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Microbial Cell Factory Engineering for Scalable Production of Bio-Commodities: Emphasis on Robustness

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Abstract

Microbial cell factories have emerged as sustainable platforms for producing bio-commodities such as biofuels, bioplastics, and pharmaceuticals. However, achieving industrial scalability remains hindered by challenges in strain robustness, including genetic instability, metabolic burden, and environmental stress tolerance. This review explores cutting-edge strategies in microbial engineering to enhance robustness, focusing on synthetic biology tools, adaptive laboratory evolution (ALE), and systems biology approaches. We discuss advances in genome-scale modeling, microbial consortia design, and resilience engineering to optimize performance in large-scale bioreactors. Case studies highlight successful applications of E. coli, S. cerevisiae, and cyanobacteria for producing compounds like polyhydroxyalkanoates (PHAs) and isoprenoids. By integrating computational predictions with experimental validation, this review underscores the importance of robustness as a cornerstone for economically viable biomanufacturing. Finally, we propose a roadmap for bridging lab-scale innovations to industrial deployment, emphasizing the synergy between metabolic flexibility and process engineering.

Keywords: Microbial cell factories, Synthetic biology, Metabolic engineering, Strain robustness, Adaptive laboratory evolution, Scalable biomanufacturing

Introduction

For over a century, fossil-based petrochemical processes have supported chemical production, but overreliance has caused pollution, climate change, and resource depletion. To address these issues, sustainable alternatives are essential (Chandrasekhar *et al*., 2022; Dattatraya Saratale *et al*., 2022; Dehaghi *et al*., 2022; Oran *et al*., 2022; Nastro *et al*., 2025). Engineered microbial cell factories offer a promising solution by converting renewable resources like non-edible biomass or CO_2 into valuable chemicals (Ashkevari *et al*., 2023; Krishnamoorthy *et al*., 2024; Singh *et al*., 2025). Fermentative production using these systems is emerging as a viable, eco-friendly replacement for traditional methods, supporting a shift toward greener industrial practices.

Fermentative production using these systems is emerging as a viable, eco-friendly replacement for traditional methods, supporting a shift toward greener industrial practices. The global shift toward sustainable production has positioned microbial cell factories as pivotal tools for synthesizing bio-commodities, reducing reliance on fossil fuels, and mitigating climate change (Cho *et al*., 2022; Tural & Şahan, 2023; Ha *et al*., 2024). Microbes such as Escherichia coli, Saccharomyces cerevisiae, and Synechocystis spp. are engineered to produce biofuels, bioplastics, and high-value chemicals through tailored metabolic pathways. Despite breakthroughs in pathway design, scalability remains a critical bottleneck, with fewer than 20% of lab-engineered strains transitioning to industrial use (Lee *et al*., 2019; Hoang *et al*., 2022; Tam *et al*., 2022; Son *et al*., 2023; Linh *et al*., 2024). A key limitation lies in microbial robustness, the ability to maintain productivity under dynamic industrial conditions, such as substrate variability, shear stress, and inhibitory byproducts.

Recent advances in genetic and metabolic engineering have enhanced microbial cell factories (MCFs) for producing bio-commodities from renewable feedstocks, yet challenges persist in pathway optimization and strain development. Retrobiosynthetic tools enable single-step reaction prediction, but de novo pathway design remains constrained by thermodynamic feasibility, metabolite toxicity, and economic viability (Saliev *et al*., 2024; Winnifrith *et al*., 2024; Abbas *et al*., 2025). Efficient enzyme deployment is critical for channeling metabolic flux toward target products, necessitating activity optimization, solubility, and cofactor compatibility in host organisms (Abdel-Hadi & Abdel-Fattah, 2022; Chaudhary *et al*., 2024; Gondo & Haryanti, 2024; Zharashueva *et al*., 2024). Balancing substrate specificity with catalytic promiscuity through rational enzyme engineering guided by AI-driven protein design tools like AlphaFold can expand pathway possibilities by creating non-natural enzymes with tailored functions. Non-model microorganisms offer untapped

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potential for biocommodity synthesis but face limitations in genetic tractability and synthetic biology toolkits (Perwitasari *et al*., 2023; Jung *et al*., 2024; Levochkina *et al*., 2024; Molas-Tuneu *et al*., 2024). Recent efforts to engineer Rhodococcus and Clostridium strains highlight progress in chassis development, yet metabolic network complexity and regulatory heterogeneity hinder predictable engineering. Integrating multi-omics data with machine learning can accelerate host selection and pathway debugging, particularly for anaerobic or extremophilic species with niche biochemical capabilities. Strategic priorities include (i) expanding enzyme sequence databases for AI-driven design, (ii) standardizing genetic parts for non-model hosts, and (iii) deploying adaptive laboratory evolution to resolve metabolic bottlenecks. Collaborative frameworks linking computational predictions, high-throughput screening, and techno-economic analysis will be essential for scaling sustainable bioproduction (Alqara *et al*., 2024; Jung *et al*., 2024).

