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Are we misreading microbial value? Reframing industrial relevance through regenerative systems thinking

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1 Introduction: microbes beyond the "factory" metaphor

Industrial microbiology has largely developed around a simple image of microorganisms as efficient "cell factories", treated as production hosts or chassis to be tuned for higher titers, rates and yields (Kim et al., 2025). In this framing, microbes are platforms that can be integrated into tightly controlled processes and benchmarked by techno-economic performance.

In parallel, the vocabulary of a circular bioeconomy has become prominent in policy documents, strategic roadmaps and scientific editorials. Microorganisms are often highlighted as key enablers for closing carbon cycles, recycling waste and replacing fossil-derived inputs (Krüger et al., 2020). Yet many implementations remain centered on feedstock substitution rather than system redesign. Biofuels and bioplastics, for instance, frequently aim to swap fossil carbon for biomass-derived inputs, while leaving production chains and end-of-life pathways largely unchanged. A strain is considered "industrial" if it can be integrated into a plant, scaled reliably and compete on unit cost.

This combination of a circular narrative with linear criteria raises a central question: is microbial value being read too narrowly? When microbes are treated primarily as factories, their role is confined to converting inputs into products within a pipeline, and even fields such as precision fermentation remain largely product-centric (Eastham and Leman, 2024). A regenerative systems perspective instead views microorganisms as living, adaptive components of larger networks that regenerate soils, waters, microbiomes and material flows. This Opinion outlines how such reframing can be made operational by bringing regenerative capacity, system integration and ecological robustness into the core definition of industrial relevance.

2 Dominant logic: productivity as the main filter of relevance

Most descriptions of "industrial" microbial platforms converge on a familiar set of traits. Desirable strains exhibit high product yield and productivity, robust performance under specific process conditions, genetic tractability and compatibility with existing reactor infrastructure and downstream processing. In practice, this profile is embodied by a small group of domesticated hosts such as *Escherichia coli*, *Saccharomyces cerevisiae*, *Corynebacterium glutamicum* and *Bacillus* spp., which underpin many of today's processes for bulk chemicals, amino acids, organic acids and enzymes (Amer and Baidoo, 2021). These chassis are repeatedly optimized and standardized via design–build–test–learn cycles, high-throughput phenotyping pipelines and machine learning–guided workflows, consolidating their position as default production systems.

Even when discussions broaden to include robustness, stability or risk reduction during scale-up, the underlying logic remains production-centered. Microbial systems are typically represented as single-input, single-output units in process flow diagrams and techno-economic assessments, with performance collapsed into titers, rates, yields and cost per unit of product. Under this representation, the dimensions of ecological complexity that characterize multispecies communities—such as division of labor, cross-feeding, niche complementarity and long-term resilience—are difficult to translate into standard metrics and therefore rarely enter formal decision criteria. As a result, wild strains and naturally assembled consortia, which evolved to operate in heterogeneous, fluctuating environments and to distribute functions across partners, often appear "noisy" or inefficient, when forced into pure-culture, fixed-input, single-product processes, even when their native interaction patterns would be advantageous at the scale of a regenerative system.

This emphasis creates blind spots. Microorganisms that excel at metabolizing heterogeneous waste streams, stabilizing microbiomes or sustaining soil functions over long timeframes may perform modestly when judged only by liters of product per hour and cost per kilogram. As a result, they tend to be sidelined, even when their most significant contributions are systemic rather than linked to a single molecule. The overall portfolio of industrial processes therefore remains concentrated around a narrow set of domesticated model organisms, while the diversity of metabolically versatile and ecologically resilient microbes stays underused (Amer and Baidoo, 2021; Antranikian and Streit, 2022). This pattern does not reflect a lack of regenerative potential on the microbial side, but the way value is defined and operationalized in industrial decision-making.

