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Integrated Biotechnological Strategies for Planetary Health and Ecosystem Restoration

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Abstract

The escalation of ecological degradation, marked by climatic instability, precipitous biodiversity loss, and systemic chemical infiltration, necessitates a shift toward integrated biotechnological intervention. This analysis considers how the trajectory of diverse advanced methodologies, including environmental DNA (eDNA) surveillance, CRISPR-based genetic restitution, and synthetic biology-driven bioremediation, might be synthesized into a unified Planetary Health Framework. By exploring the convergence of high-precision genomic engineering, AI-augmented bioinformatic modeling, and the tenets of a circular bio-economy, we examine the capacity of technological intervention to ameliorate ecological stressors and restore critical ecosystems.

Moving beyond the constraints of conventional conservation, this discourse explores frontier solutions in climate-resilient agrotechnology, photo-driven biomanufacturing, and technologically integrated urban ecology, highlighting the criticality of microbiome modulation and comprehensive genomic repositories in stabilizing the biosphere. By reconciling molecular-level precision with macro-scale systems ecology, this framework points to a trajectory for sustainable development where technological scalability is constrained by, yet optimized for, planetary boundaries. Ultimately, this review addresses the imperatives of ethical oversight and highlights the multi-sectoral governance architectures required for the responsible global deployment of these “living technologies.”

Keywords: Planetary Health, Synthetic Biology, Bioremediation, Circular Bioeconomy, Environmental Genomics

Introduction

Planetary Health operates on the fundamental premise that human well-being is intrinsically linked to the functional integrity of global ecosystems. The destabilization of Earth’s biophysical systems poses an existential risk to biodiversity and human civilization (1). The present geological epoch, the Anthropocene, is marked by the transgression of critical planetary boundaries, most notably accelerated climatic shifts, unprecedented rates of taxonomic extinction, and profound alterations in biogeochemical fluxes (2). Conventional conservation efforts, directed towards passive protection and habitat isolation, increasingly fail to mitigate multifaceted environmental disruptions. As a result, a transition to more dynamic, interventionist strategies becomes imperative.

In this context, biotechnology can facilitate a transformative shift from historically reactive conservation models to proactive, anticipatory environmental governance (3). While traditional efforts have sought to preserve ecological snapshots of the past, integrating biotechnological tools aims to engineer systemic resilience. This technological vanguard comprises a sophisticated toolkit, ranging from environmental DNA (eDNA) for granular, high-resolution biodiversity surveillance to the application of CRISPR-Cas9 for fortifying the thermal thresholds of keystone taxa (4). By harnessing molecular-level precision, it is now possible to confront ecological stressors at their source, whether through the enzymatic catabolism of recalcitrant pollutants or the artificial augmentation of genetic diversity within populations suffering from severe bottlenecks.

The assimilation of these biotechnologies into global stewardship protocols introduces complexities. It demands a radical evolution in ecological systems thinking, necessitating a move away from localized laboratory solutions toward scalable, field-deployable interventions. The present synthesis examines the convergence of synthetic biology, environmental genomics, and restorative ecology to delineate a “safe operating space” for future biocentric development. By consolidating recent empirical advances and interrogating the attendant ethical and regulatory hurdles, this paper proposes a novel framework for planetary stewardship, one that harmonizes cutting-edge technological innovation with the requirements of biosphere stability.

Microorganisms, including bacteria, yeasts, filamentous fungi, microalgae, and archaea, represent foundational biological systems with extraordinary potential to support planetary health. Their metabolic diversity, adaptability, and capacity for genetic engineering make them indispensable for sustainable biotechnological solutions aimed at climate stability, resource circularity, and the restoration of degraded ecosystems. Microbial cell factories can produce green alternatives to carbon-intensive, waste-generating industrial processes because of their metabolic flexibility, rapid growth, and ease of cultivation, enabling rapid scaling with minimal environmental burden. What is important is their ability to convert CO_2, various waste biomass, and industrial byproducts into valuable chemicals, and advanced engineering tools enable precise metabolic rewiring. Microorganisms excel at transforming environmental burdens into useful resources, e.g., converting agricultural and food waste into biomaterials, biostimulants, biofertilizers, organic acids, and microbial biomass (5). These processes support circular economy strategies by closing carbon, nitrogen, and phosphorus loops. Microbial interventions strengthen ecosystem resilience and biodiversity. Healthy ecosystems depend on balanced microbial communities; therefore, microorganisms are powerful tools for restoring compromised environments. Moreover, planetary health connects the well-being of humans, animals, and ecosystems. Microorganisms play essential roles across all dimensions, including food security, low-impact medicine, climate mitigation (carbon capture by cyanobacteria and microalgae), and environmental monitoring. Among microorganisms, yeasts, particularly Saccharomyces cerevisiae, Pichia pastoris, Yarrowia lipolytica, and a wide array of nonconventional strains, represent powerful biological platforms with broad biotechnological potential. Modern yeast biotechnology enables the production of biobased chemicals, polymers, fuels, and materials that can replace environmentally harmful petrochemical processes. Yeasts have a low environmental footprint when grown on renewable substrates, agrowastes, or even CO_2-Derived feedstocks. Precision metabolic engineering: CRISPR–Cas tools and synthetic biology allow rewiring of yeast metabolism for high-yield production of targeted compounds. Importantly, their scalability is also a key factor; therefore, industrial fermentation is established, robust, and safe. These technologies then directly contribute to circular bioeconomy strategies and significantly reduce lifecycle emissions. Many yeast species tolerate extreme environments and metabolize waste streams that would otherwise burden ecosystems. By turning agricultural residues and industrial by-products into value-added products and/or pollutants into biomass, yeasts help close carbon and nutrient loops, thereby reducing ecological stress. Beyond industrial processes, yeasts can help restore degraded ecosystems by enabling biological solutions at the interface of agriculture, soil health, and biodiversity renewal.

Yeasts can improve soil microbiomes by releasing vitamins, enzymes, and other metabolites that stimulate beneficial soil bacteria and fungi. Certain yeast strains can act as biocontrol agents, suppressing plant pathogens, and as biofertilizers, enhancing plant stress tolerance to drought, salinity, or heavy metals. Yeasts also contribute to the interconnectedness of environmental, human, and ecosystem well-being by sustainable production of essential medicines, low-cost nutritional supplements, and modern biomanufacturing infrastructure. To fully leverage yeasts for planetary health, integrated strategies combining fields with the greatest impact are being developed (5,6). These strategies include synthetic biology and ecological engineering, industrial biotechnology and the circular bioeconomy, and environmental science and metabolic modeling. From a practical standpoint, this involves multiple categories of combined microbial consortia with various types of engineered or composite microbial systems. As an example, the possible influence of environmental factors, food quality, and lifestyle on the human gut microbiome is studied, and the role of probiotics within complex microbial consortia is evaluated. The emerging concept of ecological fitting describes how probiotic organisms integrate into existing ecological niches and interact with complex microbial networks rather than acting as isolated entities. Increasing attention is being directed toward the use of probiotic consortia and so-called next-generation probiotics, which include strains capable of regulating immune pathways, modulating metabolic functions, or supporting the restoration of the intestinal barrier. Another example of a complex microbial strategy is the use of simultaneous cultivation of two types of microorganisms. Even in the case of biotechnological processing of renewable resources as input materials (e.g., biomass, sugars, solar radiation, CO_2) by heterotrophic microorganisms, only a portion of the carbon is stored as new carbon compounds. The rest is then released as CO_2 waste gas, which can be further used on site and transformed by autotrophic microorganisms rather than being released into the atmosphere. In biotechnology, co-cultivation of heterotrophic yeasts and autotrophic microalgae is a very promising strategy. Although establishing suitable conditions can be challenging, intensive research on microorganisms in co-culture can yield an almost "ideal combination" that provides an innovative solution for reducing the carbon footprint, improving O_2 /CO_2 exchange, and controlling pH. We can also hope for possible symbiotic exchange of molecules, leading to a wide variety of known high-value products and new molecules (6,7). Co-cultures of non-conventional carotenogenic yeasts and microalgae belong to the most promising systems. Red yeasts have attracted attention for their ability to process diverse waste substrates, and, moreover, they are recognized as efficient producers of high-value metabolites, including polysaccharides, lipid compounds, fatty acids, β-glucans, carotenoids, ubiquinone, and ergosterol. In addition to their metabolic versatility, carotenogenic yeasts demonstrate high stress tolerance and the ability to persist under suboptimal environmental conditions. Microalgae represent another group of microorganisms with high biotechnological relevance. Defined as autotrophic or mixotrophic eukaryotic microorganisms inhabiting aquatic environments, they are capable of producing a wide range of metabolites comparable to those synthesized by yeasts, while additionally accumulating large quantities of chlorophylls, xanthines, and other bioactive compounds. Their photosynthetic capacity also enables CO_2 fixation, making them attractive for integrated waste-processing systems with environmental benefits. To date, much of the biotechnological research involving microalgae has focused on biofuel production. More recently, increasing attention has been directed towards the co-cultivation of microalgae with other microorganisms, such as yeasts, to enhance biomass production and metabolic yield (8). Mixed cultures of microorganisms are common in natural ecological systems.

Previous studies have shown that co-cultivation of yeast and microalgae can improve growth and biomass production compared to monocultivation. Although the mechanism by which co-cultivation improves cell growth has not been clearly established, transcriptomic analysis suggests that microalgae can generate oxygen for the yeast. In contrast, the yeast provides CO_2 and inorganic nitrogen for the microalgae. Thus, the rationale for yeast–microalgae co-cultivation lies in their complementary metabolic exchanges. Yeasts release carbon dioxide during respiration, which can be utilized by microalgae for photosynthesis, while microalgae release oxygen, which supports yeast metabolism. This bidirectional gas exchange can stimulate growth in both partners. Furthermore, heterotroph–autotroph pairings reduce competition for organic carbon sources. Nevertheless, the approach can impose physiological stress on the microorganisms, potentially altering both the spectrum and quantity of metabolites produced (9). Waste valorization by co-cultivation with microalgae and yeast is a relatively new trend. The co-culture method itself presents many pitfalls, such as the complex selection of coculture partners, the correct choice of media, and then the choice of waste substrate. The prevailing trend is to try to valorize only local waste substrates or wastewater. Most research also targets biofuel production.

