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Review Article

Redefining Biotechnology for the Global South: The Role of Synthetic Biology and Computational Tools

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Abstract

Biotechnology has always played an important role in tackling global concerns, particularly in the Global South, where socioeconomic gaps sometimes stymie scientific progress. Recent advances in synthetic biology and computational technologies have the potential to revolutionize biotechnology in these locations. Synthetic biology allows for the creation and manipulation of biological systems, with promise applications in healthcare, agriculture, and environmental control. Computational methods such as machine learning and artificial intelligence help to optimize synthetic biology processes, enabling innovations that are suited to local requirements. The combination of these cutting-edge technologies with traditional biotechnological techniques has the potential to dramatically improve the Global South's ability to solve issues such as disease outbreaks, food security, and sustainable development. This abstract outline the critical intersections of synthetic biology and computational advancements and their potential to empower the Global South, highlighting the need for supportive policies and capacity-building initiatives to maximize their impact.

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Introduction

Biotechnology has become a fundamental element of socio-economic progress in the Global South, which encompasses regions in Africa, Latin America, and parts of Asia. This sector shows immense potential in addressing various challenges, including public health crises, agricultural inefficiencies, and environmental degradation. Integrating biotechnology into local contexts has led to diverse outcomes, shaped by economic, political, and socio-cultural factors.

The potential of biotechnology in the Global South is underscored by its capacity to address neglected diseases, enhance food security, and support sustainable development. Strategic planning and collaboration between public and private entities can significantly reduce health disparities [1]. Innovations in biotechnology continue to foster progress while also highlighting challenges related to limited funding and regulatory hurdles [2].

Governance and regulatory frameworks significantly influence the regional application of biotechnology. In Latin America, biosafety regulations are crafted to align technological advancements with public safety and environmental preservation (Solleiro & Galvez 2002). However, discrepancies in regulatory standards across nations can impede the seamless adoption of new biotechnological methods. In Africa, biotechnology has positively impacted economic growth by enhancing agricultural practices and healthcare, although political instability remains a barrier to sustained progress [3].

Despite its promising impact, biotechnology in the Global South faces notable challenges. One major issue is the inconsistency of regulatory practices, as globalization has not led to uniform GMO policies, resulting in fragmented approaches that differ by region [4]. Furthermore, while biotechnology projects often show potential, they may encounter resistance from local communities due to cultural reservations and concerns about genetically modified organisms (Ruivenkamp 2008).

In summary, biotechnology holds considerable promise for advancing economic and health outcomes in the Global South. Its success, however, depends on overcoming regulatory inconsistencies, addressing local resistance, and fostering comprehensive collaboration among stakeholders. By adopting innovative business strategies and inclusive policy frameworks, biotechnology can be a key driver of sustainable development in these regions.

Synthetic biology: A transformative force

Synthetic biology, a rapidly evolving interdisciplinary field, combines biology, engineering, and computational science to design and construct new biological parts, devices, and systems. It also re-engineers existing biological systems for new and improved functionalities. As a transformative force, synthetic biology offers unprecedented opportunities across various sectors, including agriculture, healthcare, and environmental management.

Synthetic biology is built upon the foundational principles of modularity, standardization, and abstraction, which collectively facilitate the systematic design and assembly of biological systems. By applying these principles, scientists can construct standardized biological components—similar to the modular design of electronic circuits—enabling the predictable engineering of novel organisms or the enhancement of existing biological functions. This approach expands the scope of synthetic biology to include the creation of synthetic genomes, the development of complex genetic circuits, and the engineering of minimal cells. These innovations underpin a wide array of applications, from sustainable biofuel production to advanced solutions in personalized medicine [5].

Synthetic biology is revolutionizing key sectors such as agriculture, healthcare, and environmental management through innovative and sustainable solutions. In agriculture, it enables the development of genetically modified crops with improved resistance to pests, diseases, and environmental stresses, while also supporting the creation of bio-based fertilizers that reduce reliance on harmful chemical inputs and lower the ecological footprint of farming practices [6]. In healthcare, synthetic biology contributes to the design of synthetic vaccines and engineered microbes that can perform therapeutic functions, such as delivering drugs directly to targeted cells, thereby advancing precision medicine [7]. Environmental applications include the engineering of microorganisms capable of degrading toxic pollutants, offering effective bioremediation strategies to counteract the negative effects of industrial activities and support ecological restoration [8].