3 Overlooked value: regenerative functions and emergent properties

Outside controlled bioreactors, microorganisms rarely function as single-product factories. Instead, they assemble into multispecies communities and microbiomes in which functions are distributed across taxa and constantly reshaped by interactions. Here, ecological complexity refers to properties that emerge at the community level: taxonomic and functional diversity, division of labor, cross-feeding and other metabolic exchanges, niche complementarity across space and time, feedbacks with the surrounding environment and redundancy that sustains function under disturbance. These features allow microbial communities to decompose complex organic matter, cycle nutrients, modulate host physiology and coordinate interactions across trophic levels, thereby supporting the regeneration of soils, waters and biogeochemical cycles (Antranikian and Streit, 2022).

This view aligns closely with the idea of regenerative systems, often illustrated through the etymology of *regenerare*, "to create again", in which life creates conditions conducive to life (Buckton et al., 2023). In agricultural systems, microbial communities are central to regenerative practices. Long-term regenerative agriculture has been shown to improve soil organic carbon, enhance nutrient availability and restructure bacterial communities in ways associated with healthier, more resilient soils (Singh et al., 2023). These benefits escape short-term yield metrics, yet they are crucial for sustained productivity and climate adaptation.

A widely implemented example is activated-sludge for municipal and industrial wastewater, in which complex microbial communities remove organic load, transform nitrogen and phosphorus, and attenuate pollutants. Metagenome-based analyses of full-scale plants indicate that the activated-sludge microbiome is structured into distinct functional niches, with different taxa contributing to carbon degradation, nutrient transformations and the handling of metals and other stressors (Wasmund et al., 2024). Full-scale transplantation experiments further show that these communities can be remarkably resilient: exchanging the entire sludge between donor and recipient wastewater treatment plants maintained effluent quality, while the recipient microbiome gradually re-established a site-specific community structure over successive solid-retention times (Dottorini et al., 2023).

Resource-oriented configurations with purple non-sulfur bacteria (PNSB) extend this logic. Photoanaerobic treatment of wastewater using PNSB has been proposed as an alternative to conventional aerobic polishing, coupling organic load removal with microbial biomass accumulation (San Martín et al., 2023). High-rate photobioreactors fed with agro-industrial or domestic effluents

can recover nitrogen and energy while producing PNSB biomass (Segura et al., 2023; Cai et al., 2025). Mixed-culture PNSB systems have also been evaluated for single-cell protein and polyhydroxyalkanoate production from domestic wastewater, linking treatment to feed and bioplastic precursors (Martin-Gamboa et al., 2023; Doki et al., 2024; Sakarika et al., 2025). Nutritional tuning of PNSB biomass grown on H_2 and CO_2 further illustrates how such platforms can supply tailored protein profiles for food and feed applications (Spanoghe et al., 2025). The primary value of these configurations lies in maintaining water quality and protecting receiving environments over the long term, simultaneously recovering resources. Yet this regenerative service is rarely described in terms of "industrial relevance", even though it underpins the viability of multiple sectors.

These cases illustrate a common pattern: value lies in microbiomes' ability to regenerate and stabilize entire environments. However, such functions are rarely encoded in criteria for industrial relevance. If performance continues to be reduced to yield and cost per kilogram, regenerative services grounded in ecological complexity remain peripheral, even when they are essential to a circular economy.

4 Omics and systems approaches as tools for regenerative insight

Multi-omics and systems biology have transformed the capacity to analyze and engineer microorganisms. Genomics, transcriptomics, proteomics and metabolomics, integrated with advanced modelling, enable detailed mapping of metabolic pathways, regulatory networks, and flux distributions. In industrial contexts, these tools are widely applied to identify bottlenecks, re-route flux and discover novel enzymes and biosynthetic pathways that support product-oriented optimization (Amer and Baidoo, 2021).

The same toolbox can, however, be directed toward different questions. Combined metagenomic and metabolomic studies of microbial consortia reveal how community composition, functional redundancy and cross-feeding contribute to robustness in waste degradation and nutrient-recovery processes. Rather than focusing solely on the yield of a particular compound, these analyses can characterize resilience, adaptability and cooperative behavior that sustain function under real-world variability (Krüger et al., 2020; Antranikian and Streit, 2022). Work on digitalization in microbiology and process engineering has also explored hybrid dynamic models that bring together omics data, process variables, and uncertainty quantification (Krüger et al., 2020). Although these frameworks are typically oriented toward improved control and predictability in established bioprocesses, they offer a basis for designing explicitly regenerative operations—for instance, processes where the primary goal is nutrient recovery, pollutant removal or microbiome restoration, and product formation is secondary or embedded in a broader system benefit.

