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Microbial Platforms for Converting Non-Food Renewable Biomass into Value-Added Chemicals and Materials: Progress over the Past Decade

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Abstract. Global dependence on fossil resources and widespread food insecurity highlight the urgent need for sustainable and resilient alternatives. Non-food renewable biomass, including agricultural residues, aquatic biomass, and organic wastes, provides abundant carbon-neutral feedstock without competing with arable land or staple food production, making it a strategic resource for advancing a sustainable bioeconomy. This review systematically summarizes the classification, physicochemical properties, and high-value utilization pathways of non-food biomass, with a particular focus on microbial platforms for its conversion into biofuels, platform chemicals, biopolymers, and protein-based materials. We discuss the limitations of conventional industrial microorganisms and highlight the transformative role of synthetic biology and metabolic engineering, including synthetic pathway design, genome editing, systems biology, and AI-assisted strain optimization. Key production technologies, application prospects, and industrialization challenges are analyzed, with inhibitor tolerance, substrate conversion efficiency, and economic feasibility identified as major bottlenecks. Future perspectives include next-generation microbial chassis, synergistic conversion strategies, microbial co-culture systems, and intelligent fermentation control. Overall, synthetic biology–driven microbial conversion of non-food biomass offers a promising technical route toward carbon neutrality and the development of circular, green bio-based industrial systems.

1 Introduction

The global economy remains heavily dependent on fossil resources, which accounted for approximately 80% of energy consumption in 2024, while approximately 2.3 billion people worldwide face food insecurity[1, 2]. This dual challenge highlights the urgent need for sustainable, non-food-based alternatives to replace fossil fuels and chemical feedstocks. Non-food renewable biomass represents an abundant and carbon-neutral resource, with estimated annual global yields exceeding 10 billion tons, without competing with arable land or staple food production. Its utilization aligns with the principles of a circular bioeconomy, providing a pathway to simultaneously mitigate fossil resource depletion, reduce greenhouse gas emissions, and valorize otherwise underutilized waste streams[3].

Among strategies for biomass valorization, microbial platforms have emerged as versatile and efficient systems for converting complex organic substrates into high-value chemicals and materials[4]. Microbial cell factories can transform lignocellulose, algal polysaccharides, and organic waste components into biofuels, organic acids, biopolymers, terpenoids, and protein-based materials. These processes deliver significant economic and environmental benefits, including renewable energy production, bioplastics synthesis, and development of sustainable functional materials, thereby supporting the transition toward low-carbon, circular industrial ecosystems. The rapid advancement of synthetic biology has further expanded opportunities for biomass utilization[5].

Despite significant progress, conventional industrial microbes and traditional fermentation strategies face notable limitations. Natural strains often exhibit low tolerance to inhibitors generated during biomass pretreatment and limited substrate utilization efficiency. Suboptimal metabolic fluxes further restrict product yields and process scalability. In response, synthetic biology and metabolic engineering have enabled systematic reprogramming of microbial hosts, including rational pathway design, CRISPR-based genome editing, and systems biology approaches integrated with artificial intelligence-assisted strain optimization. These strategies enhance carbon flux toward target products, improve robustness against inhibitory compounds, and facilitate the development of multiproduct biorefineries capable of comprehensive biomass utilization.

This review provides a comprehensive overview of recent advances in the microbial conversion of non-food renewable biomass into value-added products. Specifically, this review mainly summarizes progress reported over the past decade. It first discusses the classification, composition, and conversion strategies of

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non-food biomass, followed by an analysis of microbial hosts, engineering strategies, and synthetic biology tools. Subsequently, production technologies for major high-value chemicals and materials are summarized, highlighting current bottlenecks, including inhibitor tolerance, substrate conversion efficiency, and cost-effectiveness. Finally, emerging trends—including next-generation microbial chassis, multi-component synergistic conversion, co-culture systems, and intelligent fermentation control—are discussed, providing a roadmap for efficient, sustainable, and industrially viable microbial biomass valorization.