A pivotal trend in synthetic biology is the growing emphasis on low-cost, open-source bioengineering platforms. These initiatives are reshaping the landscape of biotechnology by democratizing access to advanced research tools and methodologies. By offering affordable genetic engineering kits and supporting community labs, they empower scientists—especially those in resource-limited settings—to engage in cutting-edge research and innovation [9]. This inclusive approach helps bridge the gap between developed and developing regions, promoting global scientific equity. Moreover, the use of open-source protocols enhances transparency and reproducibility, which are fundamental to the ethical progression of synthetic biology [10].

Despite its transformative potential, synthetic biology is accompanied by a range of ethical, biosafety, and biosecurity concerns. The engineering of synthetic organisms, while promising for fields such as medicine, agriculture, and environmental remediation, raises significant questions about unintended ecological consequences and the dual-use nature of bioengineered materials—where technologies intended for good could be misused for harmful purposes. These concerns underscore the need for comprehensive regulatory frameworks that can adapt to the rapidly evolving nature of the field [11]. International collaboration and policy harmonization are essential to establishing responsible standards for research, deployment, and risk management. Moreover, sustained investment in public dialogue and education is vital for cultivating an informed society capable of engaging with both the opportunities and the risks posed by synthetic biology (Vasilev, et al. 2021). This balanced discourse will be instrumental in guiding ethical innovation and securing societal trust.

In conclusion, synthetic biology stands as a transformative force with applications spanning agriculture, healthcare, and environmental sustainability. While its innovative potential is immense, it necessitates careful consideration of ethical and safety implications. By embracing low-cost and open-source bioengineering, synthetic biology can become more inclusive, promoting global scientific collaboration (Figure 1).

Computational tools driving biotechnological innovation

Computational tools have become pivotal in advancing biotechnology, enabling researchers to analyze massive biological datasets, model complex systems, and design synthetic organisms. These tools span bioinformatics, Artificial Intelligence (AI), Machine Learning (ML), and systems biology, collectively driving innovation in areas such as genomics, metabolic engineering, and personalized

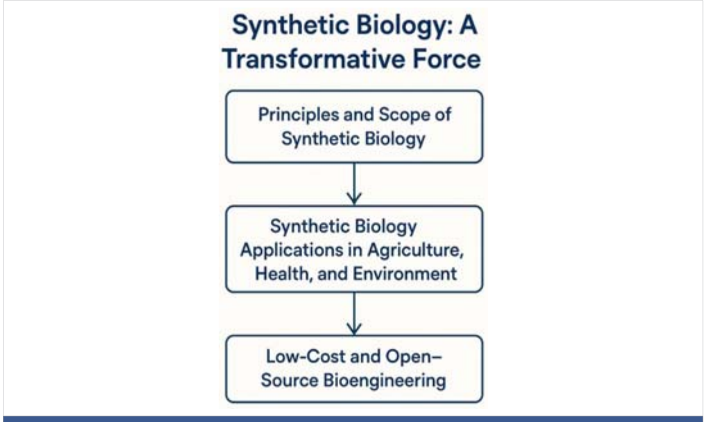

Figure 1: Synthetic Biology: A Transformative Force.

medicine. Their integration has transformed biological research from purely experimental to highly data-driven and predictive, accelerating discovery and application.

Bioinformatics is the cornerstone of computational biology, focusing on the collection, storage, and analysis of biological data, especially genomic sequences. The advent of next-generation sequencing has produced vast amounts of data, necessitating sophisticated computational algorithms for sequence alignment, gene annotation, and functional prediction. Bioinformatics pipelines enable identification of genes, regulatory elements, and evolutionary relationships that are foundational for understanding biology at the molecular level. These analyses facilitate the design and optimization of synthetic biological systems by pinpointing targets for genetic modification or pathway engineering [12]. For instance, bioinformatics approaches support the engineering of yeast strains to optimize biofuel production by identifying genes linked to metabolic fluxes [13]. By transforming raw data into actionable insights, bioinformatics accelerates hypothesis generation and experimental design.

