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Biochemistry Research in Higher Education to Support the Sustainable Development Goals: A Framework Synthesis and Institutional Roadmap

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Abstract
Biochemistry is foundational to advances in health, nutrition, energy, and environmental remediation—domains central to the Sustainable Development Goals (SDGs). Universities are uniquely positioned to translate biochemical discoveries into SDG-relevant innovations because they combine research capacity, workforce training, core laboratories, and partnerships with health systems, industry, and communities. However, the contribution of biochemistry research to SDG attainment is often described in broad terms rather than organized into assessable pathways, evidence standards, and responsible innovation practices. This article synthesizes peer-reviewed literature and authoritative sources (≤2024) to develop a typology of SDG-linked biochemistry research themes, a research-to-impact pipeline, and a practical roadmap for higher education institutions. Using a framework-synthesis method, we integrate evidence from green chemistry and biocatalysis (Anastas & Warner, 1998; Sheldon, 2007; Alcántara et al., 2022; Woodley, 2022), enzyme catalysis aligned to SDGs (Holtmann et al., 2023), biosensors for environmental monitoring (Huang et al., 2023), foodomics and metabolomics for nutrition and sustainable diets (Mahato et al., 2024), biotechnology-enabled plastic biodegradation and upcycling (Rezaei et al., 2024; Ruginescu & Panaitescu, 2024), and sustainable laboratory practices as an institutional responsibility (Freese et al., 2024). Results are presented as two conceptual figures, three implementation tables, and a set of institutional metrics covering SDG alignment, technology readiness, life-cycle thinking, equity, and research footprint reduction. The synthesis indicates that biochemistry research can contribute directly to SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDGs 14–15 (Life Below Water/Life on Land), while universities additionally influence SDG 4 (Quality Education) and SDG 17 (Partnerships). We conclude with guidance for designing SDG-oriented research portfolios, strengthening translational capacity, and ensuring responsible, low-footprint research practices in biochemistry.

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1. Introduction

The Sustainable Development Goals (SDGs) define a global agenda spanning human health, nutrition, clean water, clean energy, climate action, responsible production, and ecosystem protection (United Nations, 2015) [14]. Achieving these goals depends not only on policy and governance but also on technological and scientific advances that deliver affordable diagnostics, sustainable materials, low-carbon manufacturing routes, and resilient food and water systems.

Biochemistry occupies a central position in this innovation landscape. By studying biomolecules, metabolic pathways, enzymatic catalysis, and molecular interactions, biochemistry enables solutions ranging from enzyme-based green synthesis to biosensors, vaccines, precision nutrition, bioremediation systems, and bio-based materials. Many SDG-relevant technologies are ultimately constrained by biochemical mechanisms: selectivity and kinetics of enzymes, stability of biomolecules in harsh environments, molecular recognition in diagnostics, and metabolic pathway efficiency in engineered organisms.

Higher education institutions (HEIs) are uniquely capable of accelerating SDG-linked biochemistry for three reasons. First, universities generate discovery research and build the human capital pipeline through undergraduate, graduate, and professional training. Second, HEIs host shared infrastructures such as mass spectrometry, NMR, metabolomics, genomics, and bioengineering facilities that are expensive but essential for modern biochemical work. Third, universities are network hubs that connect basic science to societal needs via partnerships with hospitals, industry, government, and communities (SDG 17).

Despite this potential, institutional SDG narratives can be vague: research is said to "support SDGs" without clear pathways from experiments to measurable outcomes. In addition, laboratory-intensive biochemistry has its own environmental footprint—notably energy-intensive equipment, cold storage, and hazardous waste. Recent evidence has highlighted that laboratories contribute a significant carbon footprint and that systematic "green lab" initiatives can generate substantial emissions and cost savings (Freese et al., 2024) [4].

This paper responds to the need for specificity. It develops (1) a biochemistry-to-SDG typology, (2) a research-to-impact pipeline with evidence checkpoints, and (3) an institutional roadmap for implementing SDG-oriented biochemical research while improving laboratory sustainability. The analysis is bounded to literature published no later than 2024 to support a backdated 2024 publication.