2 Non-food renewable biomass

Non-food renewable biomass refers to biological resources derived from plants or animals that are unsuitable or unintended for human or animal consumption, yet can serve as sustainable carbon feedstocks for industrial biomanufacturing and biotransformation processes[6]. Compared with food-based biomass, non-food biomass avoids competition with food supply and arable land, while offering large availability, low cost, and favorable life-cycle environmental performance. Its core value lies in substituting fossil resources for the production of fuels, high-value chemicals, and functional materials through microbial and biochemical conversion technologies[7]. Owing to its inherent carbon neutrality, non-food biomass enables CO_2 recycling across its lifecycle and constitutes a key feedstock for the development of a sustainable circular bioeconomy[8]. Based on source and composition, non-food biomass can be broadly categorized into agricultural biomass, aquatic biomass, and organic biomass.

2.1 Classification of non-food renewable biomass

Based on source and composition, non-food biomass can be broadly categorized into agricultural biomass, aquatic biomass, and organic waste biomass, each exhibiting distinct structural features and conversion challenges.

2.1.1 Agricultural biomass

Agricultural biomass mainly consists of non-grain crop residues such as straw, rice husks, corn cobs, and sugarcane bagasse. With a global annual yield exceeding 10 billion tons, it represents the most abundant category of non-food biomass[9]. In China, approximately 0.9 billion tons of straw are generated annually, although the utilization rate remains below 30%. These residues are rich in cellulose (40–50%) and hemicellulose (25–35%) but exhibit strong structural recalcitrance due to high lignin content, necessitating effective pretreatment strategies. For example, steam explosion combined with dilute acid pretreatment has been shown to enhance saccharification efficiency of corn cobs, achieving glucose yields above 85%. However, seasonal availability and uneven geographical distribution constrain large-scale deployment. This underscores the need for distributed and decentralized biomass conversion systems [10].

2.1.2 Aquatic biomass

Aquatic biomass includes microalgae, macroalgae, and aquatic higher plants, offering the advantage of not competing for arable land and freshwater resources. Microalgae exhibit high photosynthetic efficiency and rapid growth; under nitrogen-limited conditions, lipid content in certain species can exceed 30% of dry weight, making them attractive feedstocks for biodiesel production[11]. Macroalgae such as kelp are rich in alginates and agar, whose polysaccharide components can be converted into platform chemicals like succinic acid via integrated enzymatic hydrolysis and fermentation processes[12]. Despite these advantages, large-scale utilization remains limited by high cultivation costs, technical complexity, regulatory constraints, and challenges in system integration[13].

2.1.3 Organic biomass

Organic biomass primarily refers to biodegradable waste streams, including municipal organic waste, livestock manure, food processing residues, and forestry by-products. These materials are characterized by heterogeneous composition, high moisture content, and susceptibility to degradation, yet their large volume and wide distribution offer substantial potential for circular economy applications. Food waste, rich in carbohydrates, proteins, and lipids, can be converted into methane through anaerobic digestion or into bioplastics such as polyhydroxyalkanoates (PHA) via microbial fermentation. However, contaminants such as plastics and heavy metals in municipal waste streams hinder biological conversion, highlighting the importance of efficient sorting and pretreatment technologies[14].

2.2 Utilization of non-food biomass

Non-food biomass is primarily converted through biochemical and thermochemical pathways. Biochemical approaches include enzymatic hydrolysis–fermentation, anaerobic digestion, and microbial synthesis, while thermochemical routes encompass gasification, pyrolysis, and hydrothermal liquefaction. These processes enable directional conversion of cellulose, hemicellulose, and lignin into energy carriers, platform chemicals, and functional materials. Second-generation biofuels such as cellulosic ethanol, biobutanol, and biomethane have achieved notable technological progress[15]. Engineered microbial platforms further enable efficient production of organic acids, including lactic acid and succinic acid, which serve as precursors for bio-based plastics and fine chemicals. In addition, biopolymers such as PHA and bacterial cellulose are increasingly applied in high-value sectors, including packaging and biomedical materials[16]. Life cycle assessment studies consistently demonstrate that non-food biomass-based biorefineries significantly reduce greenhouse gas emissions compared with petrochemical processes[17]. Recent advances are driving the transition toward multiproduct biorefineries and full-component biomass utilization.