Artificial intelligence and machine learning have revolutionized biological research by automating data analysis and enabling predictive modeling of biological processes. AI models, particularly deep learning, analyze complex patterns within biological datasets that traditional methods struggle to interpret. A hallmark achievement is AlphaFold, an AI system that predicts protein 3D structures from amino acid sequences with near-experimental accuracy, vastly reducing the time and cost of structural biology studies. This breakthrough accelerates drug discovery, enzyme engineering, and synthetic biology applications by providing accurate structural templates for molecular design [14,15]. AI further enhances metabolic engineering by predicting how genetic modifications impact cellular metabolism, enabling rational design of microbial strains for efficient chemical production [16]. Machine learning algorithms also facilitate the design of synthetic gene circuits and regulatory networks, predicting dynamic behaviors and optimizing biological functions [17].

In biomedical engineering, machine learning approaches are particularly valuable for analyzing small datasets to develop predictive models, which is crucial given the limited availability of high-quality biomedical data in many cases. These models enable personalized medicine by tailoring treatment plans based on individual genetic and phenotypic profiles, improving therapeutic efficacy and reducing adverse effects (Shaikhina, et al. 2015). Integrating AI with multi-omics data—genomic, transcriptomic, proteomic, and metabolomic—allows for a comprehensive systems-level understanding of biological processes. This integration supports the simulation and prediction of cellular responses to environmental stimuli or genetic changes, which is essential for designing synthetic organisms with specific traits or optimizing metabolic pathways [18].

Systems biology complements AI and bioinformatics by focusing on the holistic understanding of biological systems through the integration of diverse data types and computational modeling. By constructing models of metabolic, signaling, and gene regulatory networks, systems biology helps predict how alterations at one level impact the entire system. This modeling is instrumental for synthetic biology applications where biological circuits must function reliably within the cellular context [19]. Data integration from various omics platforms enables simulation of pathway dynamics and emergent properties in engineered organisms, allowing researchers to anticipate system behaviors and optimize synthetic designs before experimental implementation.

The synergy between AI and systems biology is particularly notable in the development of dynamic and adaptive biosystems. These systems utilize real-time data inputs combined with AI-driven control strategies to maintain homeostasis or optimize production under variable environmental conditions [20]. Such adaptability is crucial in agriculture, where engineered microbes or plants must respond to environmental stresses, and in healthcare, where synthetic biology can enable smart therapeutics that adjust in response to disease progression.

Despite their transformative potential, these computational technologies raise ethical and practical challenges. Data privacy concerns are paramount, especially for human genomic information, necessitating stringent safeguards. Additionally, AI models may embed biases from training data, potentially impacting the fairness and accuracy of biological predictions. There is also the risk of dual-use applications where bioengineered organisms could be misused, highlighting the need for robust biosafety and biosecurity frameworks (Su, et al, 2021). Developing ethical guidelines and fostering collaboration across biology, computer science, ethics, and policy domains is critical for responsible innovation.

Future directions in computational biotechnology include expanding protein structure databases, such as the AlphaFold Protein Structure Database, which now covers over 214 million protein sequences. This vast repository provides unprecedented resources for understanding protein function and engineering new biomolecules (Varadi, et al. 2024). Additionally, integrating AI with emerging communication technologies like 6G could facilitate global, real-time monitoring and control of synthetic biological systems, enhancing biosafety and performance optimization (Su, et al. 2021). The continual improvement of computational power and algorithms promises to further accelerate biotechnological innovation, enabling more precise, efficient, and sustainable applications in medicine, agriculture, and environmental management.

In conclusion, computational tools encompassing bioinformatics, AI, machine learning, and systems biology form the backbone of modern biotechnological innovation.

They enable detailed analysis of biological data, predictive modeling of complex systems, and the rational design of synthetic biological entities. These integrated approaches have revolutionized fields such as biofuel production, synthetic biology, and personalized medicine. While ethical and safety challenges persist, ongoing technological advancements and interdisciplinary collaboration will help realize the full potential of computational biotechnology for societal benefit (Figure 2).

