



Editorial

Unlocking new quality productive forces from biowaste valorization through the 5B initiative



A B S T R A C T

The escalating anthropogenic biomass production leads to an unprecedented rise in biowaste generation, exceeding the decomposition capacity of natural microbial communities. This disturbance of global nutrient cycling substantially threatens the habitability and thriving of Earth's life system. To address this challenge, the newly launched 5B Initiative (Biowaste, Bioconversion, Bioproduct, Biosafety, and Bioeconomy) provides a global collaborative framework that drives a paradigm shift from waste to wealth by four synergistic objectives: characterizing biowaste generation, advancing bioconversion technology, enhancing biosafety, and facilitating the bioeconomy. Integrating above objectives, the 5B initiative plan to propose a BioCyclos model framework, that traces and optimizes biomass bioconversion processes in bioresource-biowaste-bioprocess chain to promote bioeconomy and ensure biosafety. This integrated platform positions biowaste-to-bioprocess conversion alongside nature-based solutions and thereby promotes the transition toward a circular, decarbonized, and sustainable bioeconomy while restoring and maintaining balance in Earth's nutrient cycles.

1. Introduction

Nutrient cycling across the biosphere is essential to sustaining Earth's habitability and life's flourishing. Since the advent of agricultural civilization, humanity has progressively intensified biomass production, primarily plant cultivation and animal husbandry, to feed the rapidly growing population, especially in the past century. As striking indicators, the agricultural land has expanded to nearly 40 % of Earth's terrestrial surface (Foley et al., 2011), and the biomass of livestock and poultry now exceeds that of wild mammals and birds (Bar-On et al., 2018).

Yet, the expansion of anthropogenic biomass production has also led to an unprecedented rise in biowaste generation. More than 2×10^4 Mt of biowaste (dry mass) is generated annually in an 8-billion-people world (Hamelin et al., 2019). Beyond organic nutrients, such biowaste often contains residual antibiotics, veterinary drugs, heavy metals, pathogens, and other chemical contaminants derived from agricultural and industrial practices (Frey et al., 2022). Across many regions and ecosystems, biowaste loads outstrip the decomposition capacity of natural microbial communities, disrupting natural nutrient cycling. Unrecycled nutrients from biowaste disposal will be lost to the environment, and in turn, cause substantial negative ecological and environmental impacts, such as freshwater eutrophication, air pollution, soil degradation, global warming, and phosphate depletion (Galloway et al., 2008; Liu et al., 2016).

To restore balance in biosphere nutrient cycling, it is urgent to understand the biowaste generation characteristics and advance biowaste-to-bioprocess conversions and valorization by targeted enhancement of microbial decomposition functions (Aggarwal et al., 2024). In parallel, ecological and health risks must be mitigated to ensure biosafety across the entire biowaste-to-bioprocess chain. More importantly, the converted bioproducts should achieve both high value and commercial

applicability, meaning bioconversion technologies should create new quality productive forces that advance the circular bioeconomy rather than merely producing outputs. Accordingly, comprehensive cost-benefit analyses and life-cycle assessments of both conversion pathways and risk prevention measures are indispensable for understanding socioeconomic feasibility and promoting stakeholders' attitudes. Collectively, these needs motivate an integrated research framework linking biowaste, bioconversion, bioproduct, biosafety, and bioeconomy (5B) to support the sustainable development of Earth's life system (see Fig. 1).