Due to their versatile metabolic system, heterotrophic oleaginous red yeasts are capable of performing simultaneous co-production of lipids, β-glucans, carotenoid pigments, proteins, and lipids, while autotrophic microalgae can produce pigments, PUFA, β-glucans, and other biopolymers simultaneously (10). The fundamental premise of co-cultivations is the generation of enriched biomass with metabolites derived from both microorganisms. Consequently, there is a plethora of potential applications, including, but not limited to, the food, cosmetic, pharmaceutical, and animal feed industries. By targeting higher fatty acid yields, this cultivation method could also be used for biofuel production. Co-cultures have proven to be an intriguing solution for treating waste components from a multitude of industries (11). We can conclude that microorganisms form the biological foundation of sustainable biotechnological innovation. Their abilities to transform waste, restore ecosystems, support climate stability, and generate bio-based solutions place them at the heart of integrated strategies for planetary health and ecosystem recovery. Harnessing microbial potential through advanced engineering, ecological insight, and interdisciplinary collaboration will be essential for building a resilient, sustainable future.

1. Advanced Biomonitoring and Genetic Intervention: A New Frontier in Conservation

The efficacy of planetary health management depends on the early detection of ecological shifts before they cross irreversible thresholds. While taxonomic surveys have historically provided a foundational understanding of biodiversity, they are increasingly constrained by high resource demands and an inability to monitor cryptic or rapidly declining taxa across expansive, inaccessible biomes (4). Consequently, the integration of high-resolution monitoring through eDNA surveillance and the strategic implementation of genetic rescue techniques represent a transformative shift in the preservation of biological diversity.

The emergence of eDNA metabarcoding has revolutionized biomonitoring by enabling the non-invasive identification of species through genetic fragments obtained from environmental matrices such as water, soil, and air (12). The adoption of molecular-centric methodologies effectively transcends the traditional bottlenecks of invasive specimen collection and the subjectivity of morphological taxonomy, thereby establishing a high-throughput platform for near-instantaneous ecosystem surveillance. Within increasingly fragmented habitats, exacerbated by anthropogenic stressors and the erosion of genomic health, the deployment of "genetic rescue" can become a vital intervention. This approach highlights the importance of increasing genetic diversity to counteract the effects of inbreeding and to provide species with the adaptive plasticity necessary for evolution. This is a major shift from current approaches to conservation biology, where we have previously reacted to emergencies with molecular diagnostics designed to prevent them. By basing ecological management on genomics, the goal is no longer to conserve a natural system but to build a more robust biosphere from scratch.

Conservation genomics has undergone a profound evolution, pivoting from a descriptive observation of decline toward a prescriptive framework for biodiversity restitution. While previously genome analysis focused on model organisms, advances in technology have enabled the generation of high-throughput genomic data from thousands of organisms, enabling refined multi-omics approaches to gain insights and molecular clues into conservation. Genome-wide association studies (GWAS) have effectively identified genomic regions associated with genetic variation, providing a window into the process of natural selection at the genetic level (13,14). Such measures can also be extended to study temporal genetic monitoring and ignite hope for self-sustaining populations promoting conservation in an uncertain future (15). At the vanguard of this shift lies CRISPR-mediated genome engineering, which enables high-precision modifications to bolster phenotypic resilience by augmenting disease resistance and thermal thresholds within populations suffering from severe genetic bottlenecks (16).

By circumventing the protracted temporalities of natural selection, these molecular interventions facilitate and assist evolution, providing a critical buffer for species whose adaptive capacities are currently outpaced by anthropogenic environmental shifts. In parallel with in situ genomic modulation, the integration of advanced assisted reproductive technologies (ARTs) constitutes a fundamental infrastructure for long-term taxonomic recovery. Methodologies such as Somatic Cell Nuclear Transfer (SCNT) and the induction of pluripotent stem cells (iPSCs) enable the "biological resurrection" of genomic variation from cryopreserved substrates, functioning as a vital insurance mechanism against terminal extinction. These efforts are systematized through global bio-banking initiatives, such as the Frozen Ark, which ensure that the evolutionary heritage of endangered taxa is archived for future restorative deployment.

Notwithstanding the promise of these living technologies, the escalation of genetic interventions to a landscape scale, particularly via the deployment of gene drives, introduces a suite of unprecedented ecological and ethical considerations. While gene drives represent a potent modality for the extirpation of invasive species or the accelerated dissemination of beneficial alleles, their potential for horizontal gene transfer and irreversible disruption of trophic networks remains a locus of intense regulatory scrutiny (17). Consequently, the integration of such high-stakes technologies into global conservation strategies demands a multi-layered oversight architecture.

This framework must meticulously calibrate the existential risks of ecological inaction against the possibility of unintended systemic cascades. In the Anthropocene, effective planetary stewardship thus necessitates a rigorous synthesis of molecular innovation and precautionary governance to uphold the functional integrity of the biosphere. Genetic Interventions for Endangered Species. The accelerated extinction rate amongst wildlife creates a dire need for specialized conservation breeding programs. This is particularly necessitated by the imposing environmental threats posed by climate change and infectious disease outbreaks, and their effects on biodiversity and species survival (18).

While preserving genetic diversity in founder populations is the primary focus, the challenge of vulnerability to extinction remains. Hence, targeted genetic intervention is required. With the advent of environmental genomics, the identification of DNA segments critical for adaptation is now being applied to efficient biomonitoring, particularly for endangered species (14). To this end, genetic interventions to promote adaptation in threatened species include the application of artificial selection and synthetic biology in model organisms that exhibit changing phenotypes. These modifying adaptive traits are encoded by multiple loci. Genomic analyses to identify genetic variations relevant to conservation can be performed using single-nucleotide polymorphisms (SNPs), random nucleotide length polymorphisms (RFLPs), minisatellites, microsatellites, sequence analyses, and DNA fingerprinting.

The generation of high-throughput sequencing data of thousands of organismal genomes facilitates the rescue of endangered species. Identification of these adaptive loci is a central strategy for environmental geneticists. Genetic changes associated with local adaptation and their impact on fitness could be used to define conservation units and assess the potential to respond to environmental changes.

Moreover, advanced genomics can provide insight into susceptibility genes associated with infectious diseases, which can be further studied for wildlife species management and disease treatment to mitigate extinction risk (14,19). Furthermore, high-technology measures such as cloning have also been employed to diversify the genetic toolbox for conservation, particularly for the preservation of highly endangered species; they come with their own ethical and other concerns about transgenic organisms (20).

1.1.Genomic Monitoring and Habitat Preservation

The planet's health is at risk due to dramatic changes in biodiversity (21). Rapid dynamic profiling of such changes is key in guiding interventions. The advent of eDNA and environmental RNA (eRNA) methodologies has caused a paradigm shift in biodiversity quantification, permitting the non-invasive identification of taxa via genetic material in heterogeneous matrices, including lotic/lentic hydrosystems, pedogenic horizons, and atmospheric aerosols (4,12). Unlike classical morphological inventories which can be hampered by taxonomic subjectivity and sampling bias, eDNA metabarcoding offers unprecedented sensitivity and spatiotemporal resolution for the surveillance of cryptic, rare, or invasive species (22). This technology facilitates the simultaneous characterization of multi-trophic assemblages from microbial consortia to megafaunal populations, offering a comprehensive profile of an ecosystem's architecture.

The convergence of molecular diagnostics with AI-augmented remote sensing and satellite-derived hyperspectral datasets has given rise to a synergistic methodology known as "Precision Conservation". Machine learning architectures now enable multivariate cross-referencing of genomic signatures with biophysical environmental parameters, effectively forecasting habitat viability and niche occupancy amid the flux of climate shifts (23). Moreover, the integration of deep-learning protein structure predictions, exemplified by AlphaFold2, has elevated environmental monitoring from purely taxonomic identification to functional proteomic analysis (24).

Together, these technologies constitute a biofeedback mechanism capable of detecting ecological perturbations at their incipient stages. By diagnosing subtle fluctuations in transcriptomic profiles or community successions before macroscopic ecological collapse, this framework acts as an early-warning indicator for planetary health surveillance. As a result, habitat management evolves from a static, post-hoc endeavor into a dynamic, data-driven stewardship of the global biosphere (25).

1.2.Genetic Interventions for Endangered Species

Conservation genomics has undergone a profound evolution, pivoting from a descriptive observation of decline toward a prescriptive framework for biodiversity restitution. CRISPR-mediated genome engineering enables high-precision modifications to bolster phenotypic resilience by augmenting disease resistance and thermal tolerance for populations with severe genetic bottlenecks. These interventions facilitate "assisted evolution," providing a critical buffer for species whose adaptive capacities are currently outpaced by environmental shifts.

2. Biotechnological Approaches for Systemic Restoration and Circular Waste Valorization

The structural rehabilitation of damaged landscapes, coupled with the neutralization of effluent streams, is at the core of maintaining planetary health. Conventional remediation strategies frequently falter in addressing environmental pollutants such as microplastics, heavy metals, and endocrine disruptors. Synthetic biology and enzymatic engineering are emerging as biogenic alternatives. This shift facilitates a transition from traditional, resource-heavy interventions toward a precision-based biotechnological framework capable of addressing ecological damage at the molecular level.