Bridging the innovation gap in the global south

Bridging the innovation gap in the Global South necessitates a multifaceted approach that addresses infrastructural deficiencies, policy barriers, and educational disparities. One of the primary challenges lies in the persistent lack of infrastructure that hampers not only technological development but also the delivery of basic services necessary for innovation. The absence of robust digital connectivity, energy supply, and transportation systems creates an environment where innovative ideas cannot be efficiently tested or scaled. Policy environments further constrain innovation by failing to provide adequate support for Research and Development (R&D), with limited investment from both public and private sectors. Additionally, educational institutions in many parts of the Global South are under-resourced, lacking the facilities and curricula necessary to cultivate a culture of inquiry and technical competence [21].

Despite these challenges, there is significant potential for local capacity building through the development of collaborative networks. Knowledge exchange platforms and partnerships between universities, industries, and government institutions can play a vital role in fostering innovation ecosystems. Such collaborations can help bridge the gap between theoretical knowledge and practical application, aligning research agendas with local development needs. Initiatives that integrate local knowledge and community-based problem-solving approaches can empower grassroots innovators and support contextually relevant technological advancements (Soman, et al. 2014). Strengthening South-South cooperation can also serve as a powerful mechanism for sharing best practices and resources tailored to similar socio-economic conditions [22].

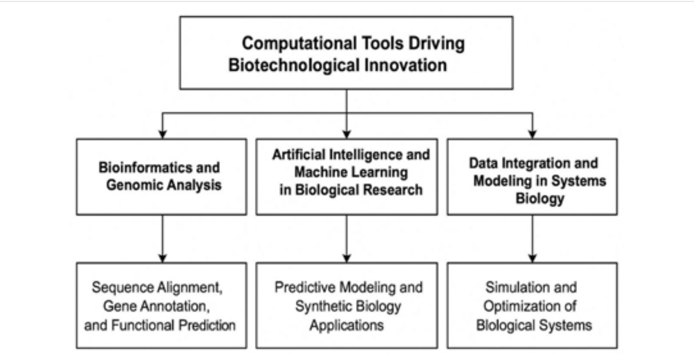

Figure 2: Computational tools driving biotechnological innovation.

An emerging trend that offers a promising route forward is the rise of decentralized and frugal innovation models. These approaches emphasize cost-effectiveness, local resource utilization, and scalability, making them well-suited to the constraints faced in many parts of the Global South. Rather than emulating Western models that often rely on high investment and advanced infrastructure, frugal innovations seek to create maximum value using minimal resources. Such innovations are not only technologically appropriate but also culturally and economically aligned with local needs (Sharma & Dahlstrand 2023). Decentralized innovation encourages regional hubs that operate independently of central authorities, enabling faster and more adaptable responses to local challenges.

To effectively implement these models, policy frameworks must evolve to support grassroots innovation and protect indigenous intellectual property. Moreover, fostering inclusive educational systems that emphasize creativity, critical thinking, and entrepreneurial skills is crucial. Investment in technical and vocational education, alongside reforms that incentivize applied research, can stimulate a new generation of innovators. Financial inclusion mechanisms such as microfinancing and innovation grants can also lower the entry barriers for small-scale inventors and startups [23].

Harnessing the opportunities presented by emerging technologies—including mobile platforms, renewable energy solutions, and data analytics—can accelerate progress if accompanied by institutional support and capacity development. Strategic adoption of these technologies tailored to local contexts enables the Global South to leapfrog traditional development pathways and carve unique trajectories in global innovation landscapes [24]. Closing the innovation gap requires not only addressing systemic deficiencies but also leveraging local ingenuity, fostering inclusive ecosystems, and committing to long-term capacity building that transcends traditional donor-recipient paradigms (Table 1).

