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Biotechnology, environment and sustainability: a journey between research, science communication and policymaking in the bioeconomy

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Abstract

The transition toward a global circular bioeconomy needs a multi-dimensional approach that integrates technical knowledge and innovation with effective science communication and robust policymaking. This manuscript examines the interconnected journey of biotechnological solutions for environmental sustainability, moving from fundamental research to real-world applications. Drawing on insights from European Commission Bioeconomy strategy and Biotech Act(s), the article explores how specialized knowledge, ranging from waste valorisation in industrial biotechnology to synthetic biology applied to microbial cell factories, can be translated into actionable policy frameworks. Key emphasis is placed on the role of science communication in distilling complex biotechnological concepts into accessible and relatable narratives for a diverse audience from policymakers to the general public. By identifying current challenges in the research-to-policy pipeline and outlining current research directions, this manuscript provides a roadmap for leveraging biotechnology to foster a more sustainable bio-based world.

Keywords Biotechnology, Bioeconomy, Biomanufacturing, Science communication, Policymaking

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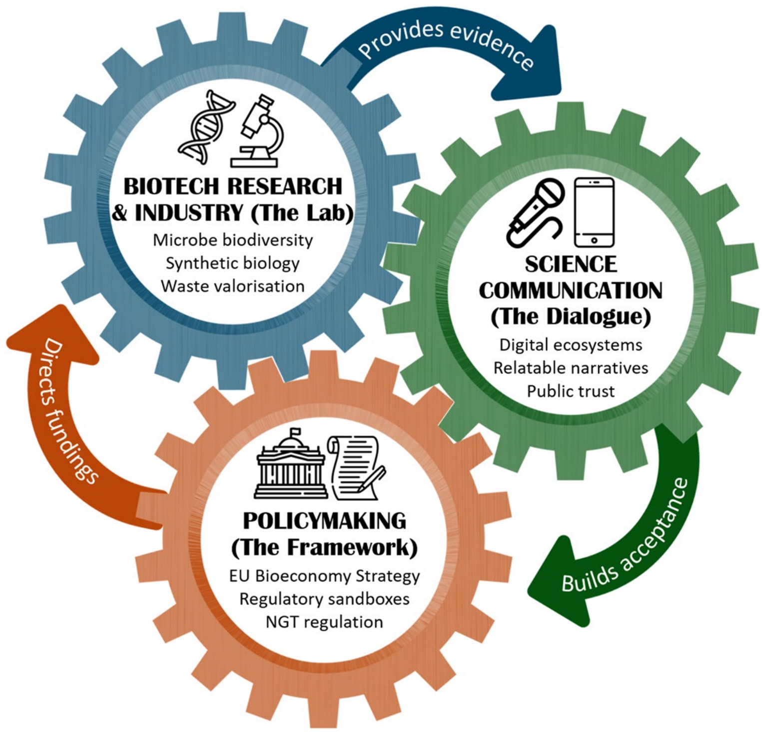
Graphical Abstract



The journey to a global circular bioeconomy

The current environmental crisis is often misdiagnosed as a series of isolated technical challenges rather than what it truly is: a deeply systemic inconsistence between linear industrial frameworks and planetary boundaries. Global production systems have extracted fossil reserves to yield materials, energy, and chemicals, treating the resulting waste streams as externalized ecological debts, and leaving manufacturing infrastructure acutely vulnerable to geopolitical volatility and resource shocks [1]. Overcoming these structural problems needs moving away from the legacy "take-make-dispose" paradigm toward an integrated circular bioeconomy. The transition aims for a defossilisation of manufacturing cycles, acknowledging that while many materials necessarily consist of carbon, this must be sourced from renewable biological resources rather than fossil reserves [2]. This transition requires more than simply replacing petroleum-derived molecules with bio-based counterparts; it demands that we rethink and redesign our relationship with organic waste and residual biomass, especially in urban areas, to ensure decarbonisation is achieved as well in parallel [3]. Open field burning and unscientific dumping of agricultural residues still account for significant global anthropogenic emissions, highlighting the urgent need to actively redirect these undervalued resource streams back into high-value production loops [3–5].

