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Synthetic biology and climate change: innovations for a sustainable future

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Abstract – Synthetic biology is emerging as a powerful field to address global climate challenges. By enabling the rational design of biological systems with programmable and sustainable functions, it offers innovative strategies for both climate change mitigation and adaptation. Recent advances have shown its potential in sectors such as agriculture, bioenergy, and the development of sustainable biomaterials. However, integrating synthetic biology into practical climate solutions remains an ongoing challenge. The objective of this review was to examine the current state of the field, identify the most promising applications for climate action, and evaluate opportunities and barriers for translating research into solutions that are scalable and applicable in the real-world. Promising applications are discussed, such as synthetic carbon fixation cycles, bioengineered microorganisms for biofuel production, microbiome engineering to enhance soil carbon sequestration, and biosensors for precision agriculture, illustrating how synthetic biology can contribute to low-carbon, and climate-resilient strategies. The work draws on a comprehensive review of recent scientific literature, international policy frameworks, and regional studies from Latin America and, mainly, Brazil. Aligned with the objectives of COP30, it emphasizes science-based strategies that integrate synthetic biology into national climate commitments, support biodiversity, and foster inclusive innovation. The review presents synthetic biology not only as a technical advancement, but as a strategic pathway for sustainable development and global cooperation.

Index terms: bioenergy, biomaterials, bioproducts, biosensors, climate change, synthetic biology, resilient agriculture.

Biologia sintética e mudanças climáticas: inovações para um futuro sustentável

Resumo – A biologia sintética está emergindo como um campo poderoso para enfrentar os desafios climáticos globais. Ao possibilitar o desenho racional de sistemas biológicos com funções programáveis e sustentáveis, oferece estratégias inovadoras tanto para a mitigação de mudanças climáticas quanto para a adaptação a elas. Avanços recentes mostraram seu potencial em setores como agricultura, bioenergia e desenvolvimento de biomateriais sustentáveis. No entanto, integrar a biologia sintética a soluções climáticas práticas ainda é um desafio em andamento. O objetivo desta revisão foi examinar o estado atual do campo, identificar as aplicações mais promissoras para a ação climática e avaliar oportunidades e barreiras, para traduzir a pesquisa em soluções escaláveis e aplicáveis no mundo real. Discutiram-se algumas aplicações promissoras como ciclos sintéticos de fixação de carbono, microrganismos bioengenheirados para produção de biocombustíveis, engenharia de microbiomas para aprimorar o sequestro de carbono no solo e biossensores para agricultura de precisão, ilustrando como a biologia sintética pode contribuir para estratégias de baixo carbono e resilientes ao clima. O trabalho baseia-se em uma revisão abrangente da literatura científica recente, de marcos regulatórios internacionais e de estudos regionais da América Latina e principalmente do Brasil. Alinhado aos objetivos da COP30, enfatiza estratégias – baseadas em ciência – que integrem a biologia sintética aos compromissos climáticos nacionais, apoiem a biodiversidade e promovam a inovação inclusiva. O artigo de revisão apresenta a biologia sintética não apenas como um avanço técnico, mas como um caminho estratégico para o desenvolvimento sustentável e a cooperação global.

Termos para indexação: bioenergia, biomateriais, bioprodutos, biossensores, mudança climática, biologia sintética, agricultura resiliente.

1. Introduction

Climate change represents one of the most pressing global challenges of the 21st century, with far-reaching implications for ecosystems, food security, water resources, and human health. The exacerbation of the greenhouse effect, largely driven by anthropogenic emissions of greenhouse gases (GHGs), has led to the increase of extreme weather events, prolonged droughts, soil degradation, and sea level rise (IPCC, 2014).

In 2023, the world reached its highest average temperature on record, with the World Meteorological Organization confirming that the global mean temperature surpassed 1.5 °C above pre-industrial levels for the first time. This milestone raised major concerns about the feasibility of meeting the goals set by the Paris Agreement, adopted in 2016, which aimed to limit global warming to below 2 °C, preferably to 1.5 °C (FAO, 2023).

Latin America plays a complex role in the global climate crisis. Although the region accounts for only about 7% of global GHGs emissions, its *per capita* income and net emissions are close to those of global averages (Ivanova et al., 2020). Its agricultural base, high biodiversity, and emerging economies make it vulnerable and strategically positioned to lead sustainable innovations. Brazil, in particular, combines vast genetic resources, advanced agricultural biotechnology, and leadership in biofuels, offering a unique opportunity to integrate nature-based and technological solutions for climate adaptation and mitigation of the impacts of climate change (Irarrázabal et al., 2025).

While mitigation strategies such as reducing emissions, reforestation, and shifting to renewable energy are essential, they may not be sufficient on their own. In this context, emerging technologies, particularly from the field of biotechnology, are gaining increasing attention as potential game-changers. Among them, synthetic biology has emerged as a powerful interdisciplinary platform, offering complementary and transformative approaches to climate action (Delisi, 2019; Symons et al., 2024). Building upon the foundations of recombinant DNA technology developed in the 1970s, synthetic biology has matured into a field capable of systematically designing and constructing biological systems with tailored functions (Ye et al., 2025). Grounded in molecular biology, genetic engineering, and computational modeling, it enables the design, construction, and reprogramming of biological systems for new functions (Carbonell et al., 2016; Oliveira et al., 2024). This capacity has opened new pathways for the development of climate-resilient crops, biosensors, carbon-capturing organisms, and sustainable biomaterials.

From this perspective, the present article examines the contributions of synthetic biology to climate solutions through a comprehensive review of recent advances. Its objective was to provide a critical assessment of ways by which synthetic biology tools and approaches can be effectively integrated into national climate strategies, particularly in the context of mitigation and adaptation efforts. It first describes the tools and methodologies that form the foundation of the field, then analyses applications across agriculture, environmental monitoring, carbon fixation, bioenergy, and bioproducts. The article also explores policy and regulatory frameworks, highlighting the strategic role of Latin America, particularly Brazil, in leveraging these technologies for sustainable development, especially in the context of the United Nations climate change conference, COP30.

2. Tools and Platforms in Synthetic Biology

Synthetic biology is driven by a dynamic and evolving suite of tools, which were designed to accelerate the design-build-test-learn (DBTL) cycle. Framed within the concepts of "build to learn" and "build to use" (Zhang et al., 2025a), these approaches integrate methodologies such as DNA synthesis and assembly, synthetic gene circuits, computational modeling, cell-free systems, and advanced genome editing platforms (Figure 1). Together, these technologies have been refined into increasingly sophisticated solutions for climate adaptation, bioinput development, and crop improvement.

At the core of modern genome engineering is the clustered interspaced short palindromic repeats/CRISPR-associated protein (CRISPR/Cas) system, a revolutionary platform that allows scientists to target and modify specific DNA sequences with high efficiency and flexibility (Doudna & Charpentier, 2014). Originally derived from bacterial immune systems, CRISPR has become a cornerstone of synthetic biology, due to its simplicity, adaptability across species, and scalability. Its widespread adoption has outpaced earlier tools such as zinc finger nucleases, and transcription activator-like effector nucleases, making it the method of choice for targeted genome editing in both prokaryotes and eukaryotes (Eid & Mahfouz, 2016; Moon et al., 2019; Sood et al., 2025).

