya, V., Vashisht, M., Jain, B., & Shrivastava, S. (2024). Transforming waste into wealth: A review on microbial conversion of organic municipal wastes to value-added products. *Discover Environment*, 2, 112. doi:10.1007/s44274-024-00144-z
- Khan, M. A., et al. (2025). Harnessing microbes and plants for bioremediation of heavy metal contaminants: Current paradigms and future perspectives. *Environmental Challenges*, 20, 101220. doi: 10.1016/j.envc.2025.101220
- Kim, N.-K., Lee, S.-H., Kim, Y., & Park, H.-D. (2022). Current understanding and perspectives in anaerobic digestion based on genome-resolved metagenomic approaches. *Bioresource Technology*, 344, 126350. doi: 10.1016/j.biortech.2021.126350
- Kumar, N., Das, S., & Basu, R. (2023). Engineering quorum sensing circuits in synthetic microbial consortia

- for biotechnological applications. *Synthetic and Systems Biotechnology*, 8(2), 98–109.
- Kumar, R., et al. (2023). Current advances in the structural biology and molecular engineering of PETase. *Frontiers in Bioengineering and Biotechnology*. doi:10.3389/fbioe.2023.1263996
- Li, L., Chai, W., Sun, C., Huang, L., Sheng, T., Song, Z., & Ma, F. (2024). Role of microalgae-bacterial consortium in wastewater treatment: A review. *Journal of Environmental Management*, 360, 121226. doi: 10.1016/j.jenvman.2024.121226
- Li, S., Zuo, X., Carpenter, M. D., Verduzco, R., & Ajo-Franklin, C. M., et al. (2025). Microbial bioelectronic sensors for environmental monitoring. *Nature Reviews Bioengineering*, 3, 30–49.
- Liu, S., Kong, Z., Guo, H., Zhang, Y., Han, X., Gao, Y., Song, G. (2024). Performance, mechanism regulation and resource recycling of bacteria-algae symbiosis system for wastewater treatment: A review. *Environmental Pollution*, 362, 125019. doi: 10.1016/j.envpol.2024.125019
- Machado, A. A., Valiarampam, J. G., & Lavanya, M. (2024). Unlocking the potential of algae for heavy metal remediation. *Water, Air, & Soil Pollution*, 235, 629. doi:10.1007/s11270-024-07436-3
- Malick, S., et al. (2025). Comprehensive approaches to heavy metal bioremediation: Integrating microbial insights and genetic innovations. *Journal of Environmental Management*, 374, 123969. doi: 10.1016/j.jenvman.2024.123969
- Mali, R. H., Ghante, P. H., Magar, S. J., Patil, N. H., & Kuthumbare, R. S. (2024). Evaluation of different microbial consortia for decomposing different wastes: An in vitro and in vivo study approach. *Journal of Advances in Biology & Biotechnology*, 27(11), 1140–1147.
- Mancini, G., et al. (2024). Microbial upcycling of food waste using anaerobic digestion for energy and single cell protein production. *Current Opinion in Food Science*, 57, 101173. doi: 10.1016/j.cofs.2024.101173
- Martínez, A., et al. (2025). Effect of operating conditions on food waste fermentation to enhance VFA production and propionic acid selectivity. *Environmental Technology & Innovation*, 39, 104324. doi: 10.1016/j.eti.2025.104324
- Matsakas, L., et al. (2025). Polyethylene biodegradation: A multifaceted approach. *Biotechnology Advances*. doi:10.1016/j.biotechadv.2025.108577
- Ostos, I., Flórez-Pardo, L. M., & Camargo, C. (2024). A metagenomic approach to demystify the anaerobic digestion black box and achieve higher biogas yield: A review. *Frontiers in Microbiology*, 15, 1437098. doi:10.3389/fmicb.2024.1437098
- Prakash, A., et al. (2025). Bacterial consortia as potential bioremediation agents for wastewater treatment: A comprehensive review. *International Journal of Advancement in Life Sciences Research*, 8(1), 16–33.
- Qattan, S. Y. (2025). Harnessing bacterial consortia for effective bioremediation: Targeted removal of heavy metals, hydrocarbons, and persistent pollutants. *Environmental Sciences Europe*, 37, 85.