Optimizing carbon utilization pathways in microbial cell factories (MCFs) is critical for achieving carbon-neutral bioproduction. Current research prioritizes engineering modular metabolic networks to valorize non-conventional feedstocks, including CO_2, methane, syngas, and food waste through synthetic autotrophy and mixotrophic systems. For instance, E. coli has been reprogrammed for CO_2 fixation via the crotonyl-coenzyme A (CoA)/ethylmalonyl-CoA/hydroxybutyryl-CoA (CETCH) cycle and formate assimilation, demonstrating scalable carbon-negative platforms (Guan *et al*., 2024; Upchezhokov *et al*., 2024; Winnifrith *et al*., 2024). However, maximizing yield-to-cost ratios for these substrates requires iterative pathway refinement using computational tools like flux balance analysis and machine learning. Parallel efforts by global biofoundries, such as the Global Biofoundry Alliance, aim to standardize automated workflows for high-throughput strain development, bridging lab-scale innovations to industrial applications (Sindhu *et al*., 2023; Jung *et al*., 2024) **(Figure 1)**. Despite progress, commercialization remains limited by metabolic inefficiencies and substrate heterogeneity. Academia-industry partnerships must prioritize scalable bioprocess integration and sustainability metrics like techno-economic viability and lifecycle assessments to ensure market feasibility (Bahamid *et al*., 2022; Chaudhary *et al*., 2024). MCFs engineered for substrate flexibility and pathway modularity hold promise for producing high-value bio-commodities, including nutraceuticals, biopharmaceuticals, and biofuels, while advancing circular bioeconomy goals (Shi *et al*., 2023; Odeh *et al*., 2024).

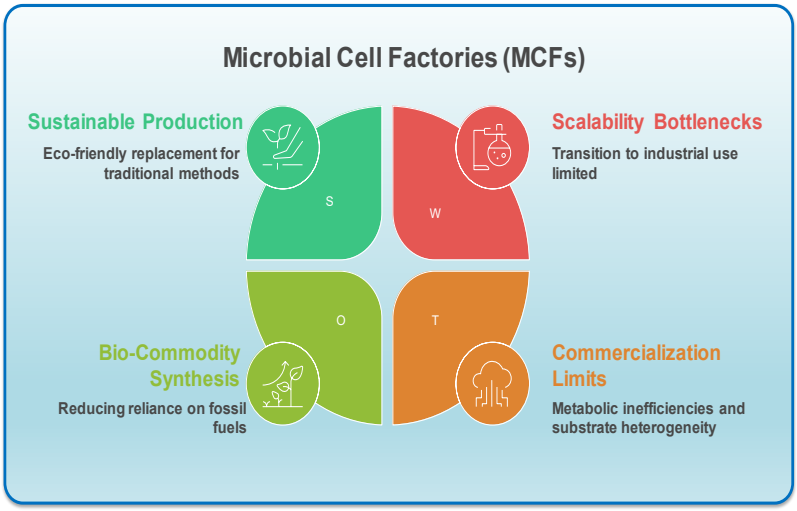

Figure 1. Key concepts of Microbial cell factories (MCFs).

MCFs are emerging as sustainable alternatives to fossil- or organism-derived bio-commodities, driven by decarbonization imperatives and petroleum resource volatility (Roy *et al*., 2016; Kumar *et al*., 2018; Chandrasekhar *et al*., 2021; İlaslan *et al*., 2023). Microbial biosynthesis leverages fermentative platforms to produce proteins, primary metabolites, and specialized compounds with lower toxicity, cost, and environmental impact than conventional methods (Makhoahle & Gaseitsiwe, 2022; Veerapandian *et al*., 2025). MCFs utilize three pathway archetypes: (i) native pathways amplified via metabolic engineering, (ii) non-native pathways transplanted from phylogenetically related species, and (iii) de novo synthetic routes designed using retrosynthetic algorithms. Strain optimization enhances robustness through transcriptional regulation, membrane transporter engineering, stress protein overexpression, and adaptive laboratory evolution (ALE), supported by machine learning-guided genome-scale metabolic models to predict flux bottlenecks (Abozor *et al*., 2022; Nastro *et al*., 2025). Industrial deployment requires chassis strains with high substrate-to-product conversion efficiency, exemplified by E. coli and S. cerevisiae engineered for amino acids, carboxylic acids, and carotenoids. Heterologous expression of plant natural products (PNPs) such as terpenoids and flavonoids demands precise compartmentalization of cytochrome P450 enzymes and precursor balancing (Akbari, 2022; Asar *et al*., 2023; Jung *et al*., 2024). While microbial synthesis of flavors/fragrances (e.g., vanillin, nootkatone) achieves gram-scale yields, commercial viability hinges on dynamic pathway regulation and cofactor recycling.