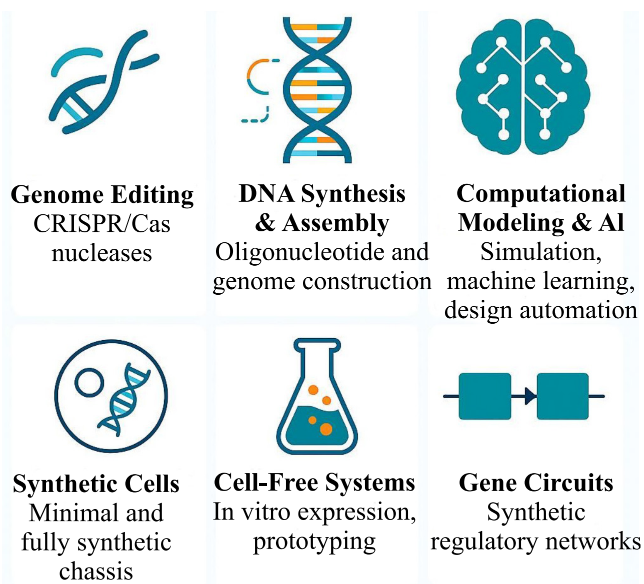

Figure 1. Core tools in synthetic biology. Conceptual overview of core synthetic biology tools categorized by function: genome editing (CRISPR/Cas systems and other nucleases), DNA synthesis and assembly (for constructing oligonucleotides and complete genomes), computational modeling and artificial intelligence (AI, for predictive design and optimization), synthetic cells (minimal or fully synthetic biological chassis), cell-free systems (for *in vitro* expression and prototyping), and gene circuits (synthetic regulatory networks that control biological functions). [Illustrative diagram generated with the assistance of artificial intelligence (GPT-4.0, OpenAI)].

The success of genome-editing technologies is closely tied to ongoing advances in DNA synthesis. Researchers can now design and construct synthetic DNA fragments, entire genes, and even whole genomes. Methods such as enzymatic synthesis, microarray-based oligonucleotide production, and automation are improving throughput, reducing costs, and enabling the creation of increasingly complex and customized genetic constructs (Ma et al., 2024). To assemble large sequences, including full genomes, techniques such as Gibson assembly and yeast-based in vivo recombination have been instrumental (Gibson et al., 2009; Shao et al., 2009). These approaches enabled landmark achievements, such as the synthesis of the *JCVI-syn1.0* and *syn3.0* genomes (Gibson et al., 2009; Hutchison et al., 2016). Although these minimal genomes are synthetic, they are still embedded in natural cellular contexts and serve primarily as tools for studying essential life functions (Bianchi et al., 2022; Bittencourt et al., 2024). The construction of DNA molecules over 100 kilobases remains challenging, but improvements in sequencing, error correction, and automation are steadily advancing the field.

Complementing genome-scale efforts, cell-free expression systems have emerged as powerful platforms for prototyping biological parts and pathways (Hunt et al., 2025). By decoupling genetic constructs from living cells, cell-free systems allow a rapid, iterative testing of gene circuits, regulatory elements, and metabolic functions (Noireaux et al., 2003; Moore et al., 2017). These systems are particularly useful for expressing toxic or unstable proteins, optimizing enzyme kinetics, or producing metabolites in well-defined conditions. Recent advances in cell-free systems have significantly expanded their utility for high-throughput protein synthesis and characterization. Optimized cell-free protein synthesis platforms enable rapid and parallel production of target proteins, streamlining experimental workflows and reducing the need for in vivo expression systems (Meyer et al., 2022). Coupling these platforms with affinity microfluidics allows of efficient and scalable analysis of protein degradation dynamics directly in cell-free extracts, providing a powerful tool for studying protein stability and turnover (Brio et al., 2022). Furthermore, innovative approaches integrating synthetic biology and protein engineering have enhanced the functional versatility of these systems, enabling precise control over protein modifications and expanding their potential applications in biotechnology (Koga et al., 2025).

The field is therefore underpinned by a growing emphasis on standardization and modularity. The development of well-characterized, reusable biological parts, such as promoters, ribosome binding sites, and terminators, enables the assembly of reliable genetic systems across diverse organisms. Despite the inherent biological variability of these parts, concerted efforts to document and optimize these components across taxa have significantly improved the reproducibility, scalability, and transferability of synthetic biology solutions (Feike et al., 2019). This foundation facilitates the integration of increasingly complex design elements, from synthetic pathways to programmable genetic circuits.

Based on these platforms, synthetic biology is also exploring the development of programmable synthetic cells. While the creation of fully autonomous synthetic cells remains an ongoing goal, current strategies focus on microencapsulated systems that combine cell-free machinery with synthetic membranes, gene circuits, or minimal metabolic pathways (Heili et al., 2024; Hunt et al., 2025). These systems do not replicate, but they can perform specific and controlled tasks, such as biosensing, carbon fixation, or biomanufacturing, within targeted environments. As technological and material science advances converge, these experimental chassis may evolve into deployable, modular units for environmental or agricultural applications (Liew et al., 2022; Gao et al., 2023).

To support the design and refinement of these systems, multi-omics approaches − integrating genomics, transcriptomics, proteomics, and metabolomics − provide comprehensive insights into cellular function (Zhang et al., 2025a). These data layers enhance the rational engineering of regulatory networks, metabolic pathways, and organismal behavior, increasing the predictability and performance of synthetic constructs. However, the growing volume and complexity of biological data require increasingly efficient and practical tools, to process and transform this information into products and knowledge.

One of the most promising solutions is machine learning (ML), a branch of artificial intelligence (AI) that seeks to mimic the human ability to recognize patterns, though in an objective, computation-driven manner. Machine learning combines predictive models with large datasets to automatically identify and classify complex patterns, enabling accurate predictions, generating new insights, and guiding the future of scientific research (Greener et al., 2022).

In synthetic biology, AI and ML are used to predict biomolecular structures and biological properties, generate new molecules, and develop climate-resilient organisms (Wu et al., 2021; Abramson et al., 2024). Notably, there are some tools such as AlphaFold, developed by DeepMind Technologies Limited, that allow the precise prediction of protein structures (Jumper et al., 2021). Beyond molecular design, AI and ML have been applied to develop conservation strategies and predict extreme climate events. Analysis of microclimate models and investigation of ecological interactions are crucial for understanding the impact of climate change on ecosystems (Levy & Shahar, 2024). Artificial intelligence has also been used to improve agriculture and develop organisms that can sequester carbon, produce sustainable fuels and chemicals, and enhance agricultural resilience (Farooq et al., 2009; Ye et al., 2025).

Together, these tools form the technological foundation of synthetic biology. Their continuous refinement and strategic integration are essential for delivering effective, scalable, and context-aware solutions to the climate crisis. As complexity increases, so does the need for interdisciplinary collaboration, guided by shared principles of innovation, openness, and sustainability.

3. Applications of Synthetic Biology for Climate Solutions

Synthetic biology is rapidly evolving from a toolbox of technologies into a platform for actionable solutions to the climate crisis. With a growing portfolio of real-world applications, it is fueling innovation in climate-resilient agriculture, renewable energy, environmental monitoring, carbon capture, and sustainable materials. Each of these applications draws upon elements of synthetic biology to develop scalable, low-carbon, and adaptive strategies (Figure 2).