2.3 Pretreatment and saccharification

Lignocellulosic biomass is a primary focus of non-food biomass valorization, with pretreatment serving as a critical step to overcome structural recalcitrance and improve cellulose accessibility[18]. Organic solvent pretreatment effectively separates lignin and enriches cellulose fractions, yielding high-quality substrates for downstream biotransformation. Saccharification relies on cellulase systems to hydrolyze polysaccharides into fermentable sugars, where optimized enzyme cocktails play a decisive role in conversion efficiency. The incorporation of lytic polysaccharide monooxygenases (LPMOs) has been shown to increase glucose release from wheat straw by up to 28%. However, pretreatment-derived inhibitors such as furfural and 5-hydroxymethylfurfural can severely impair microbial performance. Developing inhibitor-tolerant engineered strains and low-inhibitor pretreatment methods, including ionic liquid-assisted biological pretreatment, represents an effective strategy to enhance overall conversion efficiency[19].

3 Microbial hosts and engineering strategies

Microbial cell factories (MCFs) are pivotal platforms for converting non-food renewable biomass into high-value chemicals and materials. Their development marks a shift from traditional fermentation to precision synthetic biology: early approaches relied on natural strain screening and empirical optimization, whereas modern microbial engineering systematically rewires cellular metabolic networks for precise control over biomass conversion[20]. This transition positions MCFs as key drivers of sustainable manufacturing in the bioeconomy, enabling efficient conversion of lignocellulosic and other non-food biomass into diverse chemicals[21]. This section outlines the classification and limitations of traditional industrial microbes and highlights how synthetic biology and metabolic engineering overcome these constraints to construct more efficient microbial platforms.

3.1 Traditional industrial microbes

Traditional industrial microbes are typically classified into bacteria, yeasts, and filamentous fungi based on physiology and application domain. Among them, *Escherichia coli*, *Saccharomyces cerevisiae*, *Corynebacterium glutamicum*, and *Bacillus subtilis* are the most widely used industrial platforms[22].

E. coli grows rapidly, is easy to manipulate genetically, and has well-characterized metabolic pathways, making it a key host for amino acids, organic acids, biofuels, and heterologous enzyme production[23].

S. cerevisiae, as a model eukaryote, is robust under industrial conditions and has mature genetic tools, dominating the food, beverage, and bioethanol industries [24].

C. glutamicum excels in amino acid production and can utilize diverse non-food biomass substrates, including lignocellulosic hydrolysates, to produce platform chemicals and biopolymers [25].

B. subtilis, with strong extracellular enzyme secretion and GRAS status, is valuable for industrial enzyme production [26].

However, traditional microbial engineering methods have significant limitations. Classical mutagenesis and screening are inefficient, incapable of precise multi-gene regulation, and result in long strain development cycles and low success rates. Imprecise metabolic flux control causes byproduct accumulation and energy waste, limiting product yield. Moreover, natural microbes often have low tolerance to complex biomass substrates, such as inhibitors present in lignocellulosic hydrolysates, reducing conversion efficiency and product titers[27]. These challenges have driven the adoption of synthetic biology and metabolic engineering for constructing high-performance MCFs.

3.2 Synthetic biology and metabolic engineering approaches

The integration of synthetic biology and metabolic engineering provides systematic solutions to traditional limitations. Compared with conventional approaches, modern strategies offer precision, predictability, and high-throughput capabilities, enabling rational design and targeted reconstruction of microbial metabolic networks[28]. The overarching goal is to transform microbes into efficient "cell factories" that convert low-value renewable substrates into high-value products[29].

Modern microbial engineering employs three main approaches: synthetic pathway design, genome editing, and systems biology combined with artificial intelligence (AI)-assisted design[30]. Their synergistic application shifts MCF design from trial-and-error methods to data-driven rational strategies, significantly enhancing engineering efficiency and success rates[31].

3.2.1 Synthetic pathway design

Synthetic pathway design is central to building efficient MCFs, aiming to optimize carbon flux toward target products[32]. By introducing heterologous enzymes from diverse species, researchers can construct novel metabolic pathways that overcome natural metabolic limitations[33]. For instance, in biofuel production, non-natural carbon–carbon bond-forming pathways have enabled efficient synthesis of long-chain hydrocarbons from simple sugars.