This article presents a comprehensive overview of strategies for producing valuable bio-products using microorganisms as

biofactories, including compounds naturally synthesized by host cells. It discusses approaches for utilizing non-native microorganisms with desirable traits and highlights three key biosynthetic pathways in MCF design: native, non-native, and heterologous de novo routes. The article further explores MCF construction, microbial strain selection, and large-scale industrial applications. Strategies to enhance microbial robustness, including transcription factor regulation, membrane transport engineering, stress protein expression, adaptive laboratory evolution, and computational design, are also reviewed. Additionally, the article briefly discusses the microbial production of amino acids, carboxylic acids, carotenoids, flavors, fragrances, and plant natural products (PNPs), emphasizing the versatility of microbial platforms in sustainable biomanufacturing.

Biodiversity of Microbial Cell Factories

MCFs are widely used for converting substrates into value-added products, including native metabolites, heterologous compounds, and recombinant proteins. Microorganisms naturally express diverse metabolic pathways, enabling the synthesis of numerous industrially relevant chemicals. For centuries, lactic acid bacteria (LAB) and baker's yeast have been central to fermented foods and beverages (Navarrete *et al*., 2020; Liu *et al*., 2022; Özatik *et al*., 2022; Belfiore *et al*., 2024). Though only ~104 bacterial species have been cultured, microbial biodiversity remains largely untapped, offering the potential for novel product discovery and yield improvement (Thazha *et al*., 2023; Chaudhary *et al*., 2024). LAB genera such as Lactobacillus Sp., Lactococcus Sp., Streptococcus Sp., and Leuconostoc Sp. Produce a variety of compounds, including lactic acid, bioactive peptides, vitamins, γ-aminobutyric acid (GABA), and organic acids like acetic and butyric acid. Yeasts contribute to food and beverage fermentation and flavor development, including Saccharomyces cerevisiae, Candida, Kluyveromyces, and Yarrowia. Fungi such as Aspergillus niger, A. oryzae, and A. aculeatus are also significant in producing organic acids and enzymes such as citric acid, Amylase, Lipase, Protease, etc. (Navarrete *et al*., 2020; Petrova & Petrov, 2020; Graefen *et al*., 2023; Petronis *et al*., 2023; Figueroa-Valverde *et al*., 2024). Recent advances in metabolic engineering and synthetic biology have enabled the production of valuable compounds from non-native microbes. For instance, engineered Saccharomyces cerevisiae strains produce an anti-malaria drug called artemisinin and an artificial sweetener, stevia, while Pichia pastoris is used for insulin synthesis. These developments highlight the versatility and promise of engineered MCFs for sustainable biomanufacturing across multiple industries.

Designing Microbial Cell Factories

MCFs offer a sustainable and economical approach to producing valuable biochemicals using inexpensive, renewable feedstocks. These eco-friendly systems are ethically sound and easily cultured in fermenters, making them ideal for bio-based production. According to Market Research Future, the global bio-based chemicals market is projected to reach USD 163.92 billion by 2030, growing at a CAGR of 8.30% (Mickevičius *et al*., 2023; Chaudhary *et al*., 2024; Kwatra *et al*., 2024). Various microorganisms such as E. coli, Bacillus subtilis, lactic acid bacteria, Saccharomyces cerevisiae, and Aspergillus niger are widely used to synthesize products like amino acids, vitamins, enzymes, bioethanol, and proteins (Patra *et al*., 2021; Soman *et al*., 2024). Recent advancements have significantly expanded this field, leveraging tools such as genome sequencing, metabolic modeling, gene expression profiling, omics technologies, and metabolic engineering. Metabolic engineering modifies cellular metabolism to enhance the production of native or novel compounds. Traditional methods include removing metabolic bottlenecks, altering pathways, and optimizing ATP and redox balances to redirect metabolic flux (Lee *et al*., 2019; AlYousef *et al*., 2022; Chaudhary *et al*., 2024). However, industrial-scale implementation faces challenges such as toxic byproduct accumulation, low pH, and temperature extremes, often resulting in reduced productivity compared to lab-scale processes.