Case studies from the global south

Innovative applications of synthetic biology and computational tools are transforming healthcare, agriculture, and biotechnology across the Global South. A notable example is the development of affordable synthetic biology-based biosensors, especially paper-based diagnostics, which enable rapid, accurate, and low-cost detection of diseases such as malaria, dengue, and Zika in resource-limited settings. These diagnostics are user-friendly and require minimal infrastructure, making them highly suitable for rural clinics and mobile medical units (Smith et al., 2017). Furthermore, modular diagnostic platforms allow rapid adaptation to emerging pathogens, enhancing health response agility.

In agriculture, precision farming leveraging AI-powered mobile apps, drones, and satellite imaging is revolutionizing food production in regions like sub-Saharan Africa and

Table 1: Comparative Analysis of Challenges and Solutions for Bridging the Innovation Gap in the Global South.

Aspect	Challenges in the Global South	Proposed Solutions	Examples / Notes
Infrastructure	Lack of digital connectivity, energy, transportation	Invest in basic infrastructure development	Enables efficient testing and scaling of innovations
Policy Environment	Insufficient R&D support, limited public/private investment	Create supportive policies, incentivize applied research	Evolve frameworks to support grassroots innovation
Education	Under-resourced institutions, lack of inquiry-based curricula	Strengthen technical/vocational education, promote creativity	Focus on critical thinking and entrepreneurial skills
Collaborative Networks	Fragmented research-industry-government links	Develop knowledge exchange platforms, promote South-South cooperation	Align research with local development needs
Innovation Models	Overreliance on Western high-investment approaches	Promote frugal and decentralized innovation	Cost-effective, locally aligned solutions
Intellectual Property	Weak protection for indigenous innovations	Implement policies to protect local IP and support grassroots inventors	Encourages local innovation and knowledge sharing
Financial Inclusion	High entry barriers for small innovators/ startups	Provide microfinancing, innovation grants	Enables access to resources for grassroots innovators
Technology Adoption	Low uptake due to infrastructure and institutional gaps	Leverage mobile tech, renewable energy, and data analytics	Enables leapfrogging traditional development paths
Overall Strategy	Systemic deficiencies and donor-recipient dependency	Foster inclusive innovation ecosystems and long-term capacity building	Local ingenuity and sustainable development pathways

South Asia by enabling data-driven decisions for soil health, pest control, and irrigation management. The integration of machine learning with synthetic biology fosters engineered microbes that improve soil fertility and plant resilience, offering sustainable alternatives to chemical inputs [25]. This synergy supports smallholder farmers' transition to climate-resilient practices.

Community-led biotech initiatives play a pivotal role in democratizing science by co-creating context-specific solutions, focusing on low-cost biomanufacturing, waste-to-resource projects, and open-source genetic engineering platforms. These grassroots movements empower marginalized groups, promote inclusive innovation, and operate beyond traditional institutional frameworks [1].

Regionally, the deployment of synthetic biology and diagnostics varies significantly. In sub-Saharan Africa, paper-based diagnostics aligned with the ASSURED criteria—affordable, sensitive, specific, user-friendly, rapid, equipment-free, and deliverable—address healthcare infrastructure gaps but face challenges in acceptability and health system integration [26-28]. In contrast, Latin American countries such as Brazil and Mexico benefit from stronger institutional support and biotech investment, facilitating wider adoption of diagnostic technologies and advanced precision farming solutions [29]. The faster progress in Latin America reflects more supportive policy environments and commercial ecosystems, underscoring the need for tailored approaches that balance innovation with social, economic, and infrastructural realities across regions.

Collectively, these case studies demonstrate that with appropriate support and contextual adaptation, the Global South can become a dynamic hub for biotech innovation, addressing unique local challenges while connecting globally.

Ethical, Legal and Social Implications (ELSI)

The rapid advancement of synthetic biology raises critical Ethical, Legal, and Social Implications (ELSI), particularly concerning biosafety, biosecurity, intellectual property, data ownership, and equitable access. One of the foremost concerns lies in biosafety and biosecurity. The manipulation of genetic material and creation of novel organisms present risks of unintended environmental and health consequences if such organisms escape containment or interact unpredictably with natural ecosystems. Ensuring stringent regulatory frameworks and safety protocols is crucial to minimize these risks. The dual-use nature of synthetic biology—where tools designed for beneficial purposes can also be misused—further heightens biosecurity concerns. Malicious exploitation, such as in bioterrorism or the creation of harmful pathogens, necessitates comprehensive surveillance, international cooperation, and transparent risk communication [30].