Central to this evolution is the transition from a linear take-make-dispose waste model to a robust circular bio-economy, underpinned by advanced microbial interventions. Through the metabolic rewiring of specialized microorganisms, waste streams are no longer viewed as liabilities but as high-value feedstocks for bio-based synthesis. For instance, the deployment of engineered enzymes capable of depolymerizing complex synthetic polymers allows for the upcycling of industrial waste into biodegradable precursors. Furthermore, integrating CRISPR-based genomic editing with directed evolution provides a scalable pathway to enhance the catabolic efficiency of microbial communities in contaminated soils and aquatic systems. By synchronizing ecological restoration with innovative waste valorization, these biotechnological advancements provide a roadmap for reconciling industrial activity with the biosphere's inherent regenerative capacities.

2.1 Biocatalysis as Key Enabling Technology for Biomass Waste and CO_2 Valorization

Sustainable management and valorization of biomass waste are critical for preserving Earth's health, mitigating climate change, and advancing a circular bioeconomy. Microbial degradation represents a highly promising strategy for lignocellulose breakdown. Filamentous fungi and bacteria deploy diverse lignocellulolytic enzymes, including cellulases, hemicellulases, and lignin-modifying oxidases, that act synergistically to depolymerize cellulose, hemicellulose, and lignin into fermentable sugars and aromatic compounds. Compared to isolated enzyme pretreatments, living microorganisms offer greater functional diversity and resilience to environmental fluctuations such as temperature and pH, often resulting in higher pretreatment efficiency during anaerobic digestion (26,27).

A fundamental principle in pollution prevention is to minimize waste generation at its source. Biotechnology, particularly biocatalysis, offers highly selective, environmentally friendly, and energy-efficient routes to convert biomass-derived intermediates into high-value chemicals, fuels, and materials (28). Advances in protein engineering, including rational design and directed evolution, have unlocked unprecedented opportunities, enabling enzymatic processes to operate under mild conditions with exceptional chemo-, regio-, and stereoselectivity, while minimizing the use of harsh chemicals and energy-intensive operations (29). These innovations enable integrated chemo-enzymatic and microbial pathways that improve atom economy and reduce overall energy demands, supporting a forward-looking "greener-by-design" framework that embeds sustainability from early synthetic planning through industrial implementation (30). Challenges in biocatalytic biomass valorization can be addressed through efficient enzyme immobilization, appropriate reactor design and control, and reaction compartmentalization in continuous-flow systems. Reactor miniaturization, process integration for in situ product removal, and telescoping of multi-enzymatic or chemo-enzymatic reactions further enhance biocatalyst utilization, enabling intensified, more efficient, and scalable bioprocesses (31).

Among biomass-derived platform molecules, biogenic furans such as furfural and 5-hydroxymethylfurfural are particularly attractive due to their high functionality and versatility. However, their chemical upgrading is often hindered by instability and byproduct formation, leading to complex downstream processing. Biocatalysis offers a promising alternative, enabling selective transformations of furan derivatives under mild conditions, and several successful cases have demonstrated that enzymes can generate diverse furan-derived products in a highly chemoselective manner (32). For instance, continuous biocatalytic production of furfurylamine from furfural exemplifies how an intensified biocatalytic process in a miniaturized reactor with immobilized enzyme can achieve efficient biomass valorization with favorable green chemistry metrics, demonstrating practical alignment with circular economy objectives (33).

Complementing lignocellulose valorization, biocatalytic conversion of CO_2 into value-added chemicals further underscores biotechnology's pivotal role in promoting a sustainable future. Excess atmospheric CO_2 drives global warming and ocean acidification, yet enzymatic conversion of CO_2 into chemicals or fuels offers a pathway to closing the carbon cycle. Formate dehydrogenases (FDHs) catalyze the reduction of CO_2 to formate, which can serve as a platform for further conversion into formaldehyde or methanol through multi-enzyme cascades (34). The use of green solvents, such as deep eutectic solvents, enhances both CO_2 solubility and enzyme stability, simultaneously acting as CO_2 carriers and biotransformation media (35). Moreover, whole-cell and electro-biocatalytic systems, including those employing Methylobacterium extorquens, enable direct CO_2 reduction under mild conditions (36). Collectively, these strategies demonstrate that enzyme selection, cascade design, cofactor regeneration, and sustainable solvent engineering are central to achieving scalable, environmentally friendly CO_2 biocatalysis (29).

2.2 Microreactor Engineering and Process Intensification for Sustainable Biotechnology and Planetary Health

While advances in enzyme discovery, metabolic engineering, and microbial biotechnology are central to addressing global environmental challenges, the successful implementation of such solutions also critically depends on the design of efficient and controllable reaction environments. Reactor engineering therefore represents an important enabling dimension of modern biotechnology, particularly when translating laboratory discoveries into scalable and resource-efficient processes relevant for planetary health. Microreactor and microfluidic technologies provide a powerful platform for the intensification of biocatalytic and environmental processes. Owing to their small characteristic dimensions, microreactors exhibit short diffusion paths, well-defined laminar flow regimes, and exceptionally high surface-to-volume ratios. These properties enable precise control of transport phenomena including mass and heat transfer as well as accurate regulation of reaction conditions. In many reaction systems, overall efficiency and sustainability are strongly influenced by transport limitations; consequently, improving transport phenomena at the microscale can directly enhance process efficiency and reduce resource consumption. In this context, the sustainability of many biochemical and environmental transformations can be viewed through the concept of transport-controlled sustainability, where the environmental performance of a process is closely linked to the ability to control transport phenomena within the reaction environment (29). Within this framework, microreactor platforms have increasingly been explored for continuous biotransformations, biomass valorization, and integrated reaction separation processes. The immobilization of enzymes or whole cells in microstructured reactors enables stable long-term operation, while continuous-flow processing improves productivity and facilitates process monitoring and control. Microreactors also provide a favorable environment for coupling multiple reaction steps or integrating complementary technologies such as electrochemical or photocatalytic processes, enabling compact and modular systems for sustainable chemical synthesis and environmental remediation (37).

Another important aspect is the possibility of applying model-based design approaches to microreactor systems. The well-defined hydrodynamic conditions in microchannels allow rigorous description of transport phenomena and reaction kinetics, enabling predictive mathematical models to be developed for process optimization and scale-up. Such integration of transport analysis, reaction engineering, and computational modeling provides a rational framework for designing intensified biocatalytic systems with improved performance and reduced environmental footprint (37). Finally, microreactor technologies offer a scalable pathway toward practical implementation through the concept of linear scale-up/numbering-up, where multiple identical microreactor units operate in parallel while preserving the favorable microscale transport characteristics. Such modular architectures enable gradual scale-up without compromising reaction selectivity or process control. Consequently, microreactor-based process intensification represents a promising strategy for translating emerging biotechnological solutions into robust and sustainable technologies supporting circular bioeconomy concepts, carbon valorization pathways, and advanced environmental remediation strategies (38).

In this perspective, sustainable biotechnology is determined not only by the discovery of new catalysts or microorganisms, but equally by the ability to control transport phenomena and reaction environments linking fundamental chemical and biochemical engineering principles directly to the broader goals of planetary health.

2.3. Enzymatic Bioremediation of Persistent Pollutants

The global proliferation of recalcitrant synthetic polymers, most notably polyethylene terephthalate (PET), has precipitated a pervasive ecological crisis, with microplastic infiltration now documented across all trophic levels, from primary producers to apex predators. Traditional mechanical and chemical recycling methods are often hindered by high energy requirements and limitations on downcycling, necessitating a shift toward more sustainable, molecular-based solutions. Recent breakthroughs in protein engineering and computational biology have yielded highly efficient biocatalysts, exemplified by the PETase and MHETase enzymes originally identified in the bacterium *Ideonella sakaiensis*. These enzymes exhibit a remarkable capacity to depolymerize crystalline PET into its constituent monomers, terephthalic acid (TPA) and ethylene glycol (EG), under ambient conditions (39). Beyond mere degradation, current research focuses on optimizing these enzymatic pathways to facilitate bio-upcycling within a circular-economy framework. By integrating evolved biocatalysts into engineered microbial consortia, it is now feasible to metabolically channel plastic-derived monomers into high-value bioproducts, such as polyhydroxyalkanoates (PHAs) or muconic acid (40). This approach effectively reclassifies plastic waste as a renewable feedstock rather than a terminal pollutant. Furthermore, the application of directed evolution and machine learning-guided protein design has significantly enhanced the thermostability and catalytic turnover rates of these enzymes, addressing the kinetic bottlenecks that previously limited large-scale industrial implementation.

2.4. Microbial Assemblages and Fungal Networks: A Biotic Framework for Ecosystem Restoration

Restoration ecology has witnessed a shift toward the deployment of engineered microbial inoculants and synthetic consortia to remediate environments compromised by heavy metals and complex hydrocarbons. Unlike traditional monoculture applications, which often fail due to ecological competition, synthetic biology allows for the precision-engineering of multi-species assemblages with optimized metabolic pathways. These consortia function as sophisticated biosensors and bio-accumulators, capable of sequestering recalcitrant toxins, such as arsenic, cadmium, and mercury, with high substrate specificity and enhanced kinetic rates (41). By leveraging the synergistic metabolic capabilities of diverse bacterial strains, these systems can degrade or immobilize pollutants that were previously considered biologically inaccessible.

Complementary to bacterial interventions, integrating mycelium-based materials and extensive fungal networks introduces a structural dimension to landscape rehabilitation. Fungal hyphae act as a biological glue, stabilizing degraded topsoils and enhancing water retention, which is indispensable for the reforestation of arid and semi-arid biomes (42). These mycorrhizal networks facilitate nutrient exchange and inter-species communication, creating a living infrastructure that exhibits remarkable resilience. This autonomous framework is not only capable of self-repair but also demonstrates adaptive evolution in response to fluctuating environmental stressors, such as thermal shifts or altered pH levels. Consequently, the convergence of bacterial metabolic engineering and fungal structural biology provides a holistic strategy for restoring the functional integrity of anthropogenically disturbed ecosystems.