3.2.2 Gene editing tools

CRISPR-Cas9 has revolutionized microbial genome editing through RNA-guided precise cleavage, enabling gene knockouts, knock-ins, point mutations, and expression regulation via CRISPRi (interference) and CRISPRa (activation) systems. In industrial strains such as *E. coli* and *C. glutamicum*, CRISPR-Cas9 dramatically improves editing efficiency and accelerates strain construction[34]. Its high-throughput capability allows simultaneous optimization of multiple metabolic nodes, surpassing the limitations of traditional approaches.

3.2.3 Computer and machine learning-assisted design

The integration of systems biology with machine learning represents the future of microbial engineering. Systems metabolic engineering combines traditional metabolic engineering with systems biology, synthetic biology, and evolutionary engineering to provide a systematic framework for high-performance MCFs. Machine learning algorithms analyze large datasets to predict the metabolic impact of genetic modifications, optimize culture conditions, and identify key regulatory nodes, accelerating the "Design-Build-Test-Learn" (DBTL) cycle and shortening strain development timelines[31]. Figure 1 illustrates the AI-assisted DBTL framework for intelligent microbial engineering. For example, deep learning models successfully predict promoter strength, protein folding, and metabolic flux distributions, offering powerful computational tools for rational strain design[35]. This integrated approach is driving MCFs toward intelligent, automated systems, establishing a solid foundation for efficient non-food biomass conversion.

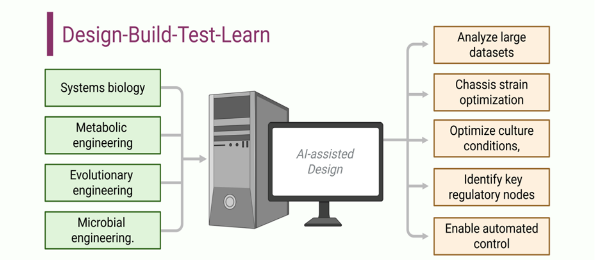

Figure 1. AI-assisted Design–Build–Test–Learn cycle for microbial engineering. The figure was created with BioRender.

4 Microbial platforms for value-added chemicals and materials

Microbial cell factories (MCFs) enable the conversion of non-food renewable biomass into diverse high-value chemicals and materials, broadly classified into four categories based on chemical properties and applications: biofuels and platform chemicals, biopolymers and bioplastics, terpenoids and aromatics, and protein-based materials[36]. Table 1 provides an overview of representative microbial products derived from non-food biomass. These products are economically significant and crucial for advancing the circular bioeconomy and reducing dependence on fossil resources. Their production complexity, technological maturity, and market readiness vary across categories. In addition to technological development, techno-economic analysis (TEA) and life-cycle assessment (LCA) are essential for evaluating the industrial feasibility and environmental sustainability of microbial production of value-added chemicals and materials.

Table 1. Overview of Microbial Products

Category	Main Products	Applications	Key Challenges
Biofuels & Chemicals	Ethanol, Butanol, Organic acids	Fuels, chemicals	Inhibitors, cost
Biopolymers	PHA, PLA, Cellulose derivatives	Packaging, medical	High cost, process complexity
Terpenoids & Aromatics	Limonene, β-carotene	Fragrances, pharmaceuticals	Pathway complexity, toxicity
Protein Materials	Microbial proteins, composites	Food, biomedical	Fermentation optimization

4.1 Biofuels and platform chemicals

Biofuels and platform chemicals are core biorefinery products with broad applications and market potential. Biofuels reduce greenhouse gas emissions, while platform chemicals serve as precursors for high-value products in chemicals, pharmaceuticals, and materials. Key products include ethanol, butanol, and organic acids, which benefit from relatively mature technologies and scalable processes[36].

4.1.1 Ethanol

Bioethanol is the most commercially established biofuel, primarily used as a fuel additive and industrial solvent. Although production processes are mature, pretreatment and enzymatic hydrolysis account for approximately 20% of total production costs[37]. Current research focuses on improving the economic feasibility of lignocellulosic ethanol by enhancing strain tolerance and mitigating byproduct and inhibitor effects.