To effectively harness the potential of synthetic biology to contribute to climate solutions, it is essential to understand how these foundational technologies translate into practical outcomes. The tools described in the previous section, including CRISPR/Cas based genome editing, synthetic cells, high-throughput platforms, and AI, provide the technical backbone enabling biological innovation across multiple sectors.

These technologies are not ends in themselves but rather serve as catalysts for transformative applications. In this section, we transition from technologies to tangible use cases, illustrating how synthetic biology is being implemented, or is poised to be implemented, to meet the demands of climate mitigation and adaptation.

3.1. Resilient agriculture

Genome-editing for abiotic stress tolerance in crops

Rising global temperatures have triggered a series of extreme weather events, including torrential rains, prolonged droughts, forest fires, and soil degradation. These phenomena lead to the loss of essential nutrients, directly harming soil productivity and contributing to the reduction of arable land, water scarcity, and the adoption of unsustainable agricultural practices, such as the excessive use of fertilizers and pesticides (WMO, 2024.). Agricultural systems are particularly vulnerable to climate change, which directly affects plant growth and crop productivity, highlighting the scenario of a significant threat to global food security (Hultgren et al., 2025).

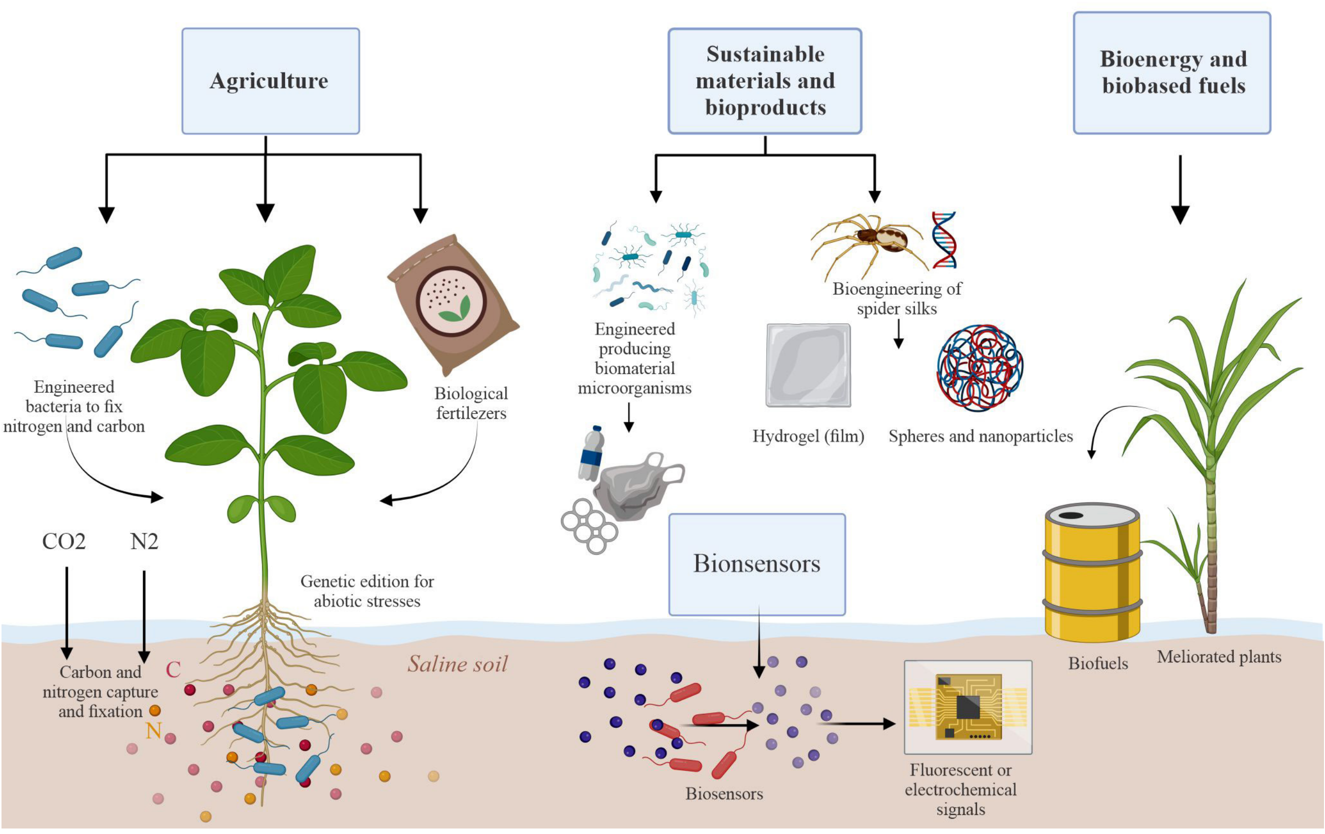

Figure 2. Applications of synthetic biology for climate solutions: The main domains where synthetic biology contributes to climate change mitigation and adaptation, which include climate-resilient agriculture, biological inputs and biofertilizers, environmental monitoring through biosensors, biological carbon capture and fixation, bioenergy production, and the development of next-generation biomaterials. Source: created in BioRender (Bittencourt, 2025a).

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Throughout evolution, plants have been continuously subjected to environmental pressures, leading to the selection of spontaneous genetic variants associated with more adaptive phenotypes. Random mutations, combined with natural selection, enabled individuals with greater stress tolerance to transmit their adaptive alleles to subsequent generations, thereby shaping complex physiological and molecular mechanisms of environmental response (Artur & Kajala, 2021; Ke et al., 2021). Among the main mechanisms of adaptation to water-related stresses are the activation of antioxidant and osmoprotectant metabolic pathways, the control of stomatal aperture mediated, mainly by abscisic acid (ABA) signaling and its cis-regulatory elements (ABREs), the deposition of cuticular waxes, the reduction of leaf area through smaller and fewer leaves, and the reinforcement of the root system to optimize water uptake (Farooq et al., 2009; Chen & Soltis, 2020; Muhammad et al., 2024). Despite the sophistication of these innate defense mechanisms, they are often insufficient under severe or prolonged environmental conditions, highlighting the need for targeted interventions such as genome editing.

Gene editing of crops using tools such as CRISPR/Cas has opened new frontiers for enhancing resilience to abiotic stresses, including drought, salinity, heat, and nutrient deficiencies (Bacha et al., 2025). By precisely modifying key regulatory genes and stress-responsive pathways, researchers can develop genetically modified plants that are better adapted to climate variability and degraded soils. These targeted edits not only enable faster and more efficient trait improvement, in comparison with conventional breeding, but they also help preserve desirable agronomic characteristics (Rönspies et al., 2021). Certain crops such as sugarcane, maize, rice, and wheat have received particular attention due to their global production volume and significance in food and biofuel supply chains (FAO, 2023). These key crops are essential for sustainable agriculture.

Given their global relevance, recent advances have focused on genome-editing applications in these major crops, showing their feasibility and effectiveness for stress tolerance. For instance, wheat (*Triticum aestivum*) has been genetically modified to enhance resilience to environmental stress. The CRISPR/Cas9 system was employed with multiplexed guide RNAs targeting the *Sal1* gene, which is implicated in drought tolerance through the metabolism of PAP (3',5'-adenosine bisphosphate). The edited wheat plants exhibited normal growth under osmotic stress conditions that mimic drought, unlike their wild-type counterparts (Abdallah et al., 2025). Edited wheat varieties also showed higher yields under drought conditions than the wild-type (Abdul Rahim et al., 2024).