To overcome these limitations, systems metabolic engineering integrates classical metabolic engineering with synthetic biology, systems biology, and evolutionary strategies. This approach enables the development of high-performance microbial strains to produce biofuels, fine chemicals, natural products, and polymers (Rangel *et al*., 2020; Padma *et al*., 2023). The design of an MCF begins with selecting a target product and a suitable carbon feedstock. Market demand and substrate economics must be carefully assessed, including composition, availability, seasonal variation, and transport cost. Low-cost, consistently available substrates are ideal. Next, the appropriate host strain and biosynthetic pathway are chosen, followed by strain engineering and optimization to improve yield and performance (Rangel *et al*., 2020; Najjar, 2023). This integrated, systems-based approach is driving the evolution of microbial platforms into efficient and scalable tools for industrial biotechnology. Over the past five years, research and development have intensified in producing valuable bio-commodities using MCFs (Jung *et al*., 2024). Most studies focus on designing MCFs by exploring individual microbial hosts and applying systematic metabolic engineering approaches (Ko *et al*., 2020; Gurubasajar *et al*., 2023). This includes developing new biosynthetic routes, constructing novel pathways, and optimizing MCFs for efficient biochemical production. **Figure 2** outlines the key design principles for pathway construction. Additionally, recent case studies highlight successful strategies for engineering microbial hosts to synthesize target biomolecules. Looking ahead, this work will address current challenges and offer insights into advancing sustainable, eco-friendly chemical manufacturing through MCFs (Choi *et al*., 2019).

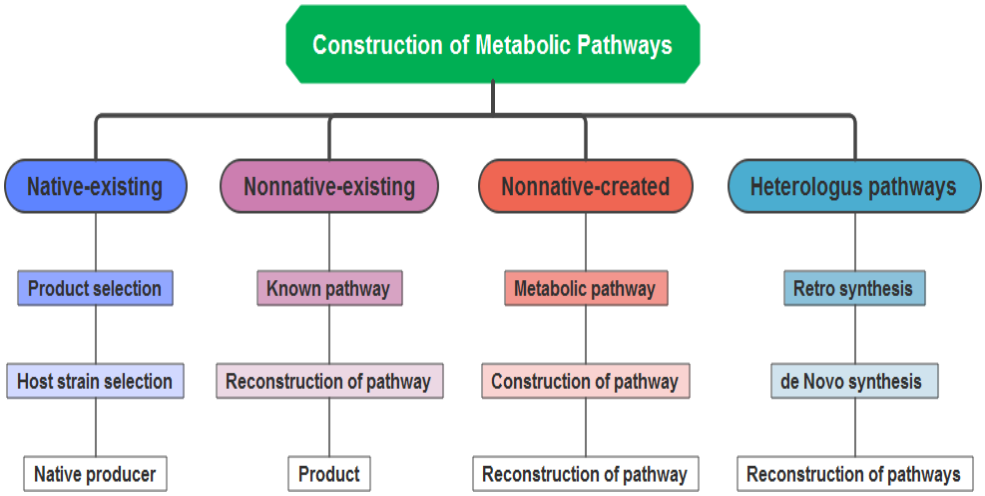

Figure 2. Flowchart illustrating the systematic design of metabolic pathways in a selected host strain for microbial cell factory development.

Scalable Bio-Product Manufacturing Using Engineered Microbial Cell Factories

The global shift towards sustainability has prompted the search for alternative production methods that minimize environmental impact. Engineered microbial cell factories are at the forefront of this movement, offering a versatile platform for the biosynthesis of valuable compounds (Roy *et al*., 2022; Chaudhary *et al*., 2024; Ranjel *et al*., 2025). These microorganisms can be genetically modified to enhance their metabolic pathways, allowing them to convert renewable resources into bio-products efficiently. There were three key methodologies: synthetic biology, metabolic engineering, and fermentation technology **(Figure 3)**.