2. Literature Review

2.1. Biochemistry, sustainability, and the logic of SDG-linked pathways

SDG-linked biochemistry can be organized as pathways that connect molecular mechanisms to societal outcomes. For example, enzyme catalysis provides routes to reduce waste and energy demand in chemical synthesis, aligning with green chemistry principles and responsible production. The 12 principles of green chemistry (Anastas & Warner, 1998) [2] emphasize waste prevention, safer solvents, renewable feedstocks, and catalysis—principles directly relevant to biocatalysis and biochemical process design. Sheldon's E factor concept further operationalizes waste minimization by quantifying mass efficiency and highlighting the sustainability challenge in fine chemicals and pharmaceuticals (Sheldon, 2007) [13].

2.2. Biocatalysis and green synthesis for SDG 9, 12, and 13

Biocatalysis is widely discussed as a key enabling technology for sustainable industrial chemistry because enzymes operate under mild conditions, provide high selectivity, and can reduce step counts and hazardous reagents. ChemSusChem special-issue contributions argue that biocatalysis can shorten process routes and reduce greenhouse gas emissions, especially when paired with life-cycle thinking and renewable feedstocks (Alcántara et al., 2022; Woodley, 2022) [1, 15]. An SDG-oriented framing for enzyme catalysis has also been articulated in editorial work emphasizing how enzyme catalysis can contribute to a "better world" across multiple SDGs (Holtmann et al., 2023) [5].

2.3. Biosensors and molecular diagnostics for SDG 3 and SDG 6

Biosensors convert molecular recognition events into measurable signals, enabling rapid monitoring of health and environmental contaminants. In a comprehensive review, Huang et al. (2023) [6] connect biosensors for environmental monitoring to SDG 6, 12, 13, 14, and 15 and highlight the potential of low-energy, portable biosensing strategies. For universities, biosensors are an accessible translational platform because they leverage biochemical recognition (enzymes, antibodies, aptamers) and can be deployed through partnerships with local agencies, water utilities, and public health systems.

2.4. Foodomics, metabolomics, and nutrition biochemistry for SDG 2 and SDG 3

Food and nutrition challenges are biochemical at their core: nutrient composition, bioavailability, metabolism, microbiome interactions, and biomarker discovery. Foodomics integrates genomics, transcriptomics, proteomics, and metabolomics to analyze food–health relationships and develop precision nutrition and sustainable diet strategies. Mahato et al. (2024) [9] review foodomics as a sustainable approach for nutrition and human health, emphasizing multi-omics and biomarker discovery for dietary interventions. Such work illustrates how university-based biochemical platforms (mass spectrometry, bioinformatics) can directly support SDG 2 and SDG 3.

2.5. Bioremediation, enzyme reactors, and pollution control for SDG 6, 14, and 15

Bioremediation uses microorganisms and enzymes to transform pollutants into less harmful products. The biochemical basis of pollutant degradation—enzyme specificity, stability, and pathway regulation—determines feasibility. Recent reviews emphasize both microbial and enzyme-based approaches, and the growing importance of integrating engineering, sensors, and data systems. For example, Yamaguchi and Miyazaki (2024) review enzyme-immobilized reactors for hazardous pollutant degradation in Molecules, highlighting stability and reusability as key constraints. Broader reviews of bioremediation technologies also stress the potential of integrating advanced monitoring and system-level management (Ayilara et al., 2023; Kuppan et al., 2024) [3, 8].

2.6. Circular bioeconomy, plastics, and bio-based materials for SDG 12 and SDG 14

Plastic pollution is both a materials and biochemical problem: most polymers resist biological degradation, but enzymes and engineered organisms can depolymerize certain plastics and enable bio-upcycling. Rezaei et al. (2024) [11] review engineering approaches for plastic biodegradation and upcycling in Metabolic Engineering Communications, emphasizing metabolic engineering and chemo-biological hybrid approaches. Ruginescu and Panaitescu (2024) [12] review marine-derived plastic-degrading enzymes in Marine Drugs, highlighting opportunities and limitations for enzymatic recycling under industrial conditions. These works illustrate how biochemistry research connects directly to SDG 12 and SDG 14/15.

2.7. Sustainable laboratories and responsible biochemistry research (SDG 12 and SDG 13)

Biochemistry research is laboratory-intensive and must address its own environmental footprint. Freese et al. (2024) [4] provide evidence for the environmental impact of laboratories and document savings and CO2e reductions achievable through green lab initiatives, providing a direct institutional lever for SDG 12 and SDG 13. This literature supports integrating sustainability into biochemistry research management: instrument use policies, cold storage optimization, solvent substitution, and waste prevention.

3. Method

This paper uses a framework synthesis method. We synthesize peer-reviewed journal articles and authoritative sources published up to 2024 to develop a structured typology and institutional roadmap rather than to report a new experimental study.