Defining the multi-dimensional approach

Approaching this scenario means recognizing that a sustainable bio-based transition cannot occur within a single laboratory or a closed policy room. It is a multi-dimensional journey spanning scientific innovation, industrial upscaling, and strategic governance. At the European level, the adoption of the *Strategic Framework for a Competitive and Sustainable EU Bioeconomy* in late 2025 has marked a definitive shift, stressing the need for better use of foundational research for industrial deployment and geopolitical autonomy [2, 6]. Achieving these targets means building a cohesive regulatory and industrial ecosystem capable of bridging the traditional gaps from "lab to fab", which, especially in the biotech sectors, is a continuum driven by an industrial ecosystem where research-based innovations must navigate two critical 'valleys of death'. These bottlenecks can be identified as the transition from demonstration to first commercial production, and the subsequent scaling to full industrial capacity [2]. This alignment relies on the cascading use of biomass, prioritizing the extraction of high-value biochemicals and secondary metabolites before executing end-of-life energy recovery [3]. Biotechnology solutions (e.g. biomanufacturing) have being crucially fast-tracked through concrete policy instruments like the EU Biotech Act I of 2025 and the upcoming Biotech Act II of 2026, which establish regulatory sandboxes to eliminate persistent market barriers [6, 7]. However, the success of this regulatory modernization relies on robust science communication, especially when considering the scientific technicalities behind many innovations, which might encounter resistance from a certain number of politicians, stakeholders and the general public (e.g. NGTs regulation). By converting complex scientific concepts and policy strategies into accessible and clear narratives, we can align technical feasibility with policy acceptance and societal trust, paving the way for the structural transitions detailed in the chapters that follow [8].

Microbial frontiers – biomass valorisation via microbial cell factories

The biological vault: microbial biodiversity for the development of bioprocesses

It has become clear to diverse stakeholders that one of the pillars of bioeconomy is industrial biotechnology. The success of modern biomanufacturing depends heavily on the stability and adaptability of its biological catalysts. Historically, industrial biotechnology relied almost exclusively on pure cultures, which can provide several advantages, such as better engineering tools and metabolic control systems. However, natural environmental microbiomes present an alternative paradigm of robust structural and metabolic resilience. In their native environments, diverse microbial communities survive through highly specialized metabolic pathways, enhanced enzyme stability, and robust stress-response adaptations. To translate this biological resilience into industrial biomanufacturing, biotechnologies are considering moving away from single-strain configurations toward strategies like the synthetic microbial consortia [9]. The study of microbial biodiversity becomes a crucial asset to be valorized, as witnessed by several projects aiming at preservation, such as the Microbiota Vault Initiative [10]. In fact, microbes, either in pure culture or in consortia, natural or engineered, are priceless repository of strategies and solutions, often shaped by millions of years of evolution, which, scientifically speaking, is a good trial-and-error test. In the bioeconomy scenario, genes, enzymes and cell factories are useful tools to be deployed to develop biomanufacturing processes based on biorefineries, to obtain bio-based solutions, useful to foster bioeconomy's position as a strategic industrial and geopolitical asset.