2.5. Advancing the Circular Bio-Economy: Redefining Industrial Metabolism

The strategic imperative of contemporary waste mitigation lies in the absolute decoupling of global economic growth from environmental degradation. Rather than pursuing incremental improvements in traditional manufacturing, advancing a circular bio-economy requires a fundamental transition toward bio-based polymers and carbon-negative construction materials. These materials, increasingly synthesized through precision microbial fermentation and biosynthetic pathways, offer a robust alternative to carbon-intensive industries such as traditional plastics and concrete production (43). By engineering microbial cell factories to utilize atmospheric CO_2 or industrial effluents as feedstocks, we can effectively invert the traditional pollution paradigm, transforming potential environmental liabilities into high-performance biological assets.

This framework redefines the ontological status of waste, viewing it not as a terminal pollutant but as a high-value biological substrate for continuous regeneration. Such a perspective fosters a model of planetary stewardship where industrial metabolism is meticulously designed to mimic the inherent resilience and closed-loop efficiency of natural ecosystems. The integration of life-cycle assessments (LCA) with synthetic biology enables the creation of products that are biodegradable by design, ensuring that, at the end of their functional life, they return to the biosphere as nutrients rather than persistent contaminants. Ultimately, the convergence of biotechnology and circular economic principles provides a viable trajectory for reconciling human industrial aspirations with the finite regenerative capacities of the Earth's systems (44).

Table 1. Synthesis of Integrated Biotechnological Management Strategies and Ecological Outcomes for Planetary Health.

Management Domain	Key Biotechnological Tool	Core Mechanism / Process	Expected Ecological Outcome	Reference Examples
Biodiversity	eDNA - Conservation Genomics	Non-invasive monitoring and CRISPR-mediated genetic rescue.	Real-time species tracking and enhanced resilience for endangered taxa.	(4)
Pollution Control	Synthetic Enzymes (PETase/MHETase)	Enzymatic depolymerization of plastic waste into monomers.	Circular biochemical economy and reduction of microplastic loading.	(39,44)
Ecosystem Restoration	CRISPR - Assisted Evolution	Development of heat-tolerant coral genotypes.	Climate-resilient marine ecosystems and reef preservation.	(45,46)
Agriculture	RNAi - Precision Microbiome Engineering	Targeted pest control and nitrogen-fixing bacterial inoculation.	Reduction in chemical pesticide use and sustainable food security.	(41,61)
Industry Materials	Mycelium - Bio-based Polymers	Microbial fermentation of sustainable materials.	Reduced industrial carbon footprint and proliferation of biodegradable alternatives.	(43)
Climate, Water; Materials (Algae)	PBRs; Algal-bacterial consortia; macroalgal biorefinery; synbio toolkits.	Photo-CCU at point sources; nutrient/contaminant removal; bioplastic precursors and protein; assisted evolution.	Reduced CO_2 emissions; improved water quality; resilient reefs; circular biomaterials and nutrition.	(62–66)
Cross-scale monitoring & Intervention	Nano-enabled precision sensors and photonic nanomaterials.	Real-time biochemical thermal sensing and plasmonic energy-driven catalytic processes.	Early detection of ecosystem stress and improved efficiency of adaptive bioremediation strategies.	(67)

2.6. Marine Ecosystem Restoration: Molecular Interventions and Spatial Resilience

The escalating trajectory of climate-induced ocean warming and acidification has fundamentally altered the paradigm of marine conservation, shifting the focus from passive protection to active, technology-driven assisted evolution. This approach is particularly critical for coral reefs, which function as the biological scaffolding for oceanic biodiversity. By using CRISPR-Cas9 and other genomic editing tools, researchers can now identify and propagate heat-tolerant genotypes in scleractinian corals, thereby enhancing their physiological resilience against mass bleaching events (45). These molecular interventions aim to accelerate the natural rate of thermal adaptation, providing a strategic buffer for reef systems as they navigate the rapid environmental fluctuations of the Anthropocene.

However, the restoration of marine biomes extends beyond genetic modification; it requires integrating large-scale spatial planning and the strategic reintroduction of key ecosystem engineers, such as seagrasses, mangroves, and kelp forests. These foundational species are essential for carbon sequestration, often referred to as Blue Carbon, and for stabilizing coastal sediments against extreme weather events (46). Furthermore, the convergence of marine biotechnology and autonomous monitoring systems has facilitated the development of high-sensitivity early warning frameworks. These systems leverage eDNA and real-time biosensors to detect the nascent stages of invasive species incursions and pathogenic outbreaks, which are increasingly common as shifting thermal isotherms reorganize marine communities (47,48). By integrating molecular resilience with robust spatial management, these multifaceted strategies offer a holistic pathway to preserve the functional and structural integrity of global marine ecosystems.

The extreme terrestrial deep subsurface environments harbor diverse microbial communities (49), representing a natural treasure trove for obtaining extreme biomolecules. Under long-term conditions of high pressure, oligotrophy, and geothermal heat, deep-earth microbes have evolved unique metabolic pathways capable of producing extremozymes (such as thermophilic proteases and cellulases) with exceptional thermal stability and tolerance, demonstrating outstanding performance in biorefining and industrial catalysis. Furthermore, the interspecies competition for survival among deep-subsurface microorganisms has driven the synthesis of complex secondary metabolites (50) , making them a critical source for mining novel antibiotics and bioactive substances, such as anti-tumor and anti-viral lead compounds. This holds significant strategic importance for overcoming the challenges of clinical drug resistance.

2.7. Synthetic Bioremediation: Engineering Microbial Solutions

Synthetic biology has transcended traditional environmental cleanup by enabling the precision engineering of microbial pathways and high-efficiency enzymes (39). This field offers a shift in perspective in addressing global threats to water security and river biodiversity by providing scalable, targeted interventions for complex pollutants. A transformative milestone in waste valorization is the molecular optimization of enzymatic systems for plastic degradation. Specifically, the engineering of PETase and MHETase variants has enabled the depolymerization of polyethylene terephthalate (PET) into its foundational, recyclable monomers within hours, circumventing the multi-century degradation timelines inherent to natural processes. When harnessed within industrial-scale bioreactor architectures, these biocatalysts underpin a resilient circular plastics economy by effectively recalibrating post-consumer waste as a high-value precursor.

Parallel to the challenges of synthetic polymers, the remediation of heavy metal and radionuclide contamination has been redefined through the strategic architecture of synthetic microbial consortia. By manipulating bacterial strains to display specialized metal-chelating peptides, such as metallothioneins, on their cellular surfaces, researchers have achieved the targeted sequestration of uranium and hexavalent chromium from compromised hydrogeological matrices (51). These biosorption modalities frequently exhibit superior cost-effectiveness and a reduced ecological footprint compared with conventional physicochemical interventions such as ion exchange or bulk chemical precipitation (52). Contemporary trajectories in the field are currently pivoting toward the operationalization of whole-cell biosensors. These engineered organisms are designed to integrate environmental sensing with immediate metabolic response, providing a real-time, autonomous diagnostic-remedial loop for complex pollution profiles. These engineered microbes are designed to detect environmental toxins, such as arsenic or mercury, at trace levels and trigger a programmed, autonomous degradation response (53). This transition from passive detection to active remediation represents the future of smart biotechnological ecosystem management.

2.8.Synthetic Bioremediation : Bioinspired and Biological Engineered Energy Storage

The Deloitte Center for Energy Solutions (2018) described the need for renewable energy and the push for battery-based energy storage. That Deloitte vision was reiterated in a 2019 report by the World Economic Forum and the Global Battery Alliance, which described batteries as a key technology for powering sustainable development and achieving the Paris Agreement. Rechargeable batteries based on Li-ion technologies continue to dominate usage for mobile phones, laptops and electric cars. Nonetheless, the growth in the demand for electric vehicles and stationary electricity storage will make the development of green lithium batteries even more important in the future. A roadmap for battery R&D includes the scenario in which current-generation Li-ion batteries are approaching their performance limits, despite planned development of new generations. Batteries of the future must have a reduced ecological footprint, exhibit outstanding lifetime and reliability, and provide enhanced safety and environmental sustainability (54). Integrating batteries, energy sources, and accumulators is a promising approach to overcoming major challenges in energy storage systems. State-of-the-art research in this direction is leading to the supercapattery device (a supercapacitor combined with a battery), which offers a high specific capacitance, enabling high specific energy without sacrificing specific power. Zhou et al. describe the major challenges to overcome for implementing multifunctional supercapacitors as (i) understanding how to control ion transport to induce electrostatic charge storage in electric-double layer capacitors or redox reactions in pseudocapacitors, and (ii) improve control of ion transport, particularly for ionic liquid electrolytes, by utilising a honeycomb core to create a structural electrolyte between electrodes (55). A major challenge for integrated energy storage systems is to reduce reliance on rare earth metals, and this can be achieved through a bioinspired, biological-engineering approach (56). Previous attempts to develop stable energy-producing systems utilising a bioinspired approach based on multiple ion-conducting membranes is exemplified by the elegant work of Funakoshi et al, who described a fluidic approach to produce a bilayer that overcame the fragility, instability and low reproducibility of the BLM method (57). The Bayley group (58) and the Schmidt group (59) further developed that approach into the double-interface-bilayer (DIB) technique. The DIB approach relies on producing individual droplets using microfluidic systems or micropipette nozzles, then arraying them into 2D or 3D formations. However, although a chain of 16 droplets, each containing the porin α-hemolysin, printed on a dimpled substrate did produce an electrical response, the current decreased sharply with the number of interfaces across which the potential was applied (58). Nonetheless, practical and stable bioinspired energy has been achieved recently by applying a systems approach to the biological engineering of energy storage (60). This recent approach meets the criteria for batteries of the future (54) by reducing reliance on rare earth metals and overcoming the limitations of existing battery technology, thereby improving the ecological footprint, environmental sustainability, and lifetime, reliability, and safety.