Sugarcane (*Saccharum* spp. hybrid), the primary source of global sugar and bioethanol production (Ghane et al., 2024), is another example. Efforts to improve traits such as yield, herbicide resistance, and reduced lignin content remain ongoing. However, sugarcane's complex genome is approximately 10 gigabases in size, with high polyploidy (2n = 100-120), and its heterozygosity presents a major challenge for genetic manipulation. Despite these obstacles, CRISPR/Cas has enabled new genome modifications. While most advances remain in the proof-of-concept stage, promising progress has been made (Prado et al., 2023). For instance, Eid & Mahfouz, (2016) used CRISPR/Cas9 to target 49 out of 59 alleles of the magnesium chelatase (MgCh) gene involved in chlorophyll biosynthesis. The resulting plants exhibited pale green leaves, but maintained or even surpassed the growth performance of unmodified plants. Such modifications could lead to increased crop yields and reduced land and water usage.

In Brazil, the Empresa Brasileira de Pesquisa Agropecuária (Embrapa) has made great advances in applying CRISPR/Cas9 to sugarcane and soybean. Using a marker-free biolistic method, targeted mutations were introduced into the *BAHD01* and *BAHD05* genes in sugarcane (Molinari et al., 2021). These modifications led to the development of Flex I and Flex II varieties, which exhibit superior biomass production and sucrose content, respectively, while also aiming to circumvent regulatory hurdles in more restrictive markets (Prado et al., 2023).

Building on these national efforts, soybean has also emerged as a priority target for genome editing, given its economic and strategic relevance in the context of a changing climate. In addition to being an essential source of protein for human and animal consumption, soybean also plays a key role in biodiesel production, and its importance is expected to grow as the effects of climate change intensify. Recently, the Comissão

Técnica Nacional de Biossegurança (the National Biosafety Technical Commission − CTNBio), in Brazil, classified as a conventional crop the highly productive cultivar developed for drought tolerance, by Embrapa, using the CRISPR/Cas gene-editing technique. This characteristic aims to reduce productivity losses, when drought events occur (Fuganti-Pagliarini et al., 2020).

In addition to drought, soil salinization represents another significant impact associated with climate change, leading to the accumulation of salts beyond plant tolerance thresholds and interfering with their growth (Hassani et al., 2021). Salt tolerance involves regulating cytoplasmic ion content, through ion homeostasis and compartmentalization, along with osmotic adjustments, to maintain cell turgor and enhanced antioxidant metabolism, including greater capacity to scavenge reactive oxygen species (ROS) (Arif et al., 2020; Kesawat et al., 2023). Gene co-expression network analysis is a valuable approach for uncovering the molecular determinants underlying salt tolerance in crops. In rice, this strategy has enabled the identification of salt stress-responsive genes, which are involved in the regulation of potassium homeostasis and root system development, through a genome-wide association study (GWAS) that correlated single nucleotide polymorphisms (SNPs) with phenotypic variation under saline conditions (Yu et al., 2018). Identifying such genes provides a fundamental basis for the rational design of targeted gene-editing strategies aimed at modulating stress-responsive pathways, thereby enhancing salt tolerance in genetically improved cultivars.

These advancements show how biotechnology and synthetic biology offer a wide array of tools to manipulate specific genes and metabolic pathways, such as those involved in the synthesis of osmoprotectants, stomatal regulation mediated by ABA and ABREs control, and ROS-mediated antioxidant mechanisms. The intensification of climate impacts calls for the adoption of integrated strategies that combine physiological knowledge, molecular advances, and cutting-edge technologies. Developing more resilient crops with enhanced adaptive capacity to abiotic stresses, such as drought and salinity, is essential to ensuring food security in the face of climate change.

Biological inputs and biofertilizers

The intensification of agriculture in recent decades has led to a strong dependence on chemical fertilizers, particularly nitrogen-based formulations. Although essential for enhancing crop productivity, these inputs are closely linked to various forms of environmental degradation. Nitrate (NO^{-}_3), for instance, is a major pollutant in aquatic ecosystems, significantly contributing to the eutrophication of both freshwater and marine bodies. Furthermore, nitrous oxide (N_2O), primarily produced through microbial processes in the soil, namely nitrification and denitrification, is a potent greenhouse gas with a high global warming potential and plays a substantial role in the depletion of the stratospheric ozone layer (WMO, 2024; Martinez-Feria et al., 2024).

In response to the pressing need for more sustainable agricultural practices, synthetic biology strategies have emerged as a powerful means to reduce dependency on chemical inputs while enhancing ecosystem resilience. Through the genetic enhancement of bacterial, fungal, and yeast strains, these approaches enable the development of microbial solutions capable of replacing, partially or entirely, the use of synthetic fertilizers (Ke et al., 2021).

Whole-genome functional genomics has become a powerful tool for systematically uncovering novel genetic functions within microbiomes. This approach has led to the identification of numerous biosynthetic gene clusters associated with secondary metabolite production, several of which have already been functionally characterized (Camargo et al., 2019, 2023). Leveraging this knowledge, researchers have engineered microorganisms with specialized functions, such as biocontrol, biofertilization, and biostimulation that directly enhance agricultural productivity (Jiang et al., 2018; Mullins et al., 2019).

In the context of biological nitrogen fixation (BNF), Ryu et al. (2020) successfully refactored and synthesized a *nif* gene cluster comprising more than 20 genes (23.5 kb), showing functional nitrogenase expression in *Escherichia coli*. More recently, the group transferred native *nif* clusters between different rhizobial species, enabling cereal crops to carry out nitrogen fixation independently. Native transcriptional regulation of the *nif* genes was replaced with genetically encoded synthetic sensors responsive to root exudates, soil bacterial metabolites, and biocontrol agents.

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Yang et al. (2018) further explored a virus-derived polyprotein strategy involving "fusion and cleavage" to streamline gene expression. By consolidating 14 essential *nif* genes into five large constructs, they demonstrated efficient nitrogenase activity and supported diazotrophic growth in *E. coli*.

These advances are now translating into practical agricultural applications, particularly in maize production, for which engineered diazotrophs can be applied directly in the field to boost crop yields. In a recent study, Martinez-Feria et al. (2024) used the parental bacteria strains *Klebsiella variicola* (*Kv*137-2253) and *Kosakonia sacchari* (*Ks*6-5687) and achieved nitrogenase derepression in high-nitrogen environments, resulting in over a 100-fold increase of enzyme activity *in vitro* conditions. The resulting commercial formulation *PIVOT BIO PROVEN* exhibited biological safety, product stability, and 0.3 ± 0.1 Mg ha^{-1} average grain yield increase.

Phosphorus – another essential nutrient – is typically present in soils as inorganic or organic phosphates, and these forms are not readily assimilated by plants. Phosphorus availability, acquisition, and transport are affected by temperature, pH, drought and high levels of carbon dioxide (Maharajan et al., 2021). Rising soil temperatures have been shown to reduce phosphorus availability, potentially disrupting nutrient cycling and diminishing the soil's capacity for carbon sequestration (Tian et al., 2024). However, applied phosphate fertilizers quickly react with divalent cations and are adsorbed to soil minerals, thus becoming unavailable to plants. To address this issue, heterologous expression of specific genes in three rhizobacterial species enabled the identification of high-activity phytases capable of hydrolyzing phytate. This conferred a significant growth advantage to *Arabidopsis thaliana* when phytate was the sole phosphorus source (Valeeva et al., 2018). These findings illustrate the potential of microbiome engineering to generate phosphate-solubilizing microorganisms, offering an environmentally friendly and cost-effective alternative to conventional phosphate fertilizers.