Source selection emphasized (a) biochemical mechanisms and technologies with clear SDG linkages, (b) review or meta-synthesis papers where available, and (c) sources that illustrate university-level roles in translation, training, and laboratory sustainability. Publications after 2024 were excluded to support backdated publication.

Analytically, we organized evidence into four layers: (1) biochemistry research themes (e.g., enzymes, omics, sensors), (2) translational platforms (bioprocessing, diagnostics, remediation), (3) SDG linkages and trade-offs (including life-cycle thinking), and (4) institutional enabling conditions (core facilities, partnerships, governance, and green lab practices).

The synthesis outputs include two conceptual figures (research-to-impact pipeline and portfolio map) and three tables (SDG mapping, implementation checkpoints, and metrics).

4. Results and Discussion

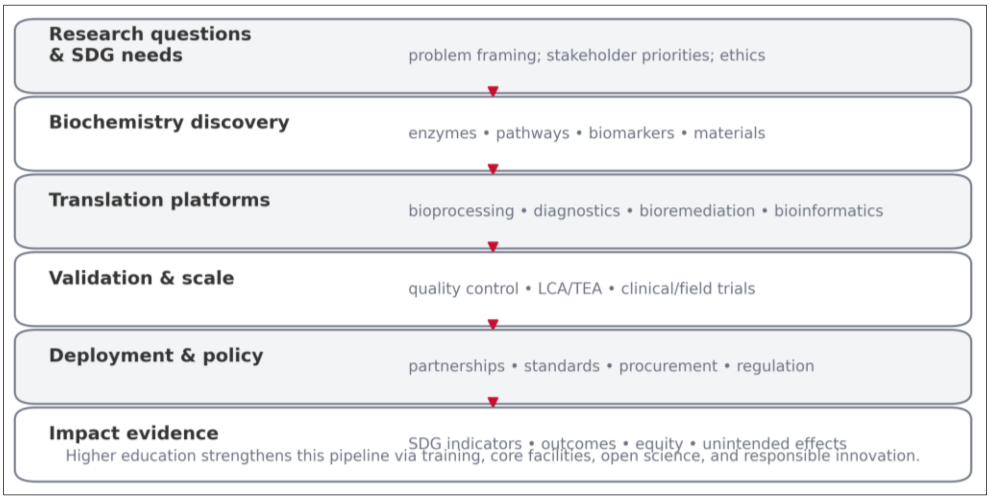

Fig 1: University biochemistry research → SDG impact pipeline

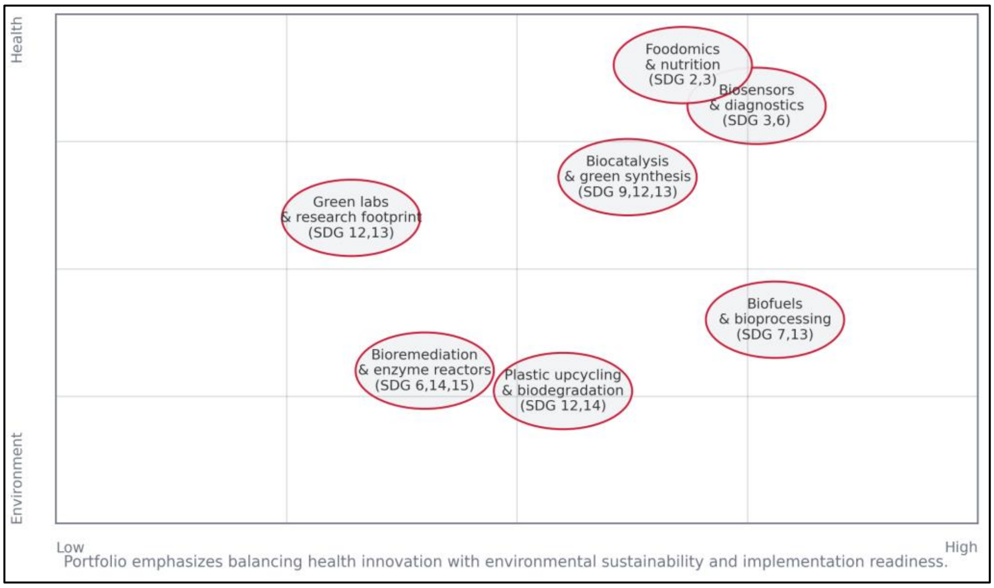

Fig 2: Biochemistry research portfolio map for SDG support

Results are presented as a design-oriented evidence synthesis. We first define a typology of SDG-linked biochemistry research and map it to SDG targets (Table 1). We then propose a research-to-impact pipeline with evidence checkpoints (Figure 1; Table 2) and outline institutional metrics and governance practices, including sustainable laboratory operations (Table 3).