2.9 Microalgae and Macroalgae: Photosynthetic Platforms for Planetary Health

Within the integrative Planetary Health paradigm developed in this work, microalgae and macroalgae occupy a uniquely polyvalent niche, functioning as living technologies that couple molecular precision with systems-ecology and circular bioeconomy design. Their photosynthetic carbon assimilation enables physiologically efficient CO_2 drawdown in engineered environments where flue-gas–coupled cultures display high volumetric fixation and rising CO_2-utilization efficiencies through membrane-based delivery and advanced reactors (66). At the same time, algae serve as versatile ecotechnological agents in aquatic restoration: microalgae remove nitrogen, phosphorus, and emerging contaminants, and coastal symbioses influence coral thermal performance, with lineage-specific tolerance and demonstrated symbiont switching (65,68,69). Their biomass architectures further embed algae within the circular bioeconomy, supplying hydrocolloids and bioplastics from seaweeds and high-functionality proteins from microalgae-routes that avoid additional land and freshwater demand (63,70,71).

In this context, the rapid advances in synthetic biology (e.g., CRISPR/Cas, organelle-targeted biosynthesis, genome-scale design) and DBTL-driven process (Design–Build–Test–Learn cycles) intensification are transforming algae into programmable, carbon-neutral biomanufacturing platforms (62,72). These capacities render algae not ancillary but keystone components of a bio-planetary restoration strategy organisms whose biological plasticity, engineering-readiness, and ecosystem functionality converge to exemplify how biotechnology can reinforce Earth-system stability while enabling just and regenerative economic transitions.

2.9.1 Photosynthetic carbon management and industrial symbiosis

Microalgae are photosynthetic microorganisms found in aquatic and humid environments. They can be eukaryotic organisms (microalgae, Chlorella vulgaris) or prokaryotic (cyanobacteria, Spirulina platensis). They are characterized by their ability to perform photosynthesis using pigments such as chlorophylls, carotenoids, and phycobiliproteins. They also exhibit unicellular or colonial organization and play a fundamental role in aquatic ecosystems as primary producers and carbon fixers.

Microalgae provide a controllable, high-density biological route to convert CO_2 into useful biomass at industrial point sources. In closed photobioreactors (PBRs), flue-gas–coupled cultures achieve volumetric biofixation on the order of ~80 to 578 $mg \cdot L^{-1} \cdot day^{-1}$, with performance set by strain genetics, gas composition (NO_x/SO_x tolerance), irradiance field, and hydrodynamics (66). Mass-transfer innovations, particularly membrane-assisted CO_2 delivery and absorption-enhanced contactors, raise CO_2 utilization from ~13–20% to >50%, improving capture per unit energy and enabling space-efficient, co-located PBRs at cement, power, or fermentation sites (73). Sustained operation under minimally conditioned exhausts hinges on dissolved-oxygen stripping, pH/CO_2 feedback control, and turbulence management, which have been formalized in control-oriented designs for continuous cultivation (74). Embedded within the bio-CCU (Biological Carbon Capture and Utilization) vision advanced in this manuscript, algal photo-assimilative capture complements enzymatic CO_2-to-formate/methanol cascades, creating dual on-site carbon pipelines for fuels, chemicals, polymers, and biomass (73,75).

2.9.2 Algal ecotechnologies for water, co-pollutants, and coastal resilience

As photosynthetic bioreactors, microalgae couple nitrogen and phosphorus removal with carbon assimilation and biomass formation, performing best as tertiary polishing within hybrid treatment trains where residence time and productivity are guaranteed (65,68). Beyond macronutrients, algae mitigate emerging contaminants via biosorption, bioaccumulation, and photo-assisted transformations and biosorb heavy metals such as Pb, Cd, and Cr (76,77). Algal–bacterial consortia (ABC) link algal O_2 production to bacterial oxidation of organics, accelerating removal of organics, dyes, and antibiotics while valorizing biomass into biofertilizers and fuels (78,79). Targeted ABCs assembled bottom-up have achieved 90% removal of benzene, toluene, and phenol (100 $mg \cdot L^{-1}$) within 7 days, illustrating designable pollutant-specific abatement (64). At the coast, algae are foundation organisms: within coral holobionts, Symbiodiniaceae composition modulates the bleaching threshold, with Durusdinium-dominated corals generally showing higher thermal tolerance, whereas Cladocopium often supplies more fixed carbon under benign conditions an explicit tolerance performance trade-off that must inform restoration planning (80). Following heat stress, adult corals can acquire novel symbiont types from the environmental rare biosphere, with some lineages rising to ~33% relative abundance (69). At the molecular edge, symbiont-targeted engineering strategies are emerging, and CRISPR mutagenesis in corals has demonstrated that HSF1 function is causal for larval thermal survival (81,82).

2.9.3 Algae-centered circular bioeconomies for materials and nutrition

Macroalgae supply hydrocolloids alginate, agar, carrageenan, and ulvan that can be formulated into bioplastic films and biocomposites; enzyme-assisted extraction, plasticization, and nanocomposite reinforcement have improved mechanical and barrier properties for packaging and biomedical uses (56,63). Seaweed materials bring non-arable cultivation, rapid growth, nutrient uptake, and carbon sequestration advantages, but require integrated biorefineries to cross cost and performance barriers (83). For polymer precursors, micro- and macroalgal hydrolysates can feed PHA fermentations; process studies specify detoxification, C/N control, and inoculum strategies, while feasibility reviews consolidate PLA/PHAs pathways aligned with biodegradation-by-design (84). On nutrition, microalgae deliver protein-dense biomass (≈50–70% DW) with balanced essential amino acids and techno-functionalities that enable beverages, dairy analogs, structured foods, and 3D-printed matrices. Cultivating food-grade lines on non-arable land and saline/brackish water, coupled with CO_2 co-utilization and biorefinery cascades, reduces footprints and improves economics; extraction advances (ultrasound, pulsed electric field, enzymes) further raise yields and digestibility . Regulatory guidance indicates that biomass grown directly on wastewater should be routed to feed or soil amendments unless contaminants are demonstrably removed, whereas controlled cultivation is suitable for food-grade production, especially in arid regions linked to greenhouse CO_2 and desalination brines (85).

2.9.4 From chassis to factories: synthetic biology, intensified reactors, and governance

In leading microalgae Chlamydomonas reinhardtii, Phaeodactylum tricornutum, and Nannochloropsis spp. CRISPR/Cas editing, modular cloning, synthetic promoter libraries, and organelle-targeted biosynthesis now enable targeted flux redirection to lipids, PUFAs, carotenoids, and terpenoids, while fortifying tolerance to high CO_2, salinity, and temperature (62). Convergence with genome-scale metabolic models and Design-Build-Test-Learn automation improves design fidelity and compresses iteration times, while photobioreactor process intensification narrows the lab-to-plant gap for stable productivity (72). Recent work has expanded algal biomanufacturing beyond metabolic products to include the biosynthesis of functional nanomaterials such as gold nanoparticles produced via algal green-synthesis routes which can enhance catalytic efficiency in bioenergy systems and exemplify the emerging convergence of algal biotechnology with advanced materials engineering (86). Within the ethical and risk-governance architecture advanced in this review biocontainment in closed PBRs, risk-tiering for open systems, transparency and monitoring engineered algae become carbon-neutral biomanufacturing platforms that convert industrial or atmospheric carbon into fuels and high-value products at scale (85).

3. Nanostructured Systems for Precision Environmental Monitoring and Adaptive Environmental Intervention.

Effective planetary health governance increasingly depends on the capacity to detect ecological perturbations at their earliest physicochemical and biological manifestations (87). While genomic surveillance approaches such as environmental DNA (eDNA) have revolutionized biodiversity monitoring by enabling non-invasive species detection across ecosystems (4,12), these tools primarily provide taxonomic and compositional insights and often lack real-time information on functional ecosystem states, including metabolic stress responses, thermal fluctuations and pollutant bioavailability. Recent perspectives in Earth system science highlight the urgent need for integrated monitoring architectures capable of capturing multiscale environmental signals that precede ecological tipping points (88). In this context, emerging frameworks based on precision monitoring and environmental theranostics are gaining attention as complementary technological frontiers. Nanostructured sensing platforms, including plasmonic nanosensors, nano-photocatalysts, and hybrid microbial–nano systems, enable responsive environmental diagnostics coupled with dynamic remediation strategies, improving pollutant degradation efficiency and supporting climate-adaptive agricultural management (89). By integrating high-resolution physicochemical detection with targeted catalytic or biological intervention, these adaptive nanoplatforms offer new opportunities to strengthen early-warning capabilities, enhance restoration efficiency and promote ecosystem resilience under accelerating anthropogenic pressures. Nanostructured sensing platforms provide exceptional analytical sensitivity due to their high surface-to-volume ratios, tunable plasmonic or luminescent properties, and capacity for molecular functionalization (90). In particular, plasmonic nanomaterials have enabled the development of surface-enhanced Raman scattering (SERS) sensors capable of detecting trace concentrations of environmental contaminants with molecular specificity. Comparative investigations of engineered gold nanostructures, including nanospheres, nanorods, and nanostars, demonstrate their potential to optimize signal enhancement and detection selectivity in complex environmental matrices (91,92). Such platforms can facilitate the monitoring of heavy metals, pesticides, endocrine disruptors, and microbial metabolites in soil and aquatic environments, thereby providing real-time diagnostic feedback to guide remediation or conservation strategies (93). Beyond molecular fingerprinting, nano-enabled monitoring technologies also enable the quantification of microenvironmental thermal gradients, which critically influence enzymatic degradation kinetics, microbial respiration, and stress-response pathways under climate variability. Luminescent nanoprobes, including fluorescent nanodiamonds and near-infrared emissive nanoparticles, have demonstrated robust lifetime-based thermometry with high spatial resolution and photostability in complex biological systems (94). Translating such nanothermometric approaches to environmental biotechnology may enable precision optimization of microbial bioreactors, climate-resilient agriculture, and assisted evolution strategies in thermally sensitive marine habitats.