Studies on PNSB further illustrate how omics-enabled approaches can resolve regenerative traits in concrete platforms. Integrated electrochemical, transcriptomic and metabolomic analyses of PNSB biofilms in microbial photo-electrosynthesis reveal how metabolic states can be tuned along redox and resource gradients (Díaz-Rullo Edreira et al., 2024). Nutrient-limited cultures of PNSB grown on H_2 and CO_2 show that nitrogen fixation and carbon allocation can be adjusted to modulate the nutritional profile of microbial biomass (Spanoghe et al., 2025). Together, these examples demonstrate how omics can be used not only to intensify production, but also to resolve the dynamics of microbial ecosystems.

Omics-enabled microbiology and systems approaches therefore provide tools to quantify traits that have traditionally remained intangible in industrial evaluation. Yet they are still predominantly deployed to optimize product output rather than regenerative performance. Used within a broader evaluative framework, omics and modelling can function as measurement systems for ecological integration, regenerative capacity, and network robustness, turning these dimensions into explicit components of industrial relevance.

5 Discussion: redefining "industrial relevance" through a regenerative lens

Microorganisms thus need to be evaluated not only as producers of target molecules but also as regenerative and collaborative agents that repair, recycle and stabilize ecological and industrial systems. The examples discussed so far indicate that microorganisms contribute value in at least two distinct ways: by producing specific molecules and by regenerating or stabilizing systems. A narrow focus on the first mode shapes which organisms, processes and research agendas are prioritized. To better align industrial microbiology with circular bioeconomy goals, the notion of "industrial relevance" can be expanded to incorporate regenerative attributes alongside classical metrics.

Three complementary dimensions can be considered:

i. Regenerative capacity – ability to restore or maintain key functions in degraded or stressed systems, such as rebuilding soil organic matter, improving water quality or re-establishing balanced microbiomes (Singh et al., 2023; Antranikian and Streit, 2022).

ii. System integration – degree to which a microbial process can be embedded into existing material and energy flows, contributing to closed-loop configurations rather than operating as a stand-alone production island (Krüger et al., 2020).

iii. Ecological robustness and modularity – presence of functional redundancy, syntrophic interactions and flexible network structures that maintain performance under variable inputs and conditions, reducing vulnerability to perturbations (Singh et al., 2023; Wasmund et al., 2024; Dottorini et al., 2023).

Taken together, these dimensions outline a simple evaluative framework in which microbial platforms are scored not only on product metrics but also on their contribution to system-level