Yang et al.[38] engineered *S. cerevisiae* (GPD2Δ FPS1Δ ADH2Δ DLD3Δ), achieving an 18.6% increase in ethanol yield relative to wild-type while reducing glycerol formation. Tsegaye et al.[39] engineered S. cerevisiae by overexpressing TrRCC1, resulting in enhanced thermotolerance and a 21.8% increase in ethanol production during simultaneous saccharification and fermentation of corn stover, with ethanol concentration reaching 44.1 g/L. Khamwachirapithak et al.[40] applied a machine learning–based approach to optimize the promoter activities of three endogenous genes, optimizing bioethanol production in S. cerevisiae by 7.4% at 40°C.

4.1.2 Butanol

Biobutanol has high energy density, low vapor pressure, and good gasoline miscibility, allowing direct use in conventional engines. Its production is more complex than ethanol, requiring strict anaerobic conditions and sophisticated separation, which increases costs. Current efforts focus on high-yield strain development and process optimization.

Kumar et al.[41] developed a consolidated bioprocessing strategy using clostridial co-cultures to enhance biobutanol production through acetone-butanol-ethanol (ABE) fermentation, 22% and 61% more than individual fermentations with *C. acetobutylicum* (Cac) and *C. pasteurianum* (Cpa) grown on pure glucose. Massadeh et al.[42] achieved a maximum butanol concentration of 18.35 g/L and a total solvent concentration of 34.85 g/L under continuous operation. Oehlenschläger et al.[43] concluded that co-cultivation and bioelectrochemical systems could tap the potential of *C. acetobutylicum* to contribute to a bio-based economy.

4.1.3 Organic acids

Organic acids, including succinic, lactic, citric, and itaconic acids, are vital platform chemicals for food, pharmaceuticals, and polymer synthesis. While production technologies are mature, hydrolysate-derived inhibitors remain a challenge. Research focuses on inhibitor-tolerant strains and continuous fermentation to improve lignocellulosic conversion efficiency.

Lee et al.[44] demonstrated that *A. succinogenes* can ferment Napier grass hydrolysate to produce succinic acid with a yield of approximately 0.58 g/g of substrate consumed under optimized conditions. Casella et al.[45] investigated the effects of lignocellulosic hydrolysate-derived inhibitors (acetic acid and furfural) on succinic acid production by *A. succinogenes* and highlighted that a higher initial inoculum concentration can mitigate the synergistic inhibitory effects of these compounds on fermentation performance; this suggests strategies to improve succinic acid yields from inhibitor-rich biomass hydrolysates. Zheng et al.[46] implemented a batch culture process using *A. succinogenes* CGMCC 1593, producing 37 g/L succinic acid within 48 h at 129% of theoretical yield, demonstrating the efficiency of continuous operation.

4.2 Biopolymers and bioplastics

Biopolymers and bioplastics replace petroleum-based plastics in packaging, medical, and agricultural applications. They offer biodegradability and biocompatibility, mitigating “white pollution.” Major products include polyhydroxyalkanoates (PHA), polylactic acid (PLA), and cellulose derivatives.

4.2.1 Polyhydroxyalkanoates (PHA)

Polyhydroxyalkanoates (PHA) are microbially synthesized biodegradable polyesters with excellent mechanical properties and biocompatibility, enabling industrial-scale applications. Production involves strain screening, fermentation optimization, and product extraction, resulting in costs that remain 2–3 times higher than petroleum-based plastics[47]. High-molecular-weight PHA synthesis requires precise metabolic and process control beyond inhibitor tolerance.

Recent technological breakthroughs have demonstrated substantial improvements in PHA production. For example, Hathi et al.[48] developed a fed-batch fermentation strategy using food waste hydrolysate with *Cupriavidus necator* to produce poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), achieving a PHBV titer of 5.32 g/L with a high 50% molar 3-hydroxyvalerate (3HV) content, which significantly enhances polymer flexibility and material performance. In another representative advance, Kamasaka et al. [50] implemented real-time monitoring of *C. necator* growth and PHA synthesis; by controlling dissolved oxygen and feeding rate, the production cycle was shortened from 72 to 48 h, leading to a 37% increase in productivity. These studies highlight how integrated strain engineering and process optimization can markedly improve PHA yield and industrial feasibility.