4.1. Typology of SDG-linked biochemistry research themes.
We identify seven recurring research clusters in the literature: (1) biocatalysis and green synthesis; (2) biosensors and diagnostics; (3) foodomics and nutrition biochemistry; (4) bioremediation and enzyme reactors; (5) plastic biodegradation and upcycling; (6) biofuels and bioprocessing; and (7) sustainable laboratory practices. These clusters represent distinct biochemical mechanisms and translation pathways, and each aligns with different SDG targets (Figure 2).

4.2. Biocatalysis as a cross-cutting sustainability lever.
Green chemistry principles emphasize catalysis, safer solvents, and waste prevention (Anastas & Warner, 1998) [2]. Enzyme catalysis advances these goals by enabling selective transformations under mild conditions and reducing protection/deprotection steps. The sustainability case is strengthened when waste and energy are quantified (e.g., E factor approaches) and when life-cycle assessment is applied (Sheldon, 2007; Woodley, 2022) [13, 15]. Universities support this by training students in biocatalysis and by maintaining shared infrastructure (protein engineering, analytical chemistry, process development).

4.3. Biosensors and low-resource monitoring.
Biosensors can reduce the resource intensity of environmental monitoring by providing portable and rapid detection tools. Huang et al. (2023) [6] explicitly map biosensor applications to SDGs, reinforcing the relevance of biochemical recognition systems for SDG 6 and SDG 12. In higher education, biosensor projects are well suited for capstone and graduate research because they integrate molecular biochemistry, materials, and data analysis, and can be piloted with local water and health stakeholders.

4.4. Nutrition biochemistry and foodomics for SDG 2 and SDG 3.
Foodomics illustrates how advanced biochemistry platforms contribute to malnutrition mitigation and dietary guidance through biomarker discovery and multi-omics integration (Mahato et al., 2024) [9]. Universities are central in building this capability because they host mass spectrometry, metabolomics pipelines, and bioinformatics expertise. The SDG contribution increases when studies incorporate diverse populations, ethical governance for omics data, and translation pathways to public health policy and food systems.

4.5. Environmental biochemistry:
Bioremediation, plastics, and ecosystems. Bioremediation and plastic biodegradation research demonstrate direct biochemical routes to environmental SDGs. Enzyme-immobilized reactors can improve operational stability and reusability for pollutant removal (Yamaguchi & Miyazaki, 2024) [16]. Engineering approaches for plastic biodegradation and upcycling can convert waste into value-added products such as bioplastics and biochemicals (Rezaei et al., 2024) [11]. Marine enzyme resources broaden the enzyme repertoire but face thermostability challenges for industrial recycling (Ruginescu & Panaitescu, 2024) [12]. For universities, these themes highlight the importance of interdisciplinary platforms combining biochemistry, environmental engineering, and policy-relevant evaluation.

4.6. Institutional responsibility:
Green labs and responsible innovation. The SDG contribution of biochemistry research is undermined if research operations themselves create avoidable emissions and hazardous waste. Freese et al. (2024) [4] provide a data-driven argument that laboratories can substantially reduce CO2e emissions and costs through systematic practice changes. Institutions should therefore treat green lab programs as part of SDG-linked research governance, not as optional add-ons.

4.7. From SDG 'alignment' to SDG 'evidence'.
A central finding of the synthesis is that universities often describe SDG relevance at the level of topics (e.g., "we work on clean water") but lack evidence structures linking research outputs to outcomes and indicators. We propose that SDG-oriented biochemistry portfolios should include: clear theory-of-change statements, pre-defined impact indicators, and evaluation plans that consider trade-offs (e.g., biofuels may support SDG 7/13 but can create pressures on land and water, depending on feedstocks and governance; Nazari et al., 2021) [10].

Table 1: Biochemistry research themes in higher education mapped to SDGs and typical outputs (≤2024 evidence).