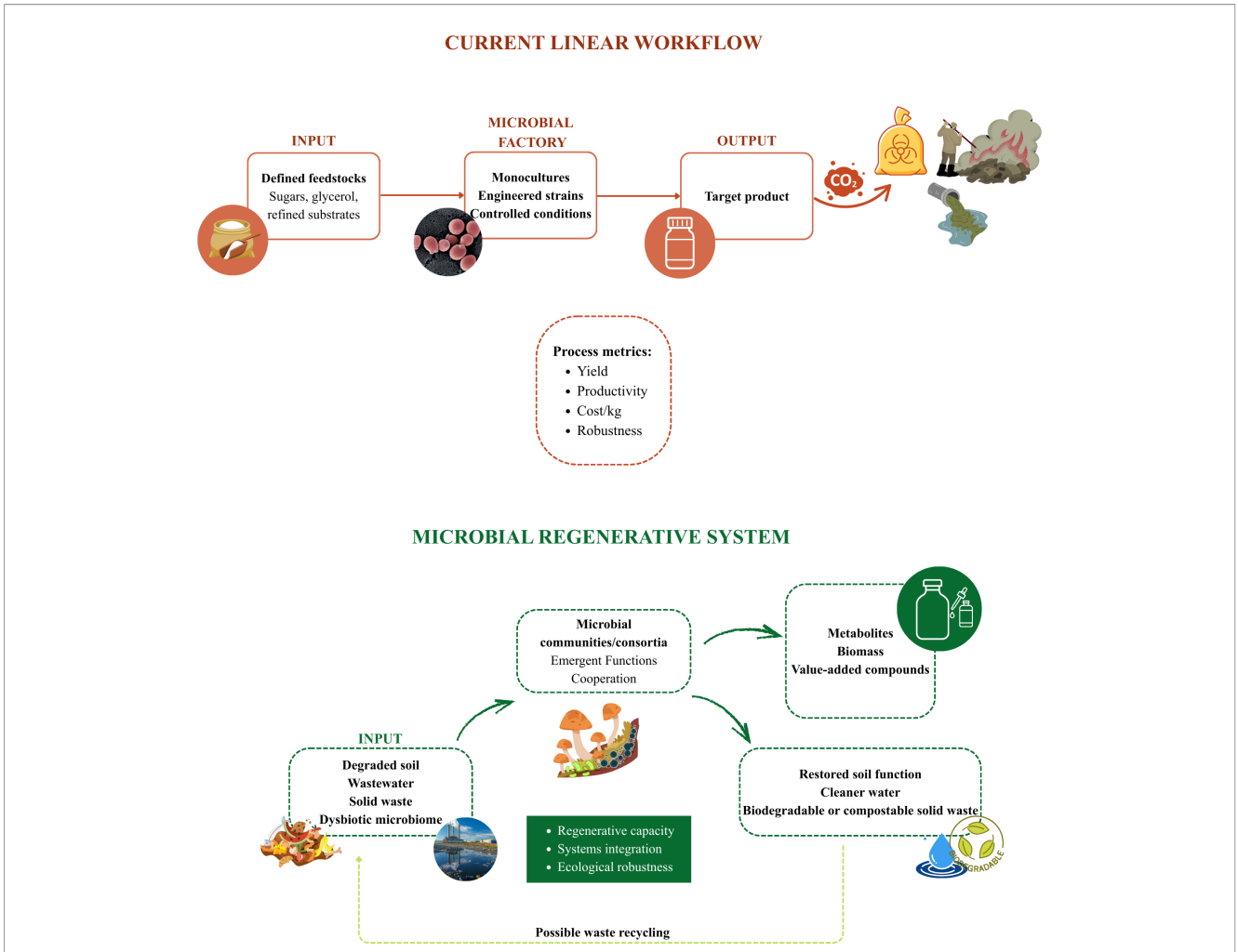

FIGURE 1
Conceptual contrast between linear and regenerative views of microbial value in industrial contexts. Upper: Linear, cell-factory framing: microorganisms are optimized to produce single target molecules from defined feedstocks and assessed mainly by titer, rate, yield and cost per kilogram. Lower: Regenerative, systems-based framing: microorganisms are embedded in ecological and industrial networks that close material loops, recover nutrients, detoxify waste and stabilize soils or microbiomes; industrial relevance includes regenerative capacity, system integration and ecological robustness, in addition to classical productivity metrics.

regeneration (Figure 1). They do not replace yield, productivity or economic feasibility, but they change what counts as a high-potential microbial platform. Under a regenerative lens, non-model organisms and consortia that perform well in waste valorization, ecosystem repair or long-term soil health become more central to industrial strategy, rather than remaining in niches labeled "environmental" or "ecological". This includes PNSB–based platforms that combine wastewater treatment with energy, nutrient and protein recovery (Segura et al., 2023; San Martín et al., 2023; Doki et al., 2024; Martin-Gamboa et al., 2023), as well as mixed-culture processes where PNSB biomass serves as a feedstock for bioplastics (Martin-Gamboa et al., 2023; Sakarika et al., 2025). In parallel, concepts such as open symbiotic cultures and microbial protein-derived bioplastics highlight how food and materials systems can be redesigned around microbial consortia rather than isolated production hosts (Javourez et al., 2024; Sakarika et al., 2025).