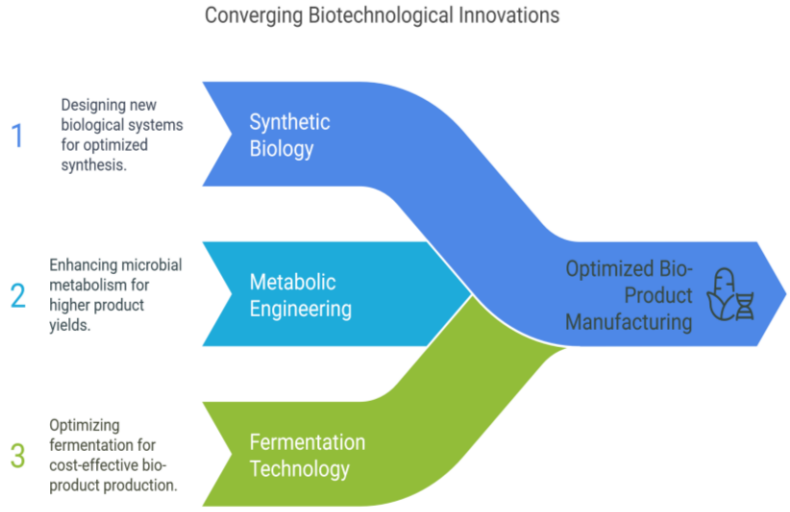

Figure 3. Converging Biotechnological innovations.

Synthetic Biology: This field combines biology and engineering principles to design and construct new biological parts, devices, and systems. By applying synthetic biology techniques, researchers can create microbial strains with optimized metabolic pathways for specific bio-product synthesis. Metabolic Engineering: It is a multidisciplinary field that emphasizes the optimization of MCFs to enhance the production of value-added compounds. This is achieved through the strategic manipulation of metabolic pathways, employing various genetic and computational strategies. Below is an expanded discussion of key metabolic engineering strategies, incorporating recent research findings and references. This involves the modification of microbial metabolism to increase the yield of desired products. Techniques such as gene editing (e.g., CRISPR-Cas9) and pathway optimization are employed to enhance the efficiency of microbial cell factories. Recent advancements have focused on optimizing the expression of introduced pathways to enhance product yields. For instance, a study by Zhang *et al*. (2022) demonstrated the de novo biosynthesis of α-aminoadipate in E. coli through multi-strategy metabolic engineering, which included the introduction of heterologous pathways **(Figure 4)**.

Fermentation Technology: Scalable fermentation processes are crucial for the industrial application of engineered microbes. Optimizing fermentation conditions, such as pH, temperature, and nutrient availability, can significantly impact the productivity and cost-effectiveness of bio-product manufacturing.

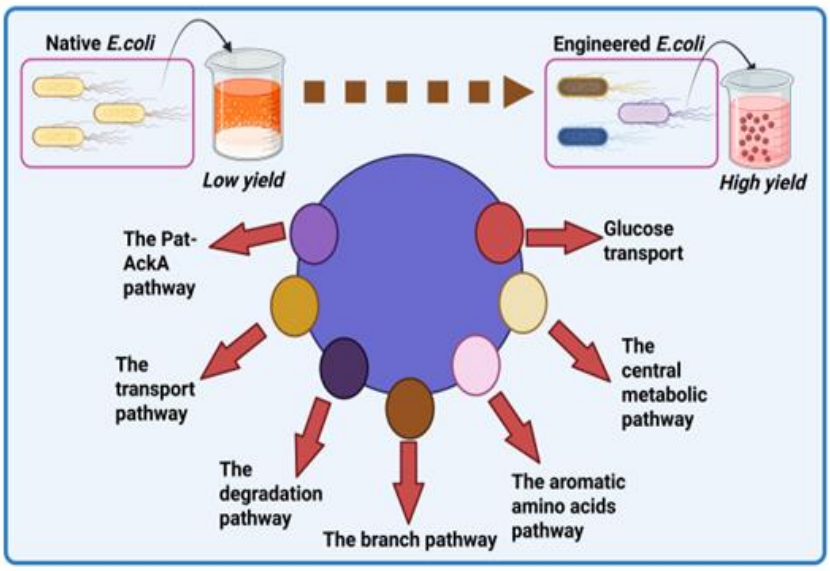

Figure 4. Schematic illustration of metabolic engineering strategies in engineered E. coli.

Advanced Microbial Cell Factory Platforms for Industrial Biosynthesis of High-Value Bio-Products

In the last decade, MCFs have emerged as a powerful tool that has the ability to address increasing demands for sustainable industrial production. In recent years, scientists have designed and developed microbial systems that can produce high-value industrially significant products by coupling the natural metabolic abilities of microbes and improving them through genetic engineering (Jung *et al*., 2024). This development has moved MCFs from academic research (lab-scale production) into industrial applications (large-scale production), making them economically sustainable methods for industries (Al Hemaidi, 2024; Das *et al*., 2024). One of the significant roles of MCF technology is in producing complex natural products. One such example is the production of artemisinic acid in engineered yeast strains, which is a precursor molecule of the antimalarial drug artemisinin. Investigators have developed effective fermentation techniques that are competitive with conventional extraction techniques in terms of efficiency as well as expense by engineering microbial hosts, for instance, Saccharomyces cerevisiae or E. coli, to trigger biosynthetic pathways (Ding & Ye, 2023). This example reveals how the MCFs fill the gap between academic research and industrial scalability.