Equally pressing are challenges related to Intellectual Property Rights (IPR) and data ownership, particularly in how they affect access and equity. The commercialization of genetic constructs and biological parts often relies on patents that can restrict availability, especially in low-resource settings. This limits participation in scientific advancement and reinforces global inequalities in research capacity and benefit sharing. Additionally, disputes over the ownership of genetic resources and digital sequence information raise concerns about the fair and ethical use of shared biological knowledge. Balancing innovation incentives with the ideals of open science and equitable access remains a complex but necessary goal [31].

Social justice issues are central to these debates, particularly in terms of who benefits from synthetic biology innovations and who bears the risks. Communities in the Global South frequently face greater exposure to bioethical risks while lacking meaningful representation in regulatory and research governance structures. This imbalance underscores the need for inclusive policymaking that incorporates diverse voices, respects indigenous knowledge, and ensures community engagement throughout the research and development process. Moreover, ethical reflections on the manipulation of life challenge fundamental views on the natural world and human responsibility. Critics argue that synthetic biology may perpetuate reductionist perspectives and disregard the cultural and philosophical significance of nature [32].

Concrete regional examples further illuminate these concerns. In Africa, the Target Malaria initiative exemplifies ethical and regulatory challenges in the deployment of gene drive mosquitoes. While the project aims to reduce malaria, it has faced scrutiny regarding informed consent, community autonomy, and power imbalances between researchers and local populations. Effective community engagement and governance structures remain critical yet challenging [33,34]. In South Asia, similar issues are evident in India's effort to commercialize genetically modified mustard, which was stalled by legal actions and public opposition. The controversy highlighted widespread concerns over biosafety, inadequate regulatory transparency, and fears of corporate control over national food systems [35].

Collectively, these challenges underscore the urgent need for a multidimensional and inclusive approach to synthetic biology governance. This entails robust international regulation, participatory governance, and ethical frameworks that align scientific innovation with societal values, ensuring responsible and equitable development across diverse global contexts (Figure 3).

Future prospects and policy recommendations

The future of synthetic biology in the Global South hinges on strengthening research infrastructure, fostering international collaboration, and promoting sustainable biotechnology ecosystems. A primary requirement for realizing the potential of synthetic biology lies in the expansion and modernization of research and educational infrastructure. Enhancing laboratory capabilities, investing in computational tools, and integrating interdisciplinary curricula at academic institutions are essential steps to prepare the next generation of scientists and innovators. These efforts must be supported by national policies that prioritize scientific research and provide consistent funding mechanisms. Without such foundational support, the innovation gap between the Global North and South is likely to widen further [36].

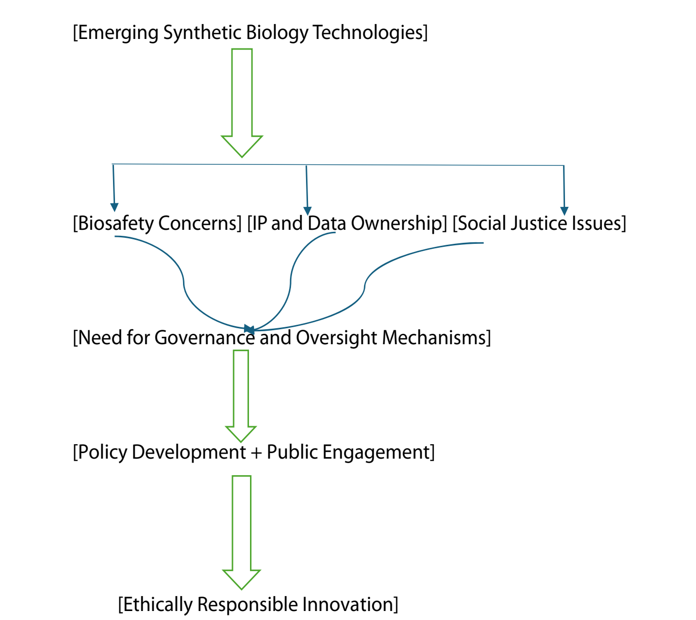

Figure 3: Ethical, Legal, and Social Implications (ELSI) of Synthetic Biology.