Moving beyond an extractive, linear model of production is essential for long-term sustainability. The circular bioeconomy is often presented as a key pathway, with microorganisms at its core. Yet, as long as microbes are mainly treated as efficient factories and evaluated on linear performance metrics, many implementations risk becoming a biological extension of the fossil paradigm: new inputs, similar logic (Krüger et al., 2020). Recent analyses of nutrient management frameworks and circular-economy initiatives for agri-food systems argue that circularity must be integrated with efficiency and sufficiency. Nevertheless, they show that operational indicators still lean heavily on biomass utilization, productivity and gross domestic product (GDP) (Spiller et al., 2024). Studies of actors' choices regarding nutrient-recovery adoption in the food-processing industry and of nitrogen-recovery supply chains reach similar conclusions: techno-economic metrics dominate decision-making even when circularity is a stated goal (Santolin et al., 2025; Vingerhoets et al., 2025). This misalignment between rhetoric and metrics helps explain why many "circular bioeconomy" initiatives translate into feedstock shifts rather than structural redesign.

Recognizing regenerative functions as part of industrial value requires adjustments at three levels: conceptual (moving beyond the factory metaphor), methodological (using omics and modeling to characterize regenerative traits) and evaluative (integrating regenerative capacity, system integration and robustness into decision frameworks). In this reframing, bioeconomy is not defined solely by replacing petroleum with cellular feedstocks, but by organizing production and regeneration around the ecological intelligence of microorganisms. Industrial microbiology, when guided by this perspective, can contribute not only new molecules but also restored systems—shifting from a focus on what microbes manufacture to what they help keep alive. Under this reframing, microbial value is anchored in system-level regeneration rather than isolated productivity. This perspective allows industrial microbiology to align more closely with the ambitions of a circular bioeconomy instead of reinforcing a green version of linear extraction. Future research agendas, industrial design choices and policy metrics will need to make this regenerative role an explicit criterion of industrial relevance, rather than a secondary co-benefit.

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References

Amer, B., and Baidoo, E. E. K. (2021). Omics-driven biotechnology for industrial applications. *Front. Bioeng Biotechnol.* 9. doi: 10.3389/fbioe.2021.613307

Antranikian, G., and Streit, W. R. (2022). Microorganisms harbor keys to a circular bioeconomy making them useful tools in fighting plastic pollution and rising CO_2 levels. *Extremophiles* 26, 10. doi: 10.1007/s00792-022-01261-4

Buckton, S. J., Fazey, I., Sharpe, B., Om, E. S., Doherty, B., Ball, P., et al. (2023). The Regenerative Lens: A conceptual framework for regenerative social-ecological systems. *One Earth* 6, 824–842. doi: 10.1016/j.oneear.2023.06.006

Cai, Y., Zhao, Y., Prado de Nicolas, A., Olias, L. G., Segura, Y., Puyol, D., et al. (2025). Coupling of purple phototrophic bacteria with bioelectrochemical blessing constructed wetland for wastewater treatment and electricity generation. *Chem. Eng. J.* 522, 168134. doi: 10.1016/j.cej.2025.168134

Díaz-Rullo Edreira, S., Vasiliadou, I. A., Prado, A., Espada, J. J., Wattiez, R., Leroy, B., et al. (2024). Elucidating metabolic tuning of mixed purple phototrophic bacteria biofilms in photoheterotrophic conditions through microbial photo-electrosynthesis. *Commun. Biol.* 7, 1526. doi: 10.1038/s42003-024-07188-0

Doki, M. M., Mehta, A. K., Chakraborty, D., Ghangrekar, M. M., Dubey, B. K., Alloul, A., et al. (2024). Recovery of purple non-sulfur bacteria-mediated single-cell protein from domestic wastewater in two-stage treatment using high rate digester and raceway pond. *Biores Technol.* 413, 131467. doi: 10.1016/j.biortech.2024.131467

Dottorini, G., Wágner, D. S., Stokholm-Bjerregaard, M., Kucheryavskiy, S., Michaelsen, T. Y., Nierychlo, M., et al. (2023). Full-scale activated sludge transplantation reveals a highly resilient community structure. *Water Res.* 229, 119454. doi: 10.1016/j.watres.2022.119454

Eastham, J. L., and Leman, A. R. (2024). Precision fermentation for food proteins: Ingredient innovations, bioprocess considerations, and outlook — A mini-review. *Curr. Opin. Food Sci.* 58, 101194. doi: 10.1016/j.cofs.2024.101194