2. Future research directions

2.1. Tailoring conversion pathways to biowaste characteristics

Biowaste, defined as biodegradable waste/residual biomass from biomass production and processing, mainly includes crop residues, animal manure, forestry residues, food processing by-products, food waste, human excretion, sewage sludge, and their corresponding digestates. Biowaste has been regarded as a vital bioresource due to its large volume and its non-competition with food resources. Annual biowaste (dry mass) generation is estimated as 2×10^4 Mt, containing about 6000 Mt of carbon (C), 230 Mt of nitrogen (N), and 40 Mt of phosphorus (P) (Hamelin et al., 2019; Kang et al., 2020). Astonishingly, biowaste C is 100-fold greater than human biomass C (~60 Mt C) (Bar-On et al., 2018). Biowaste C is most abundant in crop and forestry residues, while N and P are most plentiful in animal manure. The heterogeneity of sources results in biowaste with diverse composition and variable spatial-temporal distribution. Therefore, biowaste characteristics must be considered when developing efficient conversion pathways to extract and recover valuable nutrient resources (Raniero et al., 2025). It is also important to monitor the evolution of the overall picture of nutrients

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Fig. 1. The contents and visions of the 5B initiative.

from raw biowaste to mid-products such as digested materials.

Lignocellulose-rich biowastes, primarily crop and forestry residues, provide abundant organic C resource, yet structural recalcitrance impedes efficient biodegradation (Aggarwal et al., 2024). Prevalent conversion pathways like incineration and materialization focus on addressing technological barriers in lignocellulose decomposition, but pay little attention on improving cost-effectiveness and environmental benefits. Furthermore, seasonal changes and dispersed distribution of biowaste generation necessitates developing both on-site small-scale systems and centralized processing plants to accommodate fluctuating substrate quantities and compositions.

Nutrient-rich biowastes such as animal manure and sewage sludge offer significant fertilization value, but require careful management of hazardous contaminants including antibiotics and heavy metals. Geographic disconnection between manure generation and use locations also presents a substantial barrier to manure recycling, especially in regions dominated by intensive livestock farming (Cheng et al., 2023; Raniro et al., 2025). Separating and converting distinct nutrient components in manure into high-value bioproducts can directly mitigate nutrient surpluses while improving supply-demand matching by extending economically feasible transport distance (Cheng et al., 2025).

Readily biodegradable wastes, including food waste and food-processing by-products, contain valuable nutritional components (carbohydrates, proteins, lipids) but are often managed with an emphasis on rapid disposal rather than resource recovery and waste valorization. Emerging conversion pathways such as insect farming, microbial protein production and solid-state fermentation offer higher-value bioproducts such as nutrient-rich feed, commercial biofertilizers, biosurfactants, antibiotics, pigments and aromas (Sánchez, 2022), while reducing environmental impacts, compared to conventional treatment methods

(Javourez et al., 2025).

The imperative for future research lies in tighter integration between biowaste characteristics, efficient nature-based technologies, and high-value bioproducts, ensuring that conversion pathways are technically feasible at commercial scale, economically viable, and environmentally sustainable across diverse biowaste types and regional contexts, while simultaneously promoting employment growth, advancing bioeconomic development, and creating new quality productive forces.

2.2. Enhancing bioconversion efficiency and economic valorization

The bioconversion represents the most promising way for biowaste-to-bioproduction transformation and valorization, offering distinct advantages over purely physical or chemical treatments in terms of operational costs, environmental sustainability, and product diversity (D'Hondt et al., 2021). Microbial engineering can transform heterogeneous biowastes into valuable bioproducts including nutraceuticals, pharmaceuticals, biomaterials, and biofertilizers, for which sustainable alternatives are often limited or non-existent (Aggarwal et al., 2024; Muscat et al., 2021). Despite widespread application in biowaste management, current bioconversion technologies face significant challenges in achieving optimal nutrient recovery efficiency and maximizing bioeconomic value, particularly when scaling from laboratory to industrial implementation.

The core challenge lies in optimizing microbial conversion efficiency while minimizing energy inputs, nutrient losses and emissions. Current bioconversion systems often achieve suboptimal yields due to substrate recalcitrance, microbial community instability, and inefficient mass transfer. For instance, anaerobic digestion typically recovers only 40–60 % of the theoretical methane potential from biowaste, while

leaving nearly all of N and P in digestate (Li et al., 2026). These inefficiencies represent significant economic and resource losses that undermine the circular bioeconomy paradigm.