The integration of nanoscale sensing with autonomous monitoring infrastructures represents a further evolution in planetary diagnostics (95). Coupling nano-enabled sensors with remote sensing platforms, artificial intelligence-driven analytics, and distributed Internet-of-Things (IoT) networks may enable continuous environmental data acquisition and predictive modeling of ecosystem resilience (96). Such multimodal monitoring frameworks are essential for identifying pollution events, pathogen emergence (95), or climate-induced habitat destabilization before irreversible ecological thresholds are crossed. Importantly, nano-enabled monitoring can also provide quantitative feedback to calibrate synthetic biology-based remediation strategies by tracking microbial activity, nutrient fluxes, and pollutant degradation efficiency in real time (41). Despite their transformative potential, nanoscale environmental monitoring systems require careful consideration of environmental fate, bioaccumulation risks and regulatory governance. The development of biodegradable or functionally transient nanomaterials (97), supported by life-cycle assessment and adaptive risk frameworks, will be critical to ensure responsible deployment at ecosystem scales (53). Crucially, nanostructured systems expand the diagnostic and operational capacity of planetary stewardship strategies, enabling a transition from static environmental observation to predictive, adaptive ecosystem management that enhances restoration efficiency and long-term ecological resilience in the Anthropocene.

Extensive human industrial and urban activities have generated greenhouse gases, resulting in global warming and climate change, consequently disturbing the agricultural systems worldwide, posing a significant risk to global food security (98). Intensive agricultural practices driven by food demand contribute to greenhouse gas (GHG) emissions, soil erosion, pollution of soil and water ecosystems with agrochemicals and microplastics, deforestation, and the loss of biodiversity. Therefore, the traditional agriculture practices need to be changed for eco-friendly and sustainable farming practices, which can avoid environmental degradation and will conserve natural ecosystems. Application of bioengineered biodegradable biobased polymeric mulches derived from renewable resources (e.g. such as starch, cellulose, polyhydroxyalkanoates) as well as degradable polymers (e.g. polylactic acid PLA) could potentially serve the purpose by preventing soil erosion, reducing weed growth, controlling soil temperature, reducing soil evaporation and conserving moisture, as well as improving soil microbiota activities and fungal diversity (99). Another idea is to make use of 'living mulches' where active microbial cultures are incorporated into the material, enabling microbial degradation of the mulch in situ. Previous studies (100) demonstrated that these 'smart mulches' performed as good as the conventional plastic mulches with our any ecological risk of plastic residues (nano - and microplastics) being left in the soil. However, moving beyond the 'plastic era' in agriculture and the scalability of the bioengineered smart mulches depends on technological innovation, costs and suitable policies balancing food security with sustainable agriculture.

3.1. Precision Microbiome Engineering: Optimizing the Plant-Soil-Axis

Advanced biotechnological interventions have increasingly shifted their focus toward the intricate plant-soil-microbiome axis as a primary lever for enhancing agricultural resilience and metabolic efficiency. At the heart of this strategy is the engineering of specialized microbial consortia designed to optimize nutrient cycling within the rhizosphere. By deploying synthetically enhanced nitrogen-fixing bacteria and arbuscular mycorrhizal fungi, researchers aim to decouple modern agronomy from its intensive dependency on Haber-Bosch-derived fertilizers (41). This transition is not merely an ecological preference but a climate imperative, as the production and runoff of synthetic nitrates remain primary contributors to global greenhouse gas emissions and the catastrophic eutrophication of limnic and marine systems.

Furthermore, the paradigm of crop protection is being redefined through the application of RNA interference (RNAi) technology. Unlike conventional broad-spectrum pesticides that exert indiscriminate selection pressure on agroecosystems, RNAi provides a high-precision molecular scalpel (101). By targeting highly specific mRNA sequences essential for the survival of pathogenic organisms, this technology facilitates the silencing of vital genes without compromising the physiological health of non-target beneficial insects (61). This specificity is crucial for maintaining trophic integrity, ensuring that pest management does not trigger the secondary collapse of pollinator populations or soil-dwelling decomposers. Ultimately, integrating microbiome engineering with RNA-based biopesticides facilitates a move toward probiotic agriculture, where the biological complexity of soil is harnessed as an active component of the global food security infrastructure (61).

3.2. Bio-based Materials and Industrial Symbiosis: Engineering the Built Environment

Beyond the immediate requirements of global food systems, the synthesis of advanced bio-based polymers and structural materials represents a fundamental cornerstone of the circular bio-economy. As the limitations of fossil-fuel-dependent manufacturing become increasingly apparent, mycelium-based composites and microbially-synthesized cellulose emerge as high-performance, biodegradable alternatives to petroleum-derived plastics and energy-intensive construction materials (42). These biological substrates are no longer viewed merely as ecological substitutes; they are sophisticated materials whose mechanical properties, such as tensile strength, thermal insulation, and fire resistance, can be precisely tuned through genomic and environmental optimization.

The transformative potential of these materials lies in their ability to invert the carbon footprint of the industrial sector. Rather than functioning as carbon-neutral substitutes, engineered biomaterials can be designed to sequester carbon actively, effectively transforming the urban built environment into a vast anthropogenic carbon sink. This process is underpinned by the principles of industrial symbiosis, which replace the traditional linear flow of resources with a closed-loop framework. By utilizing lignocellulosic agricultural by-products and industrial effluents as primary substrates for microbial fermentation, this approach ensures that waste streams from the agrifood sector are upcycled into high-value precursors for the construction and packaging industries (43). Consequently, this symbiotic architecture not only mitigates the accumulation of persistent pollutants but also aligns industrial metabolism with the regenerative capacity of the biosphere, offering a scalable pathway toward a net-zero future.

3.3. Resilience through Genetic Diversity: Genomic Strategies for the Anthropocene

The integration of genomic selection and CRISPR-mediated trait enhancement represents a pivotal evolution in agricultural biotechnology, facilitating the rapid development of crop varieties that can thrive amid intensifying abiotic stressors. As the Anthropocene induces unprecedented environmental volatility characterized by hypersalinity, thermal extremes, and protracted drought cycles, the reliance on traditional breeding cycles is no longer sufficient to ensure global caloric stability. Modern genomic tools enable the precision targeting of quantitative trait loci (QTLs) associated with climate resilience, enabling the deployment of climate-smart cultivars with enhanced water-use efficiency and osmotic stress tolerance.

Crucially, this biotechnological framework departs from the 20th-century Green Revolution paradigm, which was predicated on high-input, genetically uniform monocultures that inadvertently compromised agroecological health. Instead, current advancements prioritize the restoration of genetic diversity within the field, utilizing molecular techniques to resurrect lost alleles from ancestral landraces and integrate them into modern elite lines. This approach fosters a polycultural resilience that can absorb environmental shocks while maintaining yield stability. By synthesizing the precision of molecular biology with the principles of sustainable land management, these innovations provide a robust pathway for reconciling the food demands of a burgeoning global population with the urgent need to restore the biological vitality and regenerative capacity of Earth's ecosystems (102). The integration of genomic selection and CRISPR-mediated trait enhancement represents a pivotal evolution in agricultural biotechnology, facilitating the rapid development of both crop varieties and livestock breeds capable of thriving amid intensifying abiotic and biotic stressors (103). As the Anthropocene induces unprecedented environmental volatility characterized by hypersalinity, thermal extremes, emerging pathogens, and protracted drought cycles, the reliance on traditional breeding paradigms is no longer sufficient to ensure global caloric and protein stability. Modern genomic tools enable the precision targeting of quantitative trait loci (QTLs) associated with climate resilience, supporting the deployment of climate-smart cultivars and livestock with enhanced water-use efficiency, disease resistance, thermal tolerance, and resource-use efficiency. Crucially, this biotechnological framework departs from the 20th-century Green Revolution paradigm, which was predicated on high-input, genetically uniform monocultures and narrowly selected livestock lines, thereby inadvertently compromising agroecological and genetic resilience. Instead, contemporary genomic strategies explicitly center resilience through genetic diversity, leveraging molecular tools to expand—not narrow—the allelic repertoire across both plant and animal production systems (104). By resurrecting cryptic or lost alleles from ancestral landraces, wild relatives, and indigenous livestock breeds, and introgressing them into elite germplasm and breeding lines, researchers are reconstructing heterogeneous genomic architectures that confer robustness against multifactorial stress regimes (105). This diversification operates not only at the level of single loci but across polygenic networks, enhancing adaptive capacity under non-linear and unpredictable environmental perturbations (106).

This approach is reinforced by multi-omics integration and data-driven modeling, enabling refined dissection of gene–environment interactions across crops and livestock, including microbiome-mediated traits such as feed efficiency and stress tolerance (107). When coupled with advanced phenotyping and machine learning, these approaches optimize genotype × environment × management (G × E × M) interactions, consequently enhancing system stability and productivity (108). Furthermore, epigenetic regulation contributes to adaptive plasticity by enabling dynamic gene expression in response to environmental fluctuations (109). At the agroecosystem level, reintroducing genetic diversity among crops, livestock, and microbiomes fosters integrated, polycultural systems that distribute risk and enhance ecological function (110). Precision agriculture tools further strengthen these systems by facilitating real-time environmental monitoring and adaptive management (108). However, their widespread implementation relies on addressing regulatory fragmentation and achieving societal acceptance, particularly with regard to gene-edited livestock (111).

Ultimately, the convergence of genomic selection, gene editing, and synthetic biology embeds genetic diversity as a core design principle of resilient agroecosystems. This integrated approach can support sustained productivity, improve animal welfare, and facilitate ecological restoration, providing agricultural systems with a viable means of withstanding the accelerating pressures of the Anthropocene (112).