Javourez, U., Matassa, S., Vlaeminck, S. E., and Verstraete, W. (2024). Ruminations on sustainable and safe food: Championing for open symbiotic cultures ensuring resource efficiency, eco-sustainability and affordability. *Microbial Biotechnol.* 17, e14436. doi: 10.1111/1751-7915.14436

Kim, G. B., Kim, H. R., and Lee, S. Y. (2025). Comprehensive evaluation of the capacities of microbial cell factories. *Nat. Commun.* 16, 2869. doi: 10.1038/s41467-025-58227-1

Krüger, A., Schäfers, C., Busch, P., and Antranikian, G. (2020). Digitalization in microbiology - Paving the path to sustainable circular bioeconomy. *N Biotechnol.* 25, 59:88–59:96. doi: 10.1016/j.nbt.2020.06.004

Martin-Gamboa, M., Allegue, L. D., Puyol, D., Melero, J. A., and Dufour, J. (2023). Environmental life cycle assessment of polyhydroxyalkanoates production by purple phototrophic bacteria mixed cultures. *J. Cleaner Prod* 428, 139421. doi: 10.1016/j.jclepro.2023.139421

Sakarika, M., Brancart, J., Gujar, S. A., De Meester, S., Allegue, L. D., Bastiaens, L., et al. (2025). Microbial protein-derived bioplastics from renewable substrates: Pathways, challenges, and applications in a circular economy. *Environ. Sci. Ecotechnol* 28, 100635. doi: 10.1016/j.ese.2025.100635

San Martín, J., Puyol, D., Segura, Y., Melero, J. A., and Martínez, F. (2023). A novel photoanaerobic process as a feasible alternative to the traditional aerobic treatment of refinery wastewater. *J. Water Process Eng.* 51, 103352. doi: 10.1016/j.jwpe.2022.103352

Santolin, J., Van Schoubroeck, S., Springael, J., Van Passel, S., Vlaeminck, S. E., and Spiller, M. (2025). Actors' choices in a circular economy: Leverage points and technological attributes for nutrient recovery adoption in the food-processing industry. *J. Cleaner Prod* 526, 146672. doi: 10.1016/j.jclepro.2025.146672

Segura, Y., Molina, R., Rodríguez, I., Hülsen, T., Batstone, D., Monsalvo, V., et al. (2023). Improvement of biogas production and nitrogen recovery in anaerobic digestion of purple phototrophic bacteria by thermal hydrolysis. *Biores Technol.* 367, 128250. doi: 10.1016/j.biortech.2022.128250

Singh, I., Hussain, M., Manjunath, G., Chandra, N., and Ravikanth, G. (2023). Regenerative agriculture augments bacterial community structure for a healthier soil and agriculture. *Front. Agron.* 5. doi: 10.3389/fagro.2023.1134514

Spanoghe, J., Blansaer, N., Allegue, L. D., Vermeir, P., and Vlaeminck, S. E. (2025). Carbon and ammonium limitation and nitrogen fixation alter the nutritional profile of purple non-sulphur bacteria grown on H_2 and CO_2. *Biores Technol.* 430, 132567. doi: 10.1016/j.biortech.2025.132567

Spiller, M., Vingerhoets, R., Vlaeminck, S. E., Wichern, F., and Papangelou, A. (2024). Beyond circularity! Integration of circularity, efficiency, and sufficiency for nutrient management in agri-food systems. *Nutr. Cycl Agroecosyst* 129, 287–297. doi: 10.1007/s10705-024-10339-8

Vingerhoets, R., Spiller, M., Vlaeminck, S. E., Buysse, J., and Meers, E. (2025). Centralized strategies for decentralized nitrogen recovery: A model for sustainable fertilizer supply chains. *J. Environ. Manag* 394, 127371. doi: 10.1016/j.jenvman.2025.127371

Wasmund, K., Singleton, C., Dahl Dueholm, M. K., Wagner, M., and Nielsen, P. H. (2024). The predicted secreted proteome of activated sludge microorganisms indicates distinct nutrient niches. *mSystems* 9, e0030124. doi: 10.1128/msystems.00301-24