Recent advances in microbial engineering offer promising pathways to enhance bioconversion efficiency (Aggarwal et al., 2024). Synthetic microbial consortia designed for specific biowaste can significantly improve degradation kinetics and product yields. Metabolic engineering approaches enable the redirection of microbial pathways toward desired end-products. Furthermore, enzyme engineering facilitates the development of robust biocatalysts capable of degrading recalcitrant biowaste components under industrial conditions.

Bioreactor design and process optimization constitute another critical dimension for value maximization (Shah and Bala, 2025). Advanced bioreactor configurations, including membrane bioreactors, tray reactors, trickling filters, and multi-stage systems, enable better control over environmental parameters and microbial community dynamics. Real-time monitoring and adaptive control systems can optimize process parameters (e.g., pH, temperature, hydraulic retention time) to maintain optimal conditions for microbial activity and product formation. Integration of artificial intelligence and machine learning algorithms further enhances predictive control and optimization of bioconversion processes, as some biotechnologies cannot fully be interpreted using the traditional chemical engineering modelling techniques.

The economic viability of biowaste bioconversion depends critically on producing value-added bioproducts. While energy recovery (e.g., biogas, bioethanol, green hydrogen, methanol or ammonia) remains important, the highest value opportunities lie in nutrient recovery and specific chemical material production. For example, N and P recovery as concentrated forms can provide valuable fertilizers, while protein extraction from food waste offers opportunities for animal feed and ingredients. Additionally, the production of bioactive compounds, enzymes, and biopolymers from biowaste streams represents emerging high-value markets (Shirvani, 2024).

However, scaling these technologies from laboratory to industrial implementation faces significant hurdles. Process intensification through reactor miniaturization, novel separation techniques, energy integration, and commercial downstream techniques can reduce capital and operational costs. Life cycle assessment and techno-economic analysis must guide technology development to ensure both environmental benefits and economic competitiveness, considering the entire process (Liu et al., 2023).

Ultimately, maximizing the value of biowaste bioconversion requires an integrated approach combining microbial engineering, process optimization, and market-driven bioproduct development to transform biowastes into valuable bioproducts within a circular bioeconomy framework (Muscat et al., 2021).

2.3. Ensuring biosafety across the bioconversion chain

Preventing biological risks must be integrated into the comprehensive research framework for biowaste bioconversion, to ensure both ecological and human health. The biological risk factors include known hazardous materials such as pathogenic microorganisms, antibiotic resistance genes (ARGs), and chemical contaminants (e.g., heavy metals, persistent organic pollutants, toxic gases, and microplastics), as well as unintended threats arising from engineered DNA produced by synthetic biotechnologies (Mo et al., 2024). Effective biological risk prevention requires identifying risk factors, assessing ecological and human health impacts, and interrupting transmission pathways.

Previous studies have identified conventional risk factors (as mentioned before, pathogenic microorganisms, ARGs, and chemical contaminants) from the perspective of hazardous residues in biowaste or bioproducts. Emerging risks from engineered biological systems represent a novel challenge in biowaste conversion. Synthetic biology applications, while promising for enhanced bioconversion efficiency, introduce genetically modified microorganisms (GMMs) and engineered

DNA sequences that may persist in treatment systems and potentially transfer to environmental microbiota. Advanced detection technologies, including metagenomics, biosensors, and mass spectrometry, enable comprehensive hazard profiling and real-time monitoring to identify both conventional and emerging biological risks (Mo et al., 2024).