These improvements have been enhanced by the capacity to regulate how microbes function in biosynthesis platforms. Because of their accuracy, MCFs can produce a wide range of bio-commodities, such as Acetic acid, succinic acid, polyhydroxyalkanoates (PHAs), ethanol, and biodiesel. MCFs can now produce even specialized compounds, such as natural perfumes like vanillin or anticancer drugs like Taxol (Bergeron *et al*., 2024; Jung *et al*., 2024). The secret is synthetic biology and metabolic engineering, which allow researchers to create and introduce alien or completely artificial metabolic pathways into resilient microbial hosts. MCF-derived products presently operate across numerous industries **(Figure 5)**. The amino acids (both essential and non-essential) are a vital component of the industry as the building blocks of proteins. The Corynebacterium glutamicum strains can generate hundreds of tons of lysine per year for use in animal feed. Renewable bioenergy has been a top priority recently, with algae and yeast strains designed to transform plant biomass (lignocellulosic biomass) into ethanol or butanol (Nidheesh *et al*., 2022; Singh *et al*., 2022; Naseri *et al*., 2024). Engineered Aspergillus niger produces organic acids (such as citric acid) on a large scale, which is widely utilized in the preservation of foods and medicines (Chaudhary *et al*., 2024). Further, terpenoids, a broad group of chemicals discovered in essential oils and medications, represent another frontier. MCFs may create complex terpenes such as steviol glycosides (natural sweeteners) and artemisinic acid, overcoming the constraints of plant-based extraction. MCF technology's commercial potential is growing as it develops. Industries are spending money on modular biorefineries that can quickly adjust to market demands by repurposing microbial strains for various products (Chaudhary *et al*., 2024). In the meantime, collaborations between industry and academia increase strain durability and reduce production costs. Issues remain to be resolved, such as maximizing productivity and reducing waste in large-scale fermentation, but continuous advancements in automation and systems biology hold promise.

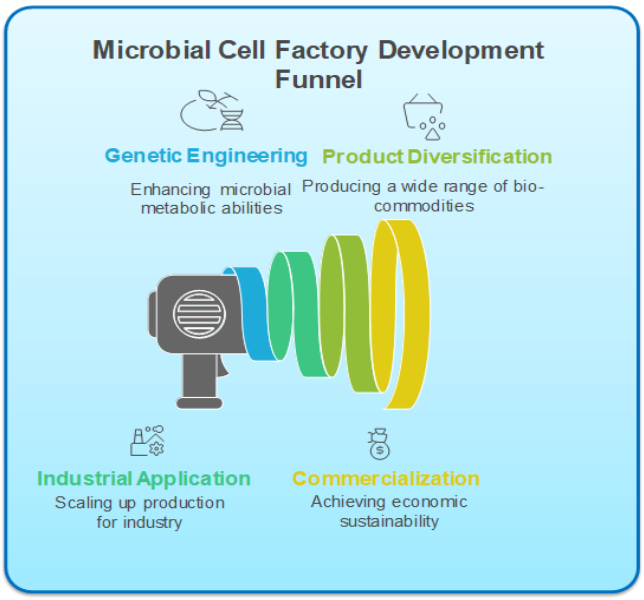

Figure 5. Microbial cell factory development funnels.

Metabolic Modeling

Metabolic modeling, particularly through genome-scale metabolic models (GEMs), serves as a pivotal tool in understanding and optimizing microbial metabolism (Liu *et al*., 2019). GEMs provide a broad framework to simulate and envisage cellular behaviors, facilitating advancements in metabolic engineering, synthetic biology, and bioprocess optimization **(Figure 6)**.

Predicting Metabolic Flux Distributions

GEMs enable the prediction of intracellular flux distributions under various conditions, offering a vision into the metabolic state of a cell. By applying constraint-based optimization techniques like Flux Balance Analysis (FBA), researchers can identify rate-limiting steps and metabolic bottlenecks. For instance, studies have utilized GEMs to analyze the metabolic fluxes in E. coli under diverse growth conditions, revealing key pathways that influence biomass production and byproduct formation (Liu *et al*., 2019).