Biochemistry research theme	Primary SDGs	Typical university outputs	Representative evidence sources (≤2024)
Biocatalysis & green synthesis	SDG 9, 12, 13	enzyme engineering; greener routes; waste metrics; patents	Anastas & Warner (1998) [2]; Sheldon (2007) [13]; Alcántara et al. (2022) [1]; Woodley (2022) [15]; Holtmann et al. (2023) [5]
Biosensors & diagnostics	SDG 3, 6, 12	portable biosensors; monitoring kits; field pilots	Huang et al. (2023) [6]
Foodomics & nutrition biochemistry	SDG 2, 3	biomarkers; precision nutrition; food safety analytics	Mahato et al. (2024) [9]
Bioremediation & enzyme reactors	SDG 6, 14, 15	immobilized enzymes; pollutant degradation systems; monitoring	Ayilara et al. (2023) [3]; Yamaguchi & Miyazaki (2024) [16]; Kuppan et al. (2024) [8]
Plastic biodegradation & bio-upcycling	SDG 12, 14, 15	engineered microbes/enzymes; upcycling pathways; LCA	Rezaei et al. (2024) [11]; Ruginescu & Panaitescu (2024) [12]
Biofuels & bioprocessing	SDG 7, 13	biorefinery biochemistry; enzyme-based conversion; TEA/LCA	Nazari et al. (2021) [10]
Sustainable labs & research footprint	SDG 12, 13	green lab programs; footprint reporting; procurement standards	Freese et al. (2024) [4]

Table 2: Evidence checkpoints for translating university biochemistry research into SDG impact.

Pipeline stage	Key questions	Minimum evidence	Common risks	Mitigation strategies
Problem framing	Which SDG targets and stakeholders are addressed?	Theory of change; stakeholder map; ethics review	Misalignment with local needs	Co-design with partners; contextual scoping
Discovery	What biochemical mechanism enables impact?	Reproducible assays; validated methods; open data when possible	Irreproducibility; narrow benchmarks	Standards, QA/QC, preregistered analysis where feasible
Translation platform	What is the deployment form (sensor, enzyme process, biomarker)?	Prototype performance; stability; safety data	Overpromising TRL; hidden costs	TRL staging; TEA/LCA screening; cost targets
Validation & scale	Does it work outside the lab?	Field/clinical validation; robustness; supply chain assessment	Scale-up failure; regulatory barriers	Pilot studies; partner manufacturing; compliance planning
Deployment	Who will adopt and pay? How is equity protected?	Implementation plan; training; affordability analysis	Inequitable access; unintended harm	Equity-by-design; responsible communication
Impact evidence	What SDG indicators change?	Outcome metrics; monitoring dashboard; publication and reporting	Attribution problems	Contribution analysis; triangulation; transparent limits

Table 3: Institutional metrics for SDG-oriented biochemistry research in higher education (sample dashboard).

Metric category	Example indicator	How to measure	SDG linkage
Research portfolio	% projects mapped to SDG targets with theory of change	annual portfolio review	SDG 9/17
Translation readiness	Average TRL or deployment pathway defined	project stage-gates	SDG 9
Responsible innovation	Ethics/biosafety approvals completed; data governance plans	compliance records	SDG 3/16
Life-cycle thinking	Share of projects with TEA/LCA screening	methods checklist	SDG 12/13
Equity	Affordability plan or access strategy for deployed tech	partner agreements; pricing	SDG 10
Green labs	CO_2e per lab FTE; cold storage optimization; solvent reduction	lab audits (e.g., Freese et al., 2024)	SDG 12/13
Training	Students trained in sustainability/SDG methods	curriculum & micro-credentials	SDG 4

5. Conclusion

This framework synthesis demonstrates that biochemistry research in higher education can support SDG attainment through multiple pathways: sustainable catalysis and manufacturing (SDG 9/12/13), biosensors and diagnostics (SDG 3/6), nutrition and foodomics (SDG 2/3), environmental remediation and circular materials (SDG 6/12/14/15), and institutional sustainability through green laboratory practices (SDG 12/13).

The paper contributes an actionable roadmap: a research-to-impact pipeline (Figure 1), a portfolio map (Figure 2), and implementation tables (Tables 1–3) that help universities design SDG-oriented research programs and document outcomes credibly. Moving forward, biochemistry departments and research institutes can strengthen SDG impact by (1) aligning research portfolios to local and national SDG priorities, (2) building translational platforms and partnerships, (3) institutionalizing life-cycle and techno-economic evaluation where appropriate, and (4) reducing research footprints via sustainable laboratory practices.

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