- Radeef, A. Y., & Najim, A. A. (2024). Microbial fuel cell: The renewable and sustainable magical system for wastewater treatment and bioenergy recovery. *Energy*, 100001. doi: 10.1016/j.energy.2024.100001
- Rathour, R. K., Sharma, D., Ullah, S., Mahmoud, E. H. M., Sharma, N., Kumar, P., & Bhatt, A. K. (2024). Bacterial–microalgal consortia for bioremediation of textile industry wastewater and resource recovery for circular economy. *Biotechnology for the Environment*, 1, 6. doi:10.1186/s44314-024-00005-2
- Soni, P. K., Anand, K., Mishra, M., & Sarkar, A. (2025). Synthetic microbial consortia for bioremediation and circular bioeconomy: A review. *International Journal of Current Microbiology and Applied Sciences*, 14(8), 161–166.
- Soon, W. L., Foo, J. L., & Chang, M. W. (2025). Microbial food waste valorization: Advances, challenges, and perspectives. *Current Opinion in Biotechnology*, 94, 103323. doi: 10.1016/j.copbio.2025.103323
- Suleiman, A. I., Opisa, A. N., Idris, M. O., et al. (2026). Bioelectrochemical energy conversion and wastewater treatment in microbial fuel cells: A review of progress, limitations, and future developments. *Bioresource Technology*, 443, 133903. doi: 10.1016/j.biortech.2025.133903
- Tanasupawat, S., et al. (2022). Microbial consortia and mixed plastic waste: Pangenomic analysis reveals potential for degradation of multiple plastic types via previously identified PET-degrading bacteria. *International Journal of Molecular Sciences*, 23(10), 5612. doi:10.3390/ijms23105612
- Velusamy, K., Periyasamy, S., Kumar, P. S., et al. (2022). Biosensor for heavy metals detection in wastewater: A review. *Chemosphere*.
- Wu, F., Kong, F., Liu, B.-F., Song, X., Ren, N.-Q., & Ren, H.-Y. (2025). Applications, challenges and prospects on efficient and reliable bacterial-algal symbiosis system for wastewater treatment: A systematic review. *Journal of Cleaner Production*, 509, 145605. doi: 10.1016/j.jclepro.2025.145605
- Zhang, J., Zhou, Q., Wang, R., Wang, H., Zeng, H., Wu, K., Ouyang, S. (2026). Microalgal–bacterial consortia for wastewater treatment. *Nature Reviews Clean Technology*. doi:10.1038/s44359-026-00212-y
- Zhang, X., et al. (2024). Microbial consortia-mediated arsenic bioremediation in agricultural soils: Current status, challenges, and solutions. *Science of the Total Environment*.

- Environment, 917, 170297. doi: 10.1016/j.scitotenv.2024.170297
- Zhang, Y., et al. (2025). Recent progresses and perspectives of polyethylene biodegradation by bacteria and fungi: A review. *Journal of Contaminant Hydrology*, 269, 104499.
- Zhang, Y., et al. (2026a). Harnessing energy from food waste via anaerobic digestion: A comprehensive review. *Applied Food Research*, 6(1), 101914. doi: 10.1016/j.afres.2026.101914.
- Zhang, Y., et al. (2026b). Microbial consortia in mine water bioremediation: Principles, design and practical applications. *Water Research*, 289, 124956. doi: 10.1016/j.watres.2025.124956.
- Zhang, Y., Shen, Y., Ding, J., Zhou, H., Zhao, H., Cheng, H., Jia, Y. (2025). Optimization of microbial consortium formulation for oily food waste composting using mixture design methodology. *Microorganisms*, 13(9), 2066. doi:10.3390/microorganisms13092066.
- Zhou, S.-P., Ke, X., Jin, L.-Q., Xue, Y.P., & Zheng, Y.-G. (2024). Sustainable management and valorization of biomass wastes using synthetic microbial consortia. *Bioresource Technology*, 395, 130391. doi: 10.1016/j.biortech.2024.130391.
- Zhou, Y., & Zeeshan Ul Haq, M. (2025). Engineering of synthetic microbial consortia for sustainable management of wastewater and polyethylene terephthalate: A comprehensive review. *International Journal of Molecular Sciences*, 26(23), 11623.