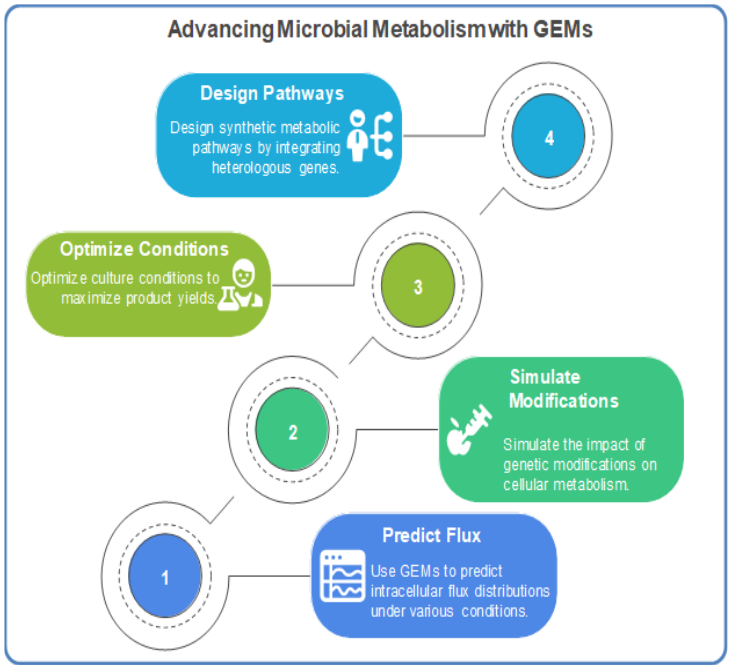

Figure 6. Advancing microbial metabolisms with GEMs

Simulating the Effects of Genetic Modifications

GEMs are instrumental in simulating the impact of genetic modifications, such as gene knockouts or overexpression, on cellular metabolism. By modifying the stoichiometric matrix to reflect these genetic changes, researchers can predict alterations in flux distributions and product yields. This approach aids in designing strains with optimized metabolic pathways for enhanced production of desired compounds (Kondo *et al*., 2013).

Optimizing Culture Conditions

Beyond genetic modifications, GEMs assist in optimizing culture conditions to maximize product yields. By integrating GEMs with process models, researchers can simulate various environmental factors, such as nutrient availability and pH levels, to determine optimal growth conditions. For example, studies have demonstrated the use of GEMs to optimize nutrient supply in algal cultures, leading to improved biomass and biofuel precursor production (Li *et al*., 2019).

Designing Synthetic Pathways

GEMs facilitate the design of synthetic metabolic pathways by integrating heterologous genes into the host organism's metabolic network. Through in silico simulations, researchers can assess the feasibility of novel pathways, predict potential bottlenecks, and optimize enzyme expression levels. This approach has been successfully applied in the engineering of microorganisms for the production of biofuels, pharmaceuticals, and specialty chemicals.

Product Recovery and Purification in Microbial Fermentation

Cell Separation

The initial step in downstream processing involves separating microbial cells from the fermentation broth. Common techniques include: (Gugel *et al*., 2025) (a). Centrifugation: Utilizes centrifugal force to sediment cells. It's effective but energy-intensive, and (b). Filtration: Employs membrane filters to separate cells based on size. Recent innovations have introduced mini-modules with built-in spacers for high-throughput ultrafiltration, improving mass transfer and permeation rates.

Cell Disruption

For intracellular products, cell disruption is necessary. Widely used cell disruption techniques are (a). Mechanical Disruption: Techniques like bead milling or high-pressure homogenization physically break open cells, and (b). Enzymatic Lysis: Utilizes specific enzymes to degrade cell walls, particularly in fungi or plants (Gugel *et al*., 2025). These methods are selected based on the cell wall composition and the desired product's sensitivity.

Extraction

To separate the product from the broth, two extraction techniques are widely used in industries. (a). Solvent Extraction: Involves partitioning the product into an organic solvent. Aqueous two-phase extraction (ATPE) has been explored for lactic acid recovery, achieving high purity levels. (b). Liquid-Liquid Extraction: Uses immiscible solvents to separate components. Advancements have led to more selective and efficient extraction processes (Gugel *et al*., 2025). These techniques are chosen based on the product's chemical properties and the broth's composition.

Chromatography

Chromatographic methods are employed for high-purity separation: (a). Affinity Chromatography: Utilizes specific interactions between the product and a ligand. Recent developments have introduced calcium-dependent affinity proteins for antibody purification, enhancing efficiency. (b). Ion Exchange Chromatography: Separates based on charge differences. It's widely used for proteins and nucleic acids. (c). Multicolumn Countercurrent Solvent Gradient Purification (MCSGP): A continuous chromatographic process that improves separation efficiency and reduces solvent consumption. These methods are integral for achieving the desired product purity.