Targeted strategies are needed to effectively interrupt the transmission of biological risk factors. Aerosol dispersion during biowaste storage and treatment and during bioproduct management represents a significant pathway for pathogen spread, which can be effectively controlled through advanced filtration systems and negative pressure containment environments. Leachate-mediated soil and water pollution requires engineered barrier systems and real-time monitoring networks to prevent migration of biological contaminants. For product-borne exposure routes, UV-treatment, thermal treatment and advanced oxidation processes have proven effective in disrupting pathogen viability while preserving product quality. The dissemination of ARGs poses a particular challenge because they can spread horizontally within microbial communities. Microbial community engineering approaches that reshape microbial populations to outcompete ARG-carrying bacteria offer promising solutions to limit environmental transmission. Similarly, engineered DNA from synthetic biology applications demonstrates unexpected persistence, maintaining functionality even after cell death. To address this emerging risk, specialized countermeasures need to be developed. For instance, dedicated nuclease-based degradation systems can specifically cleave recombinant DNA sequences. Advanced adsorption technologies can physically immobilize such engineered DNA before environmental release.

Ecological risk assessment requires addressing the complex fate and transport of these biological contaminants. Integrated assessment frameworks combining laboratory bioassays, field monitoring, and computational modeling provide holistic risk characterization across trophic levels. This includes evaluating pathogen persistence in soil-plant systems, heavy-metal bioaccumulation in food chains, and the potential ecological impacts of engineered DNA dissemination into environmental microbiota.

By integrating advanced detection, targeted intervention, and systematic monitoring, we can transform biosafety management from reactive compliance to proactive prevention. This paradigm shift unlocks the full potential of biowaste valorization while simultaneously safeguarding ecological integrity and human health against both conventional and emerging biological risks.

2.4. Promoting circular and sustainable bioeconomy for co-benefits

A well-designed bioeconomy must align with broader sustainability principles, such as the Sustainable Development Goals (SDGs), planetary boundaries, and circular economy. Unlike traditional linear economic models, a sustainable bioeconomy should not merely substitute fossil-based resources with bio-based alternatives, but create regenerative systems where biomass utilization delivers social, economic, and environmental co-benefits. This requires balancing synergies and trade-offs between bioeconomy and other sustainability principles. For instance, the bioeconomy has the potential to reduce waste (SDG 12), promote sustainable water and sanitation management (SDG 6), lower greenhouse gas emissions (SDG 13), improve health and well-being (SDG 3), and enhance food security (SDG 2) by closing nutrient loops. However, if not carefully managed, excessive biomass extraction can create trade-offs, competing with food production and placing additional pressure on land and water resources, thereby risking transgression of planetary boundaries (Warchold and Pradhan, 2025). Understanding these interactions is essential to ensure that bioeconomy strategies contribute positively to both local and global sustainability agendas. In this context, biowaste utilization emerges as a priority in bioeconomy because it avoids food competition and mitigates environmental burdens.

The direction and extent of bioconversion are key questions in the sustainable transition to a circular bioeconomy (Carus and Dammer,

2018; Muscat et al., 2021). Not all biowaste is equally suitable for all purposes, and the choice of biowaste-to-bioprocess pathways must be guided by comprehensive principles, including nutrient-use efficiency, economic viability, and environmental impacts. For example, lignocellulosic waste, such as crop residues, should be targeted for high-value bioproducts, such as biochemicals or biomaterials, rather than low-efficiency energy recovery. Cascading utilization, where biomass is repurposed through multiple value-adding stages before final disposal, further enhances efficiency, ensuring that each unit of biomass delivers maximum economic and environmental returns (Carus and Dammer, 2018). Building on existing principles, we propose that the primary goal of biowaste utilization should be to restore the balance of natural biogeochemical cycles. This goal can be achieved by a cascading utilization strategy: first, converting biowaste into regenerative nutrients that can re-enter nutrient cycles (e.g., animal feed, fertilizers, and pharmaceuticals); second, transforming it into bio-based materials (e.g., fibers and chemicals) to replace nonrenewable resources; and third, utilizing residual streams for bioenergy production. This cascading utilization strategy can ensure systemic efficiency and sustainability.