Cascading principles and the valorisation of residual biomasses

Establishing a resilient bioeconomy requires shifting industrial feedstocks away from first-generation sugars, which compete directly with food security and land use. Modern biorefineries must focus instead on the comprehensive valorisation of residual biomasses, notably heterogeneous organic waste, agricultural sidestreams, and lignocellulosic biomass (LCB) [3, 11]. Transforming such by-products into raw materials is the core principle of sustainable manufacturing. Rather than treating agro-industrial residues as environmental liabilities, advanced biorefineries view them as complex carbon-rich platforms waiting to be unlocked. Following cascading principles, all the different components should be valorised considering sector priorities and added values, while reducing wastes or, even better, further exploiting them downstream [12–14]. At the same time biorefineries are integrated facilities that co-produce biochemicals, biomaterials, and bioenergy, providing crucial services in the sectors involved in the bioeconomy. For example, biofuels remain a primary option for defossilizing sectors like aviation and maritime transport, and residual and secondary biomass streams should be utilized for energy where alternative defossilization or decarbonization solutions are absent or to ensure energy affordability. Lignocellulosic biomass is highly abundant but notoriously complex to break down, and overcoming this recalcitrance requires advanced biorefinery setups, when considered beyond the simple uses for energy (e.g. wooden pellets). Biocatalytic strategies utilizing targeted enzyme systems possibly permit pre-treatment and hydrolysis under mild conditions [3, 11]. Strategies like simultaneous saccharification and co-fermentation integrate biomass breakdown and conversion inside a single reactor system, reducing overall processing times, minimizing operational costs, and preventing the buildup of inhibitory intermediate compounds [11]. Furthermore, beyond the use of LCB (and other types of biowaste such as fat and protein-based ones), the development of microbial-based biorefineries extends to other "generations" (i.e. third and fourth), for example via the capturing of gaseous one-carbon (C1) molecules (e.g. carbon dioxide and carbon monoxide), by the use of autotrophic microbes such as microalgae, known to naturally produce several compounds of industrial relevance [15]. With this strategy it is possible to reroute industrial waste directly back into manufacturing loops, fostering the desired circular bioeconomy.

Precision fermentation as the biomanufacturing engine

At the top of this valorisation pyramid lies – at the moment – precision (or advanced) fermentation. While traditional fermentation upcycles biomass into bulk components, precision fermentation utilizes engineered microbial hosts to synthesize highly specific and customized target functional compounds. By supplying these tailored hosts with carbon sources derived from upcycled agricultural or industrial residues, biomanufacturing can generate complex molecules drastically reducing agricultural land pressure. This approach is reshaping multiple global industries such as the food sector, producing animal-free dairy proteins, functional lipids, and alternative single-cell proteins, possibly from industrial side-streams. The chemicals and materials sectors are affected by precision fermentation development via the generation of specific biochemicals, specialized enzymes, and bioactive molecules, under controlled bioreactor conditions. By pairing the natural resilience of microbial systems with the biosynthesis by precision fermentation, the modern biorefinery transitions from a low-margin processing plant into a highly versatile molecular production hub. This integration ensures an industrially viable, truly closed-loop circular bioeconomy. While full-fractionation 'zero-waste' biorefineries remain primarily conceptual due to high capital expenses (CapEx), biomass recalcitrance, and complex downstream separation costs, commercial industrial plants currently focus on specific high-yielding fractions (e.g., starch, sugars, or lipids) [14]. The broader carbon-processing industry remains dominated by fossil feedstocks, which benefit from decades of amortized infrastructure, vast economies of scale, and unpriced environmental externalities, creating a major competitiveness barrier for multi-product bio-based facilities. The Biotech Act II, set to be published at the end of 2026 by the European Commission, will possibly strengthen Europe position in the sector, since the boost of both biotechnology and biomanufacturing has been indicated as strategic for EU development and competitiveness, especially toward the United States, already investing in this sector [2, 16, 17].

The synthetic biology edge – precision engineering for sustainability

The biological toolbox (parts, circuits, and devices)

The scaling of a circular bioeconomy requires the implementation of systemic reprogramming of microbial processes [18]. At the core of modern biotechnology is the standardization of genetic parts, such as promoters and terminators, into modular toolkits that treat the cells as a customizable chassis. While traditional biomanufacturing has long relied on model hosts like the yeast *Saccharomyces cerevisiae* and the bacterium *Escherichia coli*, expanding the portfolio of robust bioprocesses demands non-conventional microbial platforms capable of thriving directly on non-food residual feedstocks. Developing advanced synthetic biology toolkits tailored to non-conventional strains can enable researchers to precisely tune metabolic flux, while drawing from untapped resources derived from the study of microbial biodiversity, in terms of genes, enzymes and hosts. By treating individual genetic sequences as interchangeable devices, scientists can assemble complex synthetic circuits that control population dynamics or pathway activation [19–21]. This level of molecular control ensures that biorefineries operate with the efficiency required to satisfy the cascading principles mandated by the updated EU Bioeconomy Strategy [2], effectively turning regional waste into valuable chemical assets.