3.4. Mitigating Chemical Dependency: Molecular and Microbiome-Based Defense

The transition toward a post-chemical agriculture is increasingly catalyzed by the deployment of high-precision molecular tools, such as RNA interference (RNAi) and next-generation biopesticides. These technologies address the fundamental flaw of conventional agrochemicals: their lack of specificity, which leads to significant collateral damage to non-target species and the broader environment. By leveraging RNAi-based applications, it is now possible to achieve targeted pest suppression by silencing essential genes in specific pathogens, thereby preserving trophic integrity and pollinator health, which are essential for ecosystem stability. This shift from broad-spectrum toxicity to sequence-specific regulation represents a landmark evolution in integrated pest management.

Parallel to these molecular interventions, engineering the plant-soil-microbiome axis has emerged as a cornerstone strategy for enhancing endogenous nutrient cycling and drought tolerance. Rather than relying on external, energy-intensive inputs, this approach harnesses the metabolic synergies of beneficial microbial consortia to unlock soil-bound nutrients and modulate plant hormonal responses to stress (41). Such biological fortification is essential for stabilizing food systems in the face of anthropogenic climate change. Furthermore, the development of climate-resilient crops genetically optimized for enhanced water-use efficiency and salinity tolerance remains an indispensable requirement for maintaining global food security on a planet where arable land is increasingly marginalized (113). Ultimately, by synthesizing microbiome engineering with precision molecular defense, agriculture can transcend its historical dependency on synthetic chemistry, aligning food production with the regenerative dynamics of the biosphere.

The nexus between human longevity and ecological stability is increasingly defined by the "Planetary Health" framework, which posits that the biochemical integrity of Earth's natural systems is the primary determinant of public health outcomes. Anthropogenic pressures have fundamentally destabilized global nutrient cycles, particularly carbon and nitrogen, triggering a cascade of metabolic disruptions that manifest as systemic malnutrition and environmental toxicity. In this context, biotechnology emerges not merely as a technical intervention but as a critical mediator of ecological restoration. In the context of synthetic biology, cellular agriculture, and lab-grown proteins, these technologies offer a promising route to decouple human nutritional requirements from biodiversity loss. In addition, judicious use of bioremediation exploits microorganisms' metabolic capabilities to detoxify anthropogenic pollutants. At the same time, green biotechnology specifically targets the development of crop phenotypes with superior nutrient-use efficiency under climatic stress. In aggregate, these recent biotechnological innovations facilitate the transition to a circular bioeconomy, aligning human physiological needs with the regenerative capacity of the biosphere (114).

It is well known that fungi can absorb pollutants such as heavy metals and radioactive materials. At the same time, this poses a risk to uninformed foragers, but it also presents an opportunity for bioremediation through continuous harvesting and removal of these fungi from the environment. Although this is a natural approach, it remains a long, laborious, and costly methodology. While biotechnology could potentially take center stage, such applications currently seem more like science fiction and are not suitable for this section.

A potential incentive for eliminating these pollutants is to integrate a bioactive molecule discovery program into the collection of macrofungi using biosensor screening tools. This would allow for the rapid mapping of bioactive molecules alongside their potential toxicity levels and modes of action within a single (115). Bioluminescent Whole-Cell Bioreporter Bacterial Panel: A Novel Screening Method for the Discovery of Antimicrobial Compounds from Fungi (115).Indeed, the macrofungal flora whose molecular potential remains largely untapped in terms of both human therapeutic potential and environmental treatment warrants such extensive research.

3.5. Bio-based Materials: Integrating Biosynthesis into Urban Environments

The systemic transition toward a functional circular economy is fundamentally contingent upon the industrial-scale adoption of microbial fermentation processes to produce high-performance, biodegradable alternatives. Bacterial cellulose and mycelium-based composites have emerged as frontline candidates to replace conventional, petroleum-derived polymers and carbon-heavy construction materials (42). Unlike other materials, these biological substrates are cultivated rather than manufactured through extractive processes, thereby offering a low-entropy approach to material production. Specifically, the flexibility of mycelium-based fungi enables the production of composites that show promise for acoustic insulation, thermal durability, and compression resistance, while offering a negative carbon footprint.

Strategically integrating such materials into urban green spaces and smart cities can help mitigate the stressors of rapid urbanization. By incorporating materials synthesized by microbes, such as modular insulation materials or biodegradable furnishings, cities can evolve from exporters of waste to integral components of a biological cycle of renewal (43). Additionally, when combined with nature-based solutions

3.6. Genomics at the Interface of Planetary and Human Health

Human health is inseparable from environmental health, as underscored by the Planetary Health framework, which emphasizes how anthropogenic changes shape disease patterns and population well-being (3). Environmental stressors, including pollution, climate change, and biodiversity loss, affect human health through complex biological pathways, many of which operate at the genomic and epigenomic levels (116). The exposome, defined as the cumulative measure of environmental exposures throughout life, provides a critical framework to integrate environmental and genomic data. Large-scale exposome studies incorporating multi-omics approaches have shown that early-life exposures, particularly during pregnancy, are linked to widespread molecular signatures, including persistent DNA methylation changes and alterations across multiple omics layers, highlighting lasting biological impacts (117). By capturing the complexity of environmental exposures and their biological consequences, the exposome framework underscores the importance of characterizing non-genetic determinants of disease at a scale comparable to that of the human genome (118). In this context, genomics acts as a bridge between environmental change and human health outcomes. Linking molecular mechanisms to ecological drivers enables a systems-level understanding of disease etiology and informs strategies to mitigate the health impacts of environmental degradation. Together, genomics and exposomics offer a powerful lens for understanding and addressing the interconnected challenges of planetary and human health.

4. Agro-Industrial By-Products: From Bioactive Compounds to Functional Applications in Human Health

The circular bio-economy paradigm applies to the systematic valorization of agri-food processing by-products, which represent an abundant, underexplored source of bioactive compounds. The by-products of the main food production chains — including grape pomace, a waste product of the wine production chain, and dairy industry by-products — represent rich sources of polyphenols, carotenoids, short-chain fatty acids (SCFAs), and bioactive peptides. These residues can be transformed, through targeted extraction and nanoformulation strategies, into functional ingredients of significant pharmaceutical, nutraceutical, and dermocosmetic relevance. The recovery of SCFAs is of translational significance - predominantly acetic, propionic, and butyric acid - from wine and dairy by-products. These metabolites, widely studied for their roles in gut-microbiome homeostasis, have recently emerged as potent modulators of skin inflammation: they act through multiple converging mechanisms, including the inhibition of histone deacetylases (HDAC), activation of G protein-coupled receptors (GPCRs), and regulation of pro-inflammatory cytokine cascade. Preclinical evidence demonstrates that acetic and butyric acid can suppress keratinocyte hyperproliferation, promote epidermal differentiation, and attenuate pathological signaling pathways - notably the JAK/STAT3 axis – that are centrally implicated in the pathogenesis of atopic dermatitis and psoriasis.

These results make SCFAs, recovered from agri-food residues, excellent candidates as active ingredients for innovative dermatological formulations, bridging the gap between waste valorization and precision therapeutic development. Beyond SCFAs, agro-industrial residues produce complex polyphenolic fractions including resveratrol, proanthocyanidins, and flavonoids from grape pomace, whose antioxidant, anti- inflammatory, and immunomodulatory activities have been extensively documented. Similarly, dairy-derived bioactive peptides exhibit measurable effects on epidermal barrier function and immune regulation. The combination of these bioactive profiles makes agri-food residues a versatile substrate for the formulation of multi-target therapeutic agents, applicable not only to topical dermo-cosmetics but also to dietary supplements and nutraceuticals aimed at the prevention and management of chronic inflammatory conditions. An important limitation to the direct clinical application of these recovered compounds is their intrinsic physicochemical properties: chemical instability, rapid diffusion, low local bioavailability, and limited target selectivity.

Nanotechnology-based delivery systems offer a robust solution to these limitations. Encapsulation of bioactive compounds within nano-structured carriers, particularly in liposomes, enables controlled and sustained release, increases local epidermal concentrations, and reduces systemic side effects. The application of nano-carrier systems with agro-industrial-derived actives thus represents a convergence point between circular bioeconomy principles and advanced pharmaceutical technology, generating upgraded products whose performance profile exceeds that of either component in isolation. From a systems perspective, this valorization framework aligns with the broader biotechnological strategy outlined throughout this review. Extending this logic to human health applications reveals a remarkable circularity: agricultural and food-processing by-products, which would otherwise contribute to environmental loading, are instead redirected toward the prevention and management of chronic diseases, including inflammatory skin disorders whose global impact continues to increase. This application domain is further underscored by the growing recognition of the gut-skin axis, through which microbially derived metabolites, such as SCFAs, exert systemic immunomodulatory effects with direct consequences for cutaneous homeostasis (119,120). Integrating agro-industrial valorization into the planetary health paradigm thus generates a dual dividend: it reduces ecological waste while simultaneously expanding the therapeutic resources available for addressing the increasing global impact of chronic inflammatory and dermatological conditions.

(NbS), These materials enhance ecosystem services in urban areas, such as rainwater infiltration and the regulation of local microclimate. This integration of biosynthetic engineering and urban ecology enables a “living architecture” that balances human settlement with the biogeochemical cycles of our planet, offering a framework for sustainable and resilient metropolitan development.