Other innovative and environmentally friendly solutions that enhance crop productivity, while reducing environmental impacts, include the use of endophyte beneficial microorganisms (including fungi and bacteria) that live within plant tissues, without causing harm, and establish mutualistic relationships with their host plants. They offer numerous benefits, such as promoting plant growth, increasing nutrient uptake, enhancing resistance to pathogens, and mitigating abiotic stresses like drought and salinity (Das et al., 2025). One example is the bacterial endophyte *Bacillus amyloliquefaciens* engineered to increase plant tolerance to abiotic stresses such as drought, salinity, and heavy metals, which enables crops to grow under suboptimal conditions, thereby improving agricultural resilience and sustainability (Munir et al., 2022).

Carbon capture and fixation

The mitigation of climate change has traditionally focused on reducing greenhouse gas emissions. However, in the face of the continuous rise in atmospheric CO_2 concentrations, and the difficulty of immediately replacing fossil energy sources, it becomes increasingly evident that complementary strategies for active carbon removal will be indispensable to limit global warming to less than 2 °C above pre-industrial levels (Friedlingstein et al., 2014).

In this context, biological carbon fixation has gained prominence as a promising alternative, especially through the action of autotrophic microorganisms and plants capable of incorporating atmospheric CO_2 into biomass. In prokaryotes, this process often occurs within specialized proteinaceous organelles known as bacterial microcompartments (BMCs) (Snyder et al., 2025). A key subclass of BMCs, carboxysomes, encapsulates the Calvin-Benson-Bassham (CBB) cycle enzymes, including the enzyme ribulose-1,5-bisphosphate carboxylase/oxigenase (RuBisCO), and enhances carbon fixation efficiency by concentrating CO_2 near the catalytic site (Kerfeld & Melnicki, 2016).

The CBB cycle is responsible for a large part of biological carbon assimilation and begins with the carboxylation catalyzed by the RuBisCO. Given the limitations imposed by the low-catalytic efficiency of RuBisCO, and the need to expand the industrial use of biological carbon fixation, advances in synthetic biology have enabled the introduction and optimization of the CBB cycle in heterotrophic microorganisms (Prywes et al., 2023). Model organisms such as *Escherichia coli*, *Saccharomyces cerevisiae*, *Komagataella phaffii*, and *Methylobacterium extorquens* AM1 have been used as chassis for this purpose, due to their well-understood physiological characteristics, rapid

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growth, and established genetic tools. Strategies such as engineering more efficient variants of RuBisCO, reconfiguring metabolic networks, optimizing energy supply, and adaptive laboratory evolution have been applied (Feng et al., 2023). Despite the advances, challenges related to the low efficiency of the system and the limitation of production at scale still persist. A recent study highlights the difficulties in heterologous expression of carboxysome gene clusters, particularly in producing functional Form 1B RuBisCo and assembling β-carboxysomes in nonnative hosts (Sun et al., 2025). To overcome these barriers, future strategies should focus on integrating external energy sources, optimizing the expression of carboxysome components, and employing catalytically superior enzymes to enhance the performance and scalability of synthetic carbon fixation platforms.

In parallel, similar strategies have been extended to plants through the convergence of synthetic biology, artificial intelligence, and plant genetics. Directed evolution, combined with machine learning, enables the development of optimized RuBisCO and nitrogenase enzymes, which are first tested in microbial chassis and later adapted for plant systems (Zhang et al., 2025b). Additional tools such as synthetic promoters responsive to environmental cues, organelle engineering, and microbiome manipulation have been explored to enhance carbon and nitrogen assimilation. These strategies are conceptually aligned with efforts to convert C_3 plants into C_4- like systems, aiming to minimize photorespiration and boost photosynthetic efficiency under high temperature and low-CO_2 conditions (Liu & Cheng, 2024). Collectively, they seek to reduce fertilizer dependency and improve crop productivity by increasing CO_2 fixation, redirecting carbon flow toward biomass and grain yield (Zheng et al., 2023).

Complementing these biologically integrated approaches, recent advances have also explored the development of programmable artificial photosynthetic cells as a synthetic platform for CO_2 capture and conversion. Gao et al. (2023) demonstrated a biotic-abiotic hybrid energy module − composed of thylakoids and cadmium telluride quantum dots − that enables efficient proton-coupled electron transfer and facilitates the autonomous regeneration of the key cofactors NADPH, NADH, and ATP, without the need for external supplementation. These artificial cells can be functionally programmed by coupling them with specific reductases, such as formate dehydrogenase or engineered nitrogenase, allowing of a highly selective conversion of CO_2 into value-added products, like formate or methane. By combining light harvesting, energy generation, and enzymatic specificity within a modular framework, this work opens new possibilities for artificial photosynthesis and scalable CO_2 utilization under controlled conditions.

These advances illustrate a growing convergence between biology, engineering, and computation in the pursuit of scalable carbon fixation strategies. While many of these approaches remain in the experimental or pre-commercial stages, they represent a shift toward programmable biological systems capable of contributing to global mitigation efforts.

3.2. Sustainable materials and bioproducts

The development of sustainable materials and bio-based products is another critical frontier in the application of synthetic biology for climate solutions, by enabling the microbial production of biodegradable polymers, functional composites, and environmentally friendly chemicals (Burgos-Morales et al., 2021). Synthetic biology offers a viable path to reduce reliance on petrochemicals and mitigate the environmental impact of traditional manufacturing processes.

Among the most prominent biopolymers are polyhydroxyalkanoates (PHAs) and polylactic acid, both synthesized from renewable biomass (Naser et al., 2021). These materials are increasingly being produced through engineered microbial strains capable of accumulating high levels of polymer precursors from agricultural waste or industrial byproducts. For instance, the integration of metabolic pathways for PHAs biosynthesis into *Escherichia coli* or *Pseudomonas putida* has yielded efficient cell factories for biodegradable plastic production (Kim et al., 2020; Gurdo et al., 2023; Manoli et al., 2023).

The integration of biotechnological and chemical approaches to nylon production represents a significant step towards a more sustainable industry. Through the genetic engineering of *Corynebacterium glutamicum*, it was possible to create a high-efficiency microbial strain for the synthesis of diaminopentane from renewable sources, replacing traditional petrochemical monomers. The bio-nylon PA5.10 obtained showed mechanical and thermal properties comparable, and

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even superior, to the conventional polymers PA6 and PA6.6, with the advantage of lower density, and potential to reduce energy consumption. This approach not only decreases the dependence on fossil fuels, but also contributes to the mitigation of environmental impacts associated with the production and disposal of synthetic polymers, aligning industrial innovation with the principles of circular economy and green chemistry (Kind et al., 2014).