Senila et al.[49] reported efficient production of poly(3-hydroxybutyrate) (PHB) from hydrolysates of delignified lignocellulosic biomass using *Bacillus megaterium* ATCC 14581. Although enzymatic hydrolysis achieved a 91.4% sugar yield, this value reflects biomass saccharification efficiency rather than final PHB fermentation yield.

4.2.2 Polylactic Acid (PLA)

PLA is a biodegradable aliphatic polyester used in packaging, medical implants, 3D printing, and textiles. Production involves microbial fermentation and chemical polymerization. Fermentation requires strict optical purity control, while polymerization demands high temperatures and catalysts.

Deng et al.[51] developed a fed-batch simultaneous saccharification and fermentation (SSF) strategy for L-lactic acid production from steam-exploded corn stover under unsterilized and non-detoxified conditions, achieving a high titer of 153.8 g/L L-lactic acid with a productivity of 1.83 g/(L·h) in a 5 L bioreactor. Kuo et al.[52] employed a D-lactate dehydrogenase gene-deficient L. paracasei 7BL strain for direct fermentation of non-detoxified lignocellulosic hydrolysate, producing 99 g/L L-lactic acid with a high yield of 0.96 g/g.

4.2.3 Cellulose derivatives

Cellulose derivatives, including nanocellulose, bacterial cellulose, and cellulose esters, possess excellent mechanical properties, biocompatibility, and functionalization potential, with applications in biomedical materials, electronics, packaging, and composites. Production complexity varies: bacterial cellulose is relatively mature but low-yielding; nanocellulose requires complex physicochemical treatments.

Li et al.[53] demonstrated that co-culturing *B. cereus* with *Komagataeibacter xylinus* in corn stover enzymatic hydrolysate significantly enhanced bacterial cellulose production, increasing the yield from 1.2 g/L to 4.4 g/L. Sharma et al.[54] developed a cost-effective production system for bacterial cellulose using *Gluconacetobacter* on rice straw hydrolysate through response surface optimization, achieving approximately 7.17 g/L bacterial cellulose under optimized conditions, with its basic physicochemical properties retained.

4.3 Terpenoids and aromatics

Terpenoids and aromatics are high-value fine chemicals used in fragrances, pharmaceuticals, cosmetics, biofuels, and functional materials. Production is complex, requiring multi-step enzymatic reactions and precise metabolic regulation. Product toxicity and separation costs limit high-concentration fermentation[55].

Muñoz-Fernández et al.[56] introduced a limonene synthase gene into *A. gossypii*, producing (S)-limonene at 1.85 g/L from lignocellulosic hydrolysate. Zhao et al.[57] engineered *S. cerevisiae* by combining overexpression of sterol ester synthesis genes ARE1 and ARE2 with deletion of phosphatidate phosphatase (PAP) genes, resulting in a 2.4-fold improvement in β-carotene production compared with the starting strain.

4.4 Protein-based materials

Protein-based materials exhibit biocompatibility, degradability, and functional diversity, suitable for food, feed, biomedical applications, and sustainable textiles. Production focuses on strain selection and fermentation optimization to establish sustainable systems independent of traditional agriculture.

Ayodele et al.[58] utilized nitrogen-fixing *K. oxytoca* M5A1 with lignocellulosic biomass in solid-state fermentation, producing 38.5 g/L protein with 65% protein content in cell dry weight, eliminating external nitrogen supplementation. Shishparenok et al.[59] developed bacterial cellulose–protein composites by producing bacterial cellulose with *K. xylinus* in lignocellulosic hydrolysate and integrating functional proteins via in situ biosynthesis, yielding a material with 48 MPa tensile strength and bioactivity suitable for wound dressing and tissue engineering.

4.5 Technological landscape and industrial relevance

Microbial platforms for converting non-food renewable biomass into value-added chemicals and materials exhibit different levels of technological maturity. Biofuels and organic acids represent the most industrially established products, whereas biopolymers such as PHA and PLA are approaching commercial-scale production. In contrast, terpenoids, aromatics, and protein-based materials, although highly valuable, remain at an early development stage due to complex biosynthetic pathways, product toxicity, and high production and downstream processing costs. Across all product categories, inhibitor tolerance, substrate conversion efficiency, and process economics remain key bottlenecks.