5. Chemical Tools for Environmental Monitoring and Fate Prediction

5.1. Analytical Chemistry in Support of Environmental Protection

Advances in analytical chemistry enable precise detection and monitoring of environmental pollutants and contaminants, as well as accurate determination of material composition. The

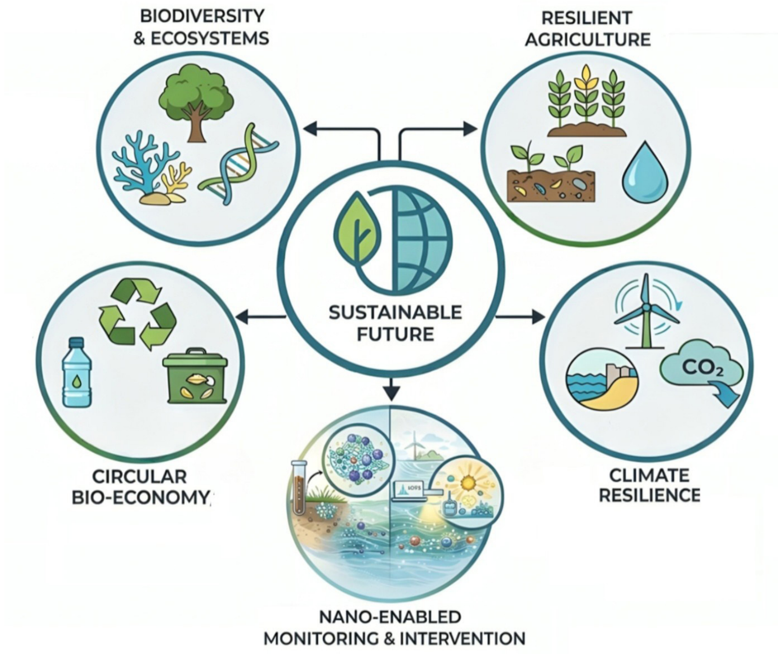

Figure 1. An integrated biotechnology framework for planetary health. Schematic representation of five complementary biotechnological domains -biodiversity and ecosystem conservation, resilient agriculture, circular bio-economy and pollution control, nano-enabled monitoring and intervention, and climate resilience- interact to support a sustainable future.

integration of mass spectrometry (MS), a highly sensitive and selective analytical technique, with complementary analytical methods, enables the identification and quantification of trace-level environmental pollutants in complex matrices, including water, soil, air, waste streams, and even living organisms, while also supporting quality control and process monitoring in industrial settings. MS is commonly coupled with chromatography (including high-performance liquid chromatography (HPLC) and gas chromatography (GC)), capillary electrophoresis (CE), inductively coupled plasma (ICP) analysis, thermal resorption (TR), proton transfer reaction (PTR), and Matrix-Assisted Laser Desorption/Ionization (MALDI), among others. These techniques allow the precise evaluation of concentrations of a variety of analytes, including elements, inorganic and organic compounds, and particulate pollutants. Effective monitoring and control of hazardous chemicals contribute to reducing environmental and human health risks, enable the safe reuse of resources, and support industry compliance with regulatory standards. The availability of detailed analytical data enhances the transparency across supply chains and facilitates the implementation of effective waste management strategies and resource recovery processes.

5.2. Quantum Chemical Modeling of Environmental Fate of Industrial and Agricultural Chemicals

Quantum chemical modeling has become an indispensable tool for understanding the environmental fate of industrial and agricultural chemicals, complementing experimental approaches by providing mechanistic and kinetic insights that are difficult or impossible to obtain in the laboratory alone. Central to this approach are density functional theory (DFT) calculations, used to compute thermodynamic and kinetic parameters for reactions such as oxidation, hydrolysis, and photodegradation. Advanced oxidative processes (AOPs), in which environmentally free radicals such as hydroxyl radicals (HO•) react with and degrade contaminants, are a particularly active area of computational study (121). A typical example is the AOP of 4-hydroxycoumarin, the parent compound of several anticoagulant drugs and rodenticide pesticides, which reacts with HO• radicals in aqueous and lipidic environments; it was shown that the actual physical environment is critical in directing the decomposition toward relatively benign products. Quantum chemical calculations of the HO•-driven degradation of pollutants can reveal mechanisms, kinetics, thermodynamics, and ecological risks, and have shown that closely related derivatized compounds exhibit markedly different environmental persistence depending on pH and molecular structure (122). The oxidation of agricultural fungicides has also been studied computationally; a DFT study of the thiram pesticide at the M06-2X level of theory showed that radical addition, hydrogen abstraction, and single-electron transfer all contribute to its HO•-initiated oxidation in water, with addition reactions at sulfur positions dominating the kinetics (123). More broadly, QM/MM hybrid methods, which model a chemically active region quantum mechanically while treating the surrounding solvent or macromolecular environments classically, have been applied to environmental chemistry, though their use remains relatively limited due to the expertise required to correctly partition the system (124). The QSAR framework, which correlates quantum chemical descriptors with experimentally observed fate parameters, has been applied to a wide diversity of manmade pollutants including pesticides, PAHs, and PCBs to predict processes spanning water dissolution, volatilisation, soil sorption, and biotic and abiotic degradation (125). Machine learning is increasingly being integrated with quantum chemistry in this space: well-constructed ML models have been used to construct potential energy surfaces to obtain thermodynamic data for atmospheric radical reactions and cluster configurations relevant to nucleation, and quantum chemistry combined with ML has been highlighted as a promising approach for predicting the environmental fate of persistent pollutants such as PCBs and PFASs (126).

6. Discussion and Future Perspectives: Governance, Ethics, and Global Stewardship

The integration of advanced biotechnologies into planetary health governance has created a complex landscape of ecological opportunities and socio-technical challenges. While the restoration potential is considered to be substantial, the implementation of these restoration efforts, especially about genome editing and synthetic microbial consortia, requires the development of a robust and rigorous Environmental Risk Assessment (ERA) approach to proactively address unintended ecological impacts, including horizontal gene transfer and impacts on non-target trophic interactions (53). A precautionary yet proactive approach is required, balancing the urgency of the climate crisis with the need for long-term biosecurity protocols.

For these technologies to actually work, we need to make genetic data accessible to everyone through transparent, open-access databases. Initiatives like the Earth BioGenome Project are indispensable in this regard, providing a digital repository of planetary biodiversity that ensures equitable access to technology and prevents the monopolization of biological resources (25) For the bioeconomy to move forward, it is important to bridge the gap between molecular research and ecological knowledge. Safety is a key issue; as the adoption of bio-digital tools grows, it is important to develop strategies to contain engineered species. Since ecosystems know no borders, it is important to develop international policies that recognize this fact and set clear ethical boundaries. According to Trivedi et al. (41), combining biotechnology with environmental science is a viable path for the Anthropocene, but only if it is built on a foundation of radical transparency and intergenerational equity.

Five complementary areas (biodiversity conservation, resilient agriculture, circular bioeconomy and pollution control, climate resilience and ecosystem restoration, and nanotechnology-assisted monitoring and response) interact to support adaptive environmental management and sustainable ecosystem functioning.

7. Conclusion: Toward a Bio-Planetary Synthesis and the Dawn of Ecological Modernization

The integration of biotechnological innovations delineated in this analysis underscores a profound ontological shift in the governance of global environmental systems. We are entering a nascent era of planetary stewardship, where the traditional dichotomy between technology and nature is no longer tenable. Rather than viewing innovation as an external imposition on the environment, we now conceptualize molecular and synthetic engineering as an inherent partner, meticulously designed to operate in synergy with Earth's complex ecological networks.

The legacy of the "Great Acceleration" has rendered one fact indisputable: the era of passive conservation has reached its conclusion. Relying solely on the sequestration of land in anticipation of natural self-recovery is now an exercise in futility. Such an approach no longer constitutes a viable defense against the environmental thresholds currently being breached. The Anthropocene necessitates a more robust intellectual and empirical pivot: a transition toward active, biologically-informed restitution. By synchronizing laboratory precision with biospheric complexity, this approach facilitates a restorative paradigm as dynamic as the environmental crises it seeks to mitigate. The systemic shift from a linear, extractive economic model to a circular, bio-based ecosystem is far more than a mere technical evolution; it is a foundational prerequisite for the long-term survival of human civilization. The framework proposed here suggests that by aligning the surgical precision of molecular biology, exemplified by CRISPR-mediated genetic rescue and synthetic enzymatic bioremediation, with macro-ecological instruments such as GIS-enabled habitat planning, we can construct a robust, dual-layered defense system for the biosphere. This Bio-Planetary Framework offers a tangible roadmap to decouple industrial progress from environmental degradation. Instead of simply mitigating environmental harm, this approach uses microbial consortia and solar-based manufacturing to transform waste into wealth. In developing the bioeconomy, it is necessary to close the gap between molecular and ecological studies. One of the main concerns is safety; with the growing use of bio-digital tools, it is necessary to develop strategies to contain engineered species. Since ecosystems do not have borders between countries, it is necessary to develop international policies that recognize this fact and define ethical boundaries.

This calls for the development of a multidisciplinary governance structure that meets the stringent criteria set by the Precautionary Principle while harnessing the immense potential of living technologies. Three structural pillars should be emphasized to ensure equity in these interventions. Most importantly, we shouldn't view technology as a replacement for nature. The goal is to engineer solutions that empower Earth's self-healing mechanisms rather than bypass them.

The ultimate objective is to enhance evolutionary resilience, ensuring that biomes possess the biological buffer necessary to withstand increasing climatic volatility.

Global Equity and the Democratization of Science: The persistent biotechnological divide between the Global North and South remains a critical barrier to global restoration. True progress requires the democratization of advanced genomic tools, climate-resilient agricultural strains, and open-access biodiversity databases. Empowering communities on the front lines of the climate crisis allows for localized, context-specific restoration efforts that are both culturally relevant and ecologically effective.

Ethical Responsibility and Dynamic Risk Governance: As we engage with high-stakes technologies, such as gene drives and synthetic organisms, continuous and multi-sectoral oversight becomes imperative. In efforts to rescue endangered species, it is essential to underpin such interventions with real-time risk management frameworks. We must ensure that these engineered solutions do not inadvertently precipitate a new environmental crisis or trigger an ecological domino effect.

Moving biotechnology into the heart of planetary health marks a fundamental shift toward true ecological modernization. In this future, human development is no longer a destabilizing force; instead, it acts as a catalyst for restoration.

We are looking at a world where urban surfaces filter the air and where progress isn't measured by how much we extract, but by the health, vitality, and biodiversity of the systems we live in. Ultimately, human ingenuity is being repurposed to protect the planet's integrity, ensuring that our civilization's path finally aligns with the biological needs of the Earth."

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None.

Ethics

Not Applicable.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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