Polysaccharides are versatile biopolymers with broad applications in biomedicine, packaging, and agriculture. In particular, *Komagataeibacter* strains have been engineered to enhance bacterial cellulose production, through targeted gene insertions or deletions, as well as by developing genetic tools to enable heterologous protein expression and control cellulose biosynthesis (Ryngajłło et al., 2020; Singh et al., 2020). Advances in synthetic biology also provide strategies to tailor the physicochemical properties of polysaccharides, enabling large- scale production of customized materials with improved functionality for specific end uses (Florea et al., 2016; Malci et al., 2024).

Spider silk–inspired proteins represent another emerging class of biomaterials. The remarkable combination of strength and elasticity found in natural silk, along with their biocompatible and biodegradable nature, have sparked significant interest in replicating these properties for large-scale, industrial-grade production (Hayashi et al., 1999; Tokareva et al., 2014; Bittencourt et al., 2022). Engineered using synthetic biology, these proteins can be produced in microbial systems and tailored for high-strength applications in textiles, biomedicine, and lightweight composites (Kiseleva et al., 2020; Bittencourt et al., 2022). Ongoing research in this area seeks to develop scalable systems for silk protein expression and post-processing to meet industrial demands (Bhattacharyya et al., 2021; Gomes & Salgueiro, 2022).

By reducing the dependence on fossil-derived materials, and lowering the carbon footprint of industrial processes, bio-based products developed through synthetic biology directly contribute to climate mitigation. Not only these innovations reduce the greenhouse-gas emissions associated with extraction, transportation, and incineration of conventional plastics, but they also offer biodegradable alternatives that prevent long-term environmental accumulation. As such, sustainable biomaterials are a key component in aligning manufacturing with climate goals and building a low-carbon, regenerative economy (Zuiderveen et al., 2023).

3.3. Environmental monitoring and biosensors

Environmental monitoring is essential for assessing the impacts of climate change and guiding mitigation strategies. Traditional chemical and physical analysis methods, while accurate, are often costly, time-consuming, and limited in scope. In contrast, biosensors analytical devices that combine biological recognition elements with signal transducers offer a rapid, sensitive, and cost-effective alternative, to detect a wide array of environmental parameters (Chadha et al., 2022). Originally developed in the 1960s to detect glucose levels (Clark Jr. & Lyons, 1962), these devices have since evolved into versatile tools for environmental applications, including pollutant detection, soil quality assessment, and climate-related monitoring. In the context of synthetic biology, the design and engineering of biosensors have expanded dramatically, enabling the creation of highly specific devices that respond to environmental stimuli with precision.

Among the most pressing environmental concerns, heavy metal contamination stands out as problem further exacerbated by climate change, which alters the soil chemistry, increases the frequency of extreme weather events, and enhances the mobilization and spread of toxic elements in the environment. In this scenario, synthetic biology has enabled the development of microbial biosensors that detect such contaminants by expressing fluorescent or electrochemical signals upon exposure to target compounds (Popenda et al., 2024). These biosensors are engineered organisms that provide a greater sensitivity and selectivity than conventional methods and can be deployed *in situ* for real-time monitoring, making them valuable tools for adaptive environmental management in a changing climate.

In addition to heavy metals, microplastic pollution represents another critical challenge, particularly in marine ecosystems where these particles are highly prevalent. While microspectroscopy remains the standard for the qualification and quantification of plastic particles larger than 100 μm, its high cost and limited sensitivity hinder the detection of smaller particles (Huang et al., 2021). To address this limitation, Puhakka & Santala (2022) developed a recombinant *Escherichia coli* whole-cell biosensor, which was engineered to detect and monitor microplastic degradation products, such as acrylic acid. This system's specificity is achieved through a genetic circuit, in which a promoter sensitive to the target monomer controls the expression of a reporter gene. In the presence of acrylic acid, the bacterial cell produces the luciferase enzyme, generating bioluminescence that signals the pollutant's presence. This approach offers a sensitive, selective, and low-cost solution for detecting plastic nanoparticles, overcoming the limitations of conventional techniques.

Whole-cell biosensors can also be engineered to detect specific metabolites, nutrient concentrations, or phytohormonal signals, expanding their application in monitoring plant health and environmental conditions. By providing real-time, *in situ* data on biochemical changes within the plant-soil system, these tools enhance our understanding of ecosystem dynamics and agricultural productivity. When integrated into precision agriculture platforms, they enable data-driven optimization of inputs such as fertilizers, irrigation, and pest control, promoting an efficient and sustainable crop management (Watstein & Styczynski, 2018).

Recent advances in cell-free biosensing platforms further expand the potential of this technology. These systems employ lyophilized reaction mixtures that can be rehydrated and activated in the field, allowing portable, on-demand diagnostics without the need for living cells. When integrated with paper-based devices, smartphone readouts, and multiplexed detection, cell-free biosensors emerge as a promising frontier for decentralized environmental monitoring (Pardee et al., 2016).

Given the challenges associated with the detecting of emerging pollutants and the growing need for more sensitive, specific, and accessible methods, synthetic biology has established itself as an innovative approach to advancing biosensors. By expanding the possibilities of molecular detection, this field reinforces the role of biosensors as key tools in environmental monitoring and in the promotion of sustainability and global health. As global threats become more diffuse, interrelated, and accelerated by climate dynamics, integrating biosensing technologies into monitoring networks and policy frameworks will be critical to ensure timely and effective responses.

3.4. Bioenergy and biobased fuels

Recent developments in the genetic engineering of yeasts and bacteria underscore their growing relevance as microbial platforms for sustainable biofuel production. This progress is largely attributed to the amenability of these organisms to genetic manipulation and their potential to express robust industrial phenotypes (Jin & Cate, 2017). In *Saccharomyces cerevisiae*, extensive synthetic biology and systems biology toolkits have enabled the reprogramming of central metabolic pathways to support the fermentation of pentose sugars, such as xylose, a major constituent of lignocellulosic biomass (Tsai et al., 2015; Madhavan et al., 2017). Parallel efforts in bacterial engineering have focused on expanding substrate versatility, with modified strains capable of metabolizing industrial off-gases, such as CO_2 and nitrogen oxides, into high-value biofuels, including ethanol, butanol, and biodiesel (Nisar et al., 2021). Notably, the metabolic engineering of *Clostridium carboxidivorans* has enhanced its ability to convert CO_2 and syngas into butanol, showing efficient gas-to-liquid conversion and improved alcohol yields (Ponsetto et al., 2024).

The search for sustainable alternatives to petroleum, such as bioalcohols, biodiesel, and bioplastics, has become a global priority in the face of increasing carbon dioxide concentrations in the atmosphere, and the increasing scarcity and cost of petroleum resources. Among the secondary alcohols produced by microorganisms, isopropanol stands out. It can be used as a biofuel, offering a partial replacement for gasoline. In addition, isopropanol serves as a substitute for methanol in the esterification of fats and oils for the production of biodiesel, reducing the tendency of crystallization at low temperatures (Akinsemolu & Onyeaka, 2023).

Hanai et al. (2007) demonstrated the use of a synthetic pathway in *Escherichia coli* for isopropanol production, expressing various gene combinations of *Clostridium acetobutylicum* ATCC 824, *E. coli* K-12 MG1655, *Clostridium beijerinckii* NRRL B593, and *Thermoanaerobacter brockii* HTD4. The E. *coli strain* with the combination of *C. acetobutylicum thl* (acetyl-coenzyme A [CoA] acetyltransferase), *E. coli* atoAD (acetoacetyl- CoA transferase), *C. acetobutylicum* *adc* (acetoacetate decarboxylase), and *C. beijerinckii adh* (secondary alcohol dehydrogenase) achieved the highest isopropanol production in stirring flasks with 43.5% (mol/mol) yield of in the production phase.