Computer-assisted design, particularly artificial intelligence (AI)-driven approaches, is increasingly employed to accelerate strain engineering, optimize metabolic pathways, and improve fermentation performance. AI-assisted tools enable data-driven optimization of microbial cell factories, enhancing consolidated bioprocessing and full-component biomass valorization (Figure 2).

Beyond technical advances, techno-economic analysis (TEA) and life-cycle assessment (LCA) are essential for evaluating the industrial feasibility and environmental sustainability of biomass-based biorefineries. Integrating TEA and LCA frameworks with synthetic biology and process engineering can guide strain design, process optimization, and scale-up strategies toward economically viable and low-carbon biomanufacturing. Such integrated assessments will be critical for translating laboratory-scale innovations into commercially competitive and sustainable bio-based production systems.

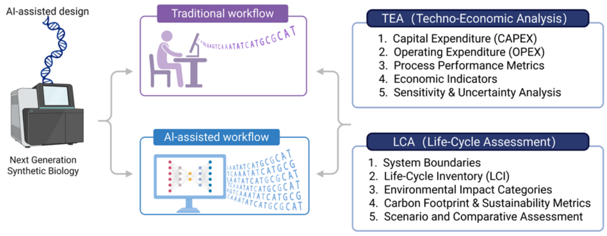

Figure 2. Integrated AI-driven synthetic biology, techno-economic analysis (TEA), and life-cycle assessment (LCA) framework for sustainable microbial biomanufacturing. The figure was created with BioRender.

5 Conclusion

The microbial conversion of non-food renewable biomass into high-value chemicals and materials has reached a critical stage, transitioning from laboratory-scale demonstrations to industrially relevant applications. Biofuels, including ethanol and butanol, and organic acids represent the most mature and scalable platforms, whereas biopolymers such as polyhydroxyalkanoates (PHA) and polylactic acid (PLA) are approaching commercial viability. High-value products such as terpenoids, aromatics, and protein-based materials, while promising, remain constrained by complex metabolic pathways, product toxicity, and high production costs. Across all product classes, common challenges include inhibitory compounds generated during lignocellulosic pretreatment, limited substrate conversion efficiency, and insufficient process integration.

Future research should prioritize the development of next-generation microbial chassis with enhanced stress tolerance, expanded substrate utilization, optimized redox balance, and robust metabolic capacity. Synthetic biology–driven strategies—including rational pathway design, CRISPR-based genome editing, and AI-assisted metabolic optimization—are essential for constructing high-performing microbial cell factories. In particular, AI and machine learning approaches can accelerate strain design by predicting the effects of multi-gene edits on metabolic fluxes, identifying optimal enzyme combinations, simulating metabolic network behavior under variable fermentation conditions, and optimizing feeding strategies in real time. AI can also guide the design of adaptive co-culture systems, model dynamic interactions between strains, and propose strategies for minimizing byproduct formation and maximizing target product yields.

Multi-component synergistic conversion and microbial co-culture systems offer promising approaches for valorizing all biomass fractions, particularly recalcitrant lignin, while dynamic regulation systems—such as metabolite-responsive genetic circuits integrated with AI-driven feedback control—can facilitate spatiotemporal coordination of metabolic fluxes, improve productivity, and enable automated, data-driven biomanufacturing. By integrating real-time sensor data with predictive AI models, fermentation parameters can be dynamically adjusted to maintain optimal conditions for microbial growth and product synthesis, reducing process variability and enhancing overall efficiency.

Integrating these AI-assisted strategies will accelerate the development of consolidated bioprocessing platforms, maximize biomass utilization, reduce production costs, and enhance the economic feasibility of bio-based products. Furthermore, integrating techno-economic analysis (TEA) and life-cycle assessment (LCA) frameworks will be essential for guiding industrial scale-up, cost optimization, and environmental impact mitigation of bio-based production systems. Beyond technological innovation, microbial biomass valorization contributes directly to carbon emission mitigation, circular bioeconomy development, and sustainable industrial ecosystems. With continued interdisciplinary collaboration and the convergence of synthetic biology, systems biology, and computational intelligence, microbial conversion of non-food biomass is poised to become a cornerstone of green biomanufacturing, providing critical technological support for sustainable resource utilization and global carbon neutrality goals.

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