International partnerships and open science are critical drivers of inclusive innovation. Collaborative efforts between institutions in the Global North and South can facilitate knowledge transfer, joint training programs, and access to shared resources. Open-access databases, collaborative platforms, and distributed research models democratize participation and reduce dependency on costly proprietary technologies. These approaches foster capacity building and ensure that scientific advancements benefit a broader population rather than remaining concentrated in developed regions. However, partnerships must be grounded in mutual respect and equitable terms to avoid reproducing historical imbalances in scientific collaboration [37].

A sustainable biotech ecosystem for the Global South must be rooted in local context and aligned with environmental, economic, and societal goals. This involves integrating synthetic biology applications into sectors such as agriculture, healthcare, energy, and environmental management to address regional challenges. Frugal innovation models and decentralized approaches offer pathways to adapt biotechnologies to low-resource environments, emphasizing cost-effectiveness and resilience. Policy frameworks must support entrepreneurship, ethical governance, and inclusive innovation to build a robust ecosystem that can evolve with technological advancements [38]. In addition, fostering public engagement and responsible communication of science is vital to build trust and address societal concerns related to emerging technologies [39].

To actualize the potential of synthetic biology in the Global South, governments should implement targeted strategies such as establishing national synthetic biology roadmaps, creating dedicated funding schemes for interdisciplinary research, incentivizing academia-industry collaborations, and investing in regional centers of excellence equipped with state-of-the-art infrastructure. Additionally, policy frameworks should support startup incubators, streamline regulatory pathways, and promote STEM education through curriculum reforms and scholarships focused on biotechnology. For private stakeholders, actionable strategies include forming public-private partnerships to co-develop low-cost biotechnologies, investing in local talent through fellowship programs and technical training, supporting open innovation platforms, and integrating corporate social responsibility initiatives that align biotech development with societal needs. Both sectors should collaborate to build robust intellectual property frameworks that protect innovation while ensuring accessibility, and jointly foster regional and international networks to scale innovation and market entry.

Looking ahead, policy interventions must prioritize strategic investments in education, collaborative networks, and infrastructure, thereby enabling the Global South to emerge as a key contributor to the synthetic biology revolution. This vision requires sustained commitment and alignment of scientific, economic, and ethical priorities across national and international levels.

Conclusion

The Global South has historically faced challenges in leveraging biotechnology to address its unique socio-economic and environmental issues. However, the advent of synthetic biology and computational tools offers a pivotal opportunity to transform the region's biotechnological landscape. Synthetic biology provides the flexibility to design biological systems tailored to specific needs, from developing low-cost biosensors to creating resilient crop varieties. Simultaneously, computational advancements, particularly artificial intelligence and machine learning, have revolutionized data analysis, enabling the rapid optimization of synthetic biology applications. For instance, integrating AI in metabolic pathway optimization can drastically improve biofuel production, while machine learning can enhance disease modeling and vaccine development.

Despite these advancements, the effective deployment of synthetic biology in the Global South requires addressing multiple challenges, including limited research infrastructure, regulatory hurdles, and the need for skilled professionals. A strategic approach involves fostering collaborations between academic institutions, industry stakeholders, and government bodies to build sustainable biotechnological ecosystems. Additionally, ethical considerations, including biosecurity and equitable access, must be prioritized to ensure responsible innovation. Policymakers should focus on creating supportive regulatory frameworks that encourage innovation while addressing bioethical concerns. Capacity building through education and training is equally essential to empower local scientists and technicians to harness these technologies effectively.

Ultimately, redefining biotechnology for the Global South necessitates a holistic strategy that integrates synthetic biology, computational advancements, and inclusive innovation policies. By fostering a synergistic approach, the Global South can not only address its current challenges but also contribute significantly to global biotechnological progress, positioning itself as a key player in the future of sustainable innovation.

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