Microalgae have also gained traction as next-generation chassis for biofuel synthesis, owing to their high lipid productivity and rapid biomass accumulation. Through targeted metabolic rewiring, strains of *Chlamydomonas reinhardtii* have been engineered to enhance lipid accumulation under nutrient-limited conditions, such as severe iron deficiency, thereby advancing their utility for biodiesel production (Devadasu & Subramanyam, 2021). At the frontier of this field, methanotrophic and acetogenic microorganisms are being explored for their capacity to assimilate methane and CO_2 directly into energy-dense biofuels and platform chemicals (Trotsenko & Khmelenina, 2005). These strategies not only offer avenues for greenhouse gas mitigation, but they also support the development of synthetic methylotrophs capable of converting methanol into diverse bio-based products (Whitaker et al., 2015).

Further innovations include integrating AI-guided protein design and genome-scale modeling, to optimize metabolic fluxes and enzyme pathways involved in biofuel biosynthesis. Machine learning has accelerated the discovery of key regulatory nodes and improved strain design for high-yield production (Kim et al., 2020; Patra et al., 2023).

However, technical and socioeconomic challenges remain, which include the economic competitiveness of biofuels, the scalability of microbial platforms, and regulatory uncertainties in the deployment of genetically engineered organisms. Addressing these challenges requires sustained investment in research and development, cross-sectoral partnerships, and policy support for low-carbon fuels.

Despite these hurdles, synthetic biology continues to push the frontier of renewable energy. As the technologies mature, they hold the potential to produce next-generation biofuels tailored for the aviation, shipping, and heavy industry sectors that are difficult to decarbonize by other means. The convergence of biological innovation and energy transition is thus a critical pillar in the global response to climate change.

4. Bioeconomy, Sustainability, and Public Policy

The successful integration of synthetic biology into climate action depends on technical excellence and the strength of public policy, institutional vision, and social legitimacy (Robinson & Nadal, 2025). In a context of growing environmental urgency, translating this powerful technological platform into real-world impact will require countries, particularly in the Global South, to modernize their regulatory frameworks, invest in infrastructure, and rethink the relationship between innovation and equity (Gomez-Hinostroza et al., 2023) (Figure 3).

In this regard, the United Nations Framework Convention on Climate Change (UNFCCC) provides an essential policy architecture for organizing global climate actions. Instruments such as Nationally Determined Contributions (NDCs), Long-Term Strategies (LTS), and the Global Stocktake offer strategic entry points for formally recognizing the role of synthetic biology in mitigation and adaptation pathways. Aligning synthetic biology with these mechanisms could help ensure its potential is responsibly harnessed and its benefits equitably distributed.

Regulation is one of the most critical challenges. Synthetic biology presents new risk profiles, involving modular genetic designs, synthetic genomes, and novel host organisms. Yet most existing biosafety frameworks are still grounded in models developed for first-generation genetically modified organisms (FAO, 2023). Updating these systems to include context- specific assessments already in place, in several high-income countries, is essential to balance precaution with innovation. Brazil, for instance, has made important strides by distinguishing gene-edited organisms from transgenics, streamlining approvals for low-risk applications. However, Latin America still faces institutional gaps, and international harmonization remains limited (Li et al., 2021).

In addition to regulatory modernization, sustained public investment is essential. Biofoundries, automated platforms for biological engineering, are emerging globally as critical infrastructure in synthetic biology ecosystems, enabling the rapid design, build, and testing of engineered biological systems. By industrializing the biodesign process, these facilities can accelerate innovation, expand training opportunities for scientists, lower the cost of entry for startups and early-stage researchers, and reduce dependency on limited or centralized infrastructure (Symons et al., 2024). These efforts must be accompanied by targeted funding for collaborative research and development, interdisciplinary programs, and innovation aligned with climate goals.

Market incentives can further accelerate the adoption of synthetic biology-derived solutions. Green public procurement, carbon credit mechanisms, and regulatory support for low-carbon products have already shown positive effects in sectors like renewable energy and organic agriculture (Eppe et al., 2025; Malehmirchegini & Chapman, 2025). Similar policy instruments could be tailored to support biosynthetic fertilizers, climate-smart crops, and biodegradable biomaterials, especially if linked to robust certification frameworks. While several national reports have already highlighted the promising mitigation potential of engineered biology (Symons et al., 2024; Kuiken, 2025; Robinson & Nadal, 2025), future Intergovernmental Panel on Climate Change (IPCC) assessments could benefit from a systematic review of the field, to ensure that its contributions are rigorously evaluated and reflected in climate policy at both national and global levels.

Nevertheless, policy must go beyond economic instruments. Intellectual property and access to genetic resources remain highly sensitive issues, especially in biodiversity-rich regions. Fair benefit-sharing mechanisms and governance of digital sequence information are critical to ensure that local communities and countries retain sovereignty over their bioresources. Biotechnology offers a sustainable route to manufacturing, but closing the loop toward safeguarding biodiversity remains challenging. Here, partnerships with Indigenous Peoples and Local Communities can promote an ethical and circular bioeconomy (Astolfi et al., 2025). Latin America −