CRISPR and New Genomic Techniques (NGTs) in the EU

The deployment of CRISPR-based platforms and related New Genomic Techniques (NGTs) allows researchers to introduce targeted mutations that unlock features without introducing foreign DNA. However, rigid regulatory definitions under GMOs directives severely bottlenecked the European commercialization of gene-edited plants. European policy is currently undergoing a decisive, market-oriented modernization, thanks to a milestone provisional agreement finalised in 2026. This decision establishes a distinct dual-category framework, exempting conventional-equivalent 'NGT-1' modifications from GMOs labelling and authorization requirements while maintaining traditional risk-proportionate oversight for more complex 'NGT-2' configurations [22]. This regulatory relaxation is structurally integrated into a broader legislative roadmap aimed at securing continental autonomy in the bioeconomy-related sectors. Nevertheless, despite the huge relevance of such legislation on plant biotechnology and applications thereof, microbial cell factories are practically excluded from these exemptions. In fact, while CRISPR technologies are widely applied to microorganisms, without deploying transgenesis gene editing alone has a limited effect on microbial phenotypes of industrial interest. Therefore, while EU policymakers are unlocking the possibility to use NGT-derived crops, it is important to stress the need for clear and correct communication on the issue of genetically modified microorganisms (GMMs), which are often the protagonists of bioprocesses in the context of biomanufacturing and precision fermentation, especially when synthetic biology is involved.

The narrative maze – science communication as a strategic tool in the deployment of biotechnology in the bioeconomy

Breaking the academic bubble: beyond the deficit model

For decades, science communication tripped over the 'information deficit model': the flawed assumption that public scepticism disappears the moment you provide people with proper information, simply due to a lack of scientific knowledge [23, 24]. In industrial biotechnology and synthetic biology, this perspective has repeatedly failed, often leading to deep-seated public resistance and regulatory gridlock [25, 26]. To build an authentic circular bio-economy, truly engaging civil society, science communication must transition from a unidirectional lecture into a multi-directional dialogue, while embracing a multi-media approach. Scientists can no longer afford to remain isolated within academic bubbles; they must actively step into public spheres to contextualize their research within broader societal, economic and environmental values and priorities. When researchers utilize well-crafted narratives, they co-create transformative knowledge, allowing diverse stakeholders to understand not just how a specific microbial cell factory or a bio-based process functions, but why its deployment matters for regional resilience, defossilisation and decarbonization. At the same time to both avoid overselling of relevant research and increase their reach beyond the peers' circle, researchers and institutions should seek professional support from expert science communicators and even "influencers", to embrace the aforementioned multi-directional and multi-media approach.

Digital architecture and the power of social ecosystems

In the contemporary media landscape, peer-reviewed journals are no longer the exclusive gatekeepers of scientific authority. Digital platforms such as LinkedIn, Instagram, and dedicated collaborative networks have evolved into essential spaces for real-time scientific dissemination and professional engagement. The European Commission itself has involved several digital content creators, both at international and national level, to show and narrate the often complex dynamics of policymaking. By operating strategically across these digital ecosystems, scientists and institutions can build decentralized communities of practice. This direct accessibility serves a dual purpose: it humanizes the researcher, transforming the archetype of the scientist into an approachable expert, and it provides a rapid-response mechanism against online misinformation. At the same time, cultivating a robust digital presence allows science communicators to directly engage with industry professionals, regulatory specialists, and young researchers simultaneously, shortening the traditional multi-year delay between laboratory discovery and broader market awareness. These figures should therefore be more involved in the dissemination part of scientific projects.