The regional context of bioproduct supply and demand is pivotal in determining the most effective bioeconomy strategy. For example, energy-limited or fossil-fuel-dependent regions, biowaste-to-energy pathways such as biogas or biochar production may offer critical benefits by displacing nonrenewable and polluting fuels. Conversely, in areas with abundant renewable energy, bioenergy may be a lower priority compared to higher-value bioproducts. Similarly, nutrient-rich waste, such as animal manure, should be converted into biofertilizers only where agricultural demand exists, to avoid oversupply and unintended nutrient pollution (Cheng et al., 2025). In nutrient-surplus regions, converting such biowaste into transportable nutrient concentrates (e.g., struvite pellets) can help redistribute them to nutrient-deficient areas and close loops at a broader scale. Therefore, an optimal bioeconomy strategy may not exist, because no single strategy can be universally applied to all regions. The design of bioeconomy strategies must be regional-specific, adapting to local circumstances and urgent requirements.

Achieving a circular bioeconomy also requires transcending technological solutions to integrate socioeconomic dimensions (Khanna et al., 2024). Trade-offs among economic costs, environmental benefits, and social justice should be considered to guide the circularity level (Khanna et al., 2024). Policy coherence is essential; specifically, subsidies, regulations, and sustainability targets should incentivize systemic circularity rather than isolated bio-based substitutions. By grounding bioeconomy development in context-specific, circular, and co-benefit-driven approaches, we can ensure that biomass valorization strengthens rather than disrupts the delicate balance of social-ecological systems. The ultimate goal is a bioeconomy that not only reduces waste and emissions but also enhances resource security, supports livelihoods, and regenerates ecosystems (Bracco et al., 2019).

3. Launch of the 5B initiative: A global collaborative framework

In response to the escalating anthropogenic disturbances to biosphere nutrient cycles, the 5B Initiative emerges as a pioneering international coalition uniting interdisciplinary scientific expertise (see Fig. 1). This groundbreaking collaboration is dedicated to transforming biowastes into high-value bioproducts. Through these efforts, the 5B Initiative will contribute to the sustainable development of Earth's life system by better integrating bioeconomy strategies with sustainability agendas (Warchold et al., 2025).

The 5B initiative pursues four synergistic objectives and one integrated model framework to address the complex challenges outlined in previous sections. First, it aims to comprehensively characterize global and regional biowaste generation, elucidating spatial-temporal variability and compositional heterogeneity. This foundational mapping provides the essential database for targeted intervention strategies.

Second, the initiative focuses on developing and optimizing advanced bioconversion technologies to transform diverse biowaste into valuable bioproducts. These efficient bioconversion technologies aim to maximize nutrient recovery efficiency and economic benefits while minimizing planetary burdens, thereby enriching nature-based solutions. Third, biosafety enhancement is a critical pillar that mitigates risks associated with biowaste bioconversion by comprehensive preventing and controlling conventional and emerging biological risk factors. Fourth, the initiative aims to design integrated and scalable management pathways aligned with bioeconomy principles, ensuring environmental sustainability, economic viability, and social equity in implementation. Integrating above objectives, the 5B initiative plan to propose a BioCyclos model framework, that traces and optimizes biomass bioconversion processes in bioresource-biowaste-bioprocess chain to promote bioeconomy and ensure biosafety.

Through interdisciplinary collaboration, technological innovation, and scalable solution development, the 5B Initiative establishes a cohesive roadmap not only for global biowaste valorization but also for simultaneous bioproduct production. This strategic framework advances the critical transition toward a circular, decarbonized, and sustainable bioeconomy, positioning biowaste-to-bioprocess conversion as a cornerstone of sustainable development. Current members of the 5B initiative, listed as co-authors of this paper, collectively emphasize the urgency of global collaboration to achieve these goals perfectly aligning to the United Nations 2030 Agenda for Sustainable Development consisting of 17 SDGs. We warmly invite researchers, practitioners, and stakeholders across disciplines to join the 5B initiative and contribute their expertise toward advancing the circular bioeconomy worldwide. Please contact Prof. Zengwei Yuan if you are interested.

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