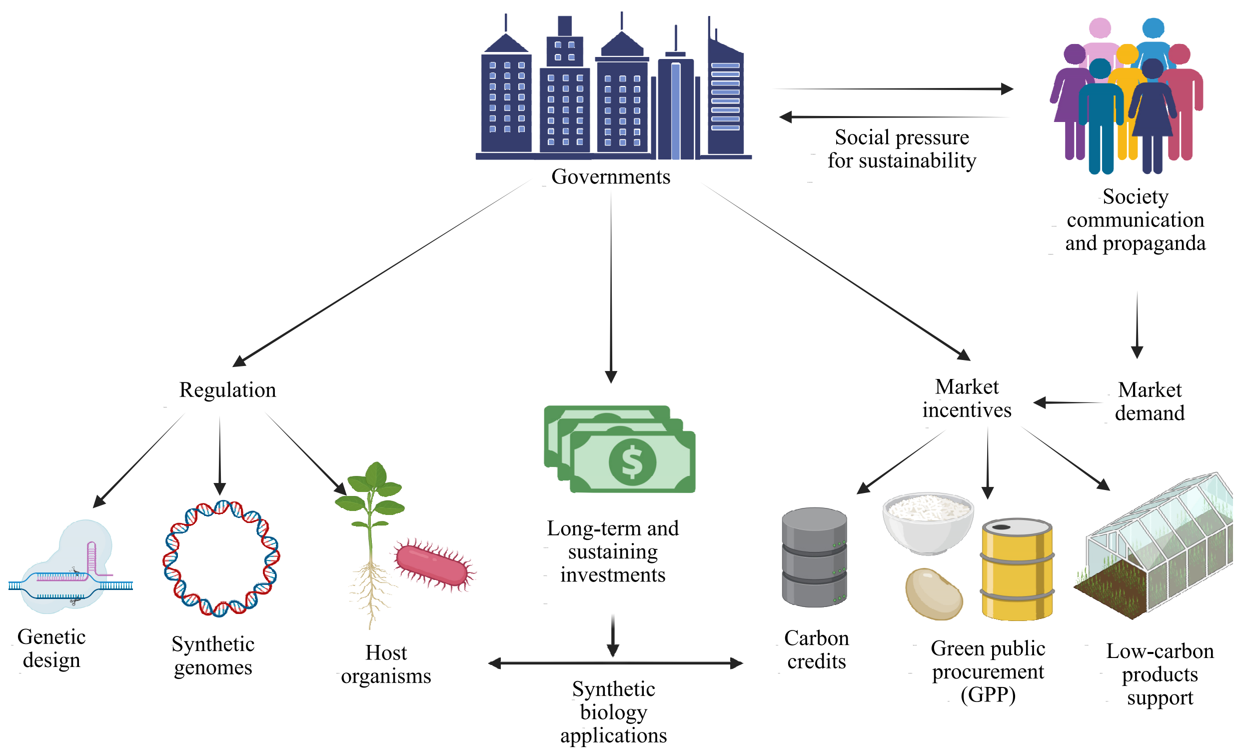

Figure 3. Enabling conditions for integrating synthetic biology into climate policy and sustainable bioeconomy strategies. This diagram illustrates how government policies, regulatory frameworks, and public awareness campaigns can foster the development and adoption of synthetic biology solutions to address climate change. By promoting sustainable products and technologies, these measures can drive consumer demand and encourage investment in the bioeconomy sector. Source: created in BioRender (Bittencourt, 2025b).

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home to vast microbial and plant diversity − has a unique voice to contribute in global discussions on access and equity (Conference of the Parties to the Convention on Biological Diversity, 2022; Gomez-Hinostroza et al., 2023)

Furthermore, public engagement should be taken seriously. The history of biotechnology is marked by societal resistance, often due to lack of transparency, inadequate communication, or exclusion of key stakeholders. Building trust requires inclusive dialogue, not only with scientific and policy elites, but also with farmers, Indigenous groups, youth, and civil society organizations (Stirling et al., 2018; Carter & Mankad, 2021; Irarrázabal et al., 2025). Responsible innovation is not just about managing risks, it is about co-designing futures. Synthetic biology should be part of this same democratic conversation.

Fully embedding synthetic biology into climate strategies will require more than scientific readiness; it demands coordinated public policies, inclusive governance, long-term investments, and systemic support for innovation. Positioned at the convergence of agriculture, energy, health, and environmental restoration, synthetic biology offers a strategic lever for sustainable development and bioeconomy expansion.

5. Perspectives for Latin America and Brazil

Latin America stands at a pivotal intersection marked by an acute climate vulnerability and immense biotechnological potential, rooted in its biodiversity, agricultural legacy, and emerging scientific ecosystems. Home to over 40% of global biodiversity and a significant share of the world's freshwater and arable land (The Nature Conservancy, 2023), the region is both disproportionately affected by climate change and exceptionally positioned to lead nature- based and biotechnology-enabled responses. In this context, synthetic biology offers more than technical fixes; it represents an opportunity to redefine innovation on the region's own terms.

Brazil, in particular, has long been recognized as a global leader in tropical agriculture and biofuels. The successful deployment of sugarcane ethanol, biological nitrogen fixation, and genetically improved crops provides a foundation for new biotech frontiers (Jaiswal et al., 2017; Soumare et al., 2020; Abdul Aziz et al., 2022). Today, this legacy is being reimagined through the lens of synthetic biology, with the use of native genes, synthetic chassis, and systems biology to engineer climate-resilient solutions. Whether through microbial biofertilizers, carbon-fixing plant pathways, or biodegradable proteins inspired by spider silk, Brazilian institutions are already showing what a bioeconomy rooted in biodiversity can look like (Bittencourt et al., 2022; Kumar et al., 2022; Weigmann, 2019).

A key enabler to harness biodiversity as a biotechnological innovation will be the regional cooperation for the Desarrollo Tecnológico Agroalimentario y Agroindustrial del Cono Sur (PROCISUR), Programa Iberoamericano de Ciencia y Tecnología para el Desarrollo (CYTED), and the Inter-American Institute for Cooperation on Agriculture (IICA) that have created platforms for shared research agendas, infrastructure, and policy coordination. By aligning goals across countries, Latin America can strengthen its voice in global biotechnology governance, while also building the scientific autonomy needed to respond to local challenges. Establishing shared biofoundries, high-throughput screening labs, and regional genomic databases could be a way to tackle climate change impacts not just for researchers, but also for farmers, entrepreneurs, and educators throughout the continent.

However, leadership shouldalso be inclusive. Latin America's agricultural landscape is deeply unequal, with family farmers and Indigenous communities often excluded from decision-making processes. These groups are not only the most vulnerable to climate change, but they are also stewards of ecological knowledge and biodiversity. Innovation that ignores them will fail; innovation that empowers them could define a new model of development. This means tailoring synthetic biology tools to real needs, co-developing solutions, and ensuring fair and equitable benefit-sharing at every stage of the innovation cycle.

Brazil's presidency of COP30 presents a powerful opportunity to elevate this agenda. Hosting the conference in the Amazon is a symbolic and strategic act, one that signals the country's intent to link environmental stewardship with cutting-edge science. By championing synthetic biology as a pillar of climate action, Brazil and its neighbors can reshape global narratives surrounding biotechnology. No longer merely recipients of technology, Latin American countries are uniquely positioned to shift

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from technology recipients to global co-creators of a new bioeconomy − one that is ecologically grounded, socially inclusive, and globally strategic.

6. Concluding Remarks

Synthetic biology is an emerging field that stands at the forefront of addressing climate change challenges. By enabling the rational design and programming of biological systems, it offers novel pathways to tackle some of the most pressing challenges of our time, including food security, environmental degradation, biodiversity loss, and greenhouse gas accumulation. Unlike traditional mitigation strategies, synthetic biology allows of programmable, scalable, and multifunctional solutions tailored to diverse ecological and economic realities.

Throughout this article, we have examined how synthetic biology is being deployed to enhance crop resilience, create biological alternatives to synthetic fertilizers, monitor environmental pollutants with precision, fix atmospheric carbon via engineered pathways, and develop biofuels and sustainable biomaterials. These applications are part of a broader transition toward a circular, low-carbon bioeconomy that aligns biotechnology with climate policy, innovation, and sustainability goals.

Yet the impact of this field will depend not only on its scientific and technical merit, but also on how responsibly and equitably it will be governed. Challenges related to biosafety, intellectual property, global regulatory harmonization, and public participation will decisively shape its trajectory. Latin America – and Brazil in particular − holds a strategic position in this landscape. With its biodiversity, institutional experience, and scientific leadership, the region can become a driving force for biotechnology leveraging biological resources to mitigate climate change.

As the world prepares for COP30 and other climate milestones, it is time to recognize synthetic biology not as a distant frontier, but as a critical tool for transformative change. With responsible stewardship, strategic investment, and inclusive innovation, synthetic biology can and should be a cornerstone of global climate resilience.

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Data availability statement

Data available: research data are available in the published article.

Declaration of use of AI technologies

During the preparation of this work, the author used GPT-4.0, OpenAI in order to create Figure 1. After this use, the author(s) reviewed and edited the content as needed and take(s) full responsibility for it.

Conflict of interest statement

The authors declare no conflicts of interest.

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