Fostering public trust in precision fermentation and synthetic biology

Public perception remains one of the most volatile variables in the scaling of industrial biotechnology. Emerging fields like precision fermentation and synthetic biology frequently trigger instinctual public concerns regarding unnaturalness or hidden corporate monopolies, echoing the historic backlashes against early genetically modified crops. Overcoming these anxieties requires proactive transparency. Communicators must in fact clearly separate precision fermentation, where GMMs are confined inside closed bioreactors to synthesize functional molecules before being separated from the final product, from open-environment genetic interventions such as NGT crops. Fostering public trust means openly discussing not only the possible environmental benefits of these bio-based processes, but also addressing legitimate questions regarding safety, allergenicity, and corporate ownership. In this context, the gained public trust can act as a catalyst for 'regulatory agility' by the legislators: tools such as regulatory sandboxes under the Biotech Acts allow firms to test disruptive innovations in controlled environments, effectively reducing time-to-market and increasing the probability of securing private funding. The involvement of companies in this process is crucial to the consumers, policymakers and themselves. Many voluntary industry initiatives are planned in the EU Bioeconomy Strategy, such as the Bio-based Europe Alliance (BEA), which aims to align market expectations and ensure a predictable demand of EUR 10 billion for bio-based materials by 2030 and the European Bioeconomy Regulators and Innovators' Forum as a structured space for firms to engage early with regulators to coordinate risk assessments and remove market entry barriers [2]. By building transparent, narrative-driven bridges, science communication transforms societal hesitation into informed public support, paving the way for stable, long-term policy integration. In this case a top-down approach can be desirable in the sense of direct involvement of institutions and companies in the communication pipeline towards the public, while advocating for a bottom-up dialogue from the public as well. In this scenario the use of social media can overcome the classic barriers between science and society, especially when dealing with such complex topics.

The path forward for the next generation of biotechnologists

As we approach environmental and geopolitical challenges, the next generation of industrial biotechnologists must look beyond traditional academic boundaries. Expertise on fermentation chemistry, metabolic engineering, and multi-omics data analysis must be paired with an advanced understanding of economics, public communication strategies, and legislations. From the economics perspective, bio-manufactured products are currently often more expensive than fossil-based competitors [16], and the EU faces a structural annual investment gap of approximately EUR 40 billion in the biotechnology sector, which hinders the scaling of biomanufacturing and advanced bio-based materials [7]. To address this investment gap and achieve market competitiveness, targeted regulatory interventions beyond technological advancement are required. Key mechanisms proposed under recent EU policy frameworks, including the EU Biotech Act initiative and the updated EU Bioeconomy Strategy, focus on creating lead markets via mandatory bio-based procurement/content targets, refining Product Environmental Footprint (PEF) methodologies to accurately reflect biogenic carbon storage, and establishing regulatory sandboxes to accelerate time-to-market for innovative biomanufacturing [2, 7, 16, 27]. Examples of recent EU regulatory interventions that fostered competitiveness of certain sectors close to the bioeconomy or environmental related topics are the Renewable Energy Directives (REDs), Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation, and Single-Use Plastics Directive (SUP).

The path forward demands an integrated approach that respects ecological limits while improving the boundaries of technological feasibility. Speaking of multidisciplinary approach, several relevant topics in biotechnology have been omitted in this manuscript such as red biotech and medicine, the issue of intellectual property and patent applications, and the ground-breaking impact of artificial intelligence in these sectors. Nevertheless, these issues are crucially orthogonal to all the matters disclosed here, and should be taken into account, especially by policymakers. The fact that the Directorate-General for Health & Food Safety (DG SANTE) of the European Commission was in charge of the Biotech Act attests to the strong connection of all these sectors. Therefore, by embracing this multi-dimensional role, the scientific community can transform industrial biotechnology from a niche alternative sector into the dominant manufacturing standard, fulfilling the need of a truly circular and resilient global society.

Authors' contributions
S.B.: Conceptualization, Supervision, Writing – original draft, Writing – review & editing, Preparing Figure. The author read and approved the final manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
S.B. declares to be part of the editorial board of "Biotechnology for Biofuels and Bioproducts" and "Microbial Cell Factories" by BMC.

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