Crystallization

For products that can form solid phases, widely used techniques are (a). Precipitation: Induces solid formation by changing solvent conditions, and (b). Crystallization: Forms pure solid crystals from a solution. It's particularly useful for high-value compounds like antibiotics. These techniques are selected based on the product's solubility and stability.

Conclusion

Designing microbial cell factories is a complex but rewarding endeavor that requires a deep understanding of various biological, chemical, and engineering principles. It begins with the careful selection of host strains that possess the necessary characteristics for efficient product production, such as high growth rates, the ability to tolerate environmental stress, or inherent pathways for producing valuable compounds. This is followed by metabolic engineering strategies, which involve the manipulation of microbial metabolic pathways to optimize the flow of metabolites towards the desired products. Through the targeted introduction, deletion, or overexpression of genes, metabolic engineers can enhance the productivity of the microorganism. Equally important is bioprocess optimization, which focuses on fine-tuning fermentation conditions, such as nutrient supply, pH, temperature, and oxygen levels, to maximize yield and minimize costs. Effective product recovery and purification methods must then be employed to isolate and purify the target product from the fermentation broth, ensuring high purity and minimizing downstream processing costs. The integration of these components—strain selection, metabolic engineering, bioprocess optimization, and product recovery—enables the development of highly efficient and sustainable microbial cell factories. As the field progresses, continued advancements in genetic engineering, such as CRISPR-Cas9 and synthetic biology, along with computational tools like metabolic modeling and high-throughput screening, will further enhance the capabilities of microbial cell factories, expanding the range of compounds they can produce and making biomanufacturing more economically viable and environmentally sustainable for the future.

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References

Abbas, I. K., Hareeja, M. M., Jaber, S. A., Qader, A. B., Mahal, R. K., Salih, O. S., & Hussein, A. A. (2025). Impact of preparation techniques on formulation and characterization of captopril effervescent granules. *Journal of Advanced Pharmacy Education and Research, 15*(2), 51–56. doi:10.51847/8aO2P1Lp5P

Abdel-Hadi, B., & Abdel-Fattah, S. R. (2022). Clinical pharmacist intervention in appendectomy - Dexmedetomidine as an adjunct therapy. *Journal of Advanced Pharmacy Education and Research, 12*(2), 1–5. doi:10.51847/AYOZXtLMrj

Abozor, B. M., & Abduljawad, A. A. (2022). Obesity and demographics influence on periapical lesions, dental caries, and oral health in adults. *Annals of Dental Specialty, 10*(3), 31–38. doi:10.51847/85ojmUYR3S

Akbari, M. (2022). Is there an alternative therapy for refractory vernal keratoconjunctivitis? *Journal of Advanced Pharmacy Education and Research, 12*(3), 54–58. doi:10.51847/LGMe2jFqWh

Al Hemaidi, S. S. (2024). Effectiveness of botulinum toxin (Botox) for treatment of nystagmus: a review. *World Journal of Environmental Biosciences, 13*(4), 14–17. doi:10.51847/kqbONHsU0o

Alqara, M. H., Alqara, A. H., & AlKhathlan, A. (2024). Recent advances in minimally invasive dentistry: a narrative review of the literature. *Annals of Dental Specialty, 12*(3), 28–33. doi:10.51847/GdqueflPmp

AlYousef, R. A., Abualnaja, A. A., AlNojaidi, J. H., AlDosari, Y. N., AlKhalaf, S. A., AlQahtani, N. J., AlDosari, D. A., AlKhalaf, A. A., & Alharbi, M. S. (2022). Lower back pain in athletes and non-athletes: a group comparison of risk factors and pain management. *World Journal of Environmental Biosciences, 11*(3), 36–44. doi:10.51847/kVriSL1OCS

Asar, M. E., Saleh, E., & Ghaneapur, M. (2023). Innovative and motivational SDT-based approach to promote Iranian women's physical activity. *Journal of Advanced Pharmacy Education and Research, 13*(1), 62–65. doi:10.51847/gcrJpRS1SU

Ashkevari, S. B., & Ghasemi, B. (2023). The impact of strategic leadership on organizational performance with regard to the role of organizational innovation. *Journal of Organizational Behavior Research, 8*(2), 40–53. doi:10.51847/vSDdNm6S8t

Bahamid, A. A., AlHudaithi, F. S., Aldawsari, A. N., Eyyd, A. K., Alsadhan, N. Y., & Alshahrani, F. A. M. (2022). Success of orthodontic space closure vs. implant in the management of missing first molar: Systematic review. *Annals of Dental Specialty, 10*(4), 9–14. doi:10.51847/jDPeo7jLvg

Belfiore, C. I., Galofaro, V., Cotroneo, D., Lopis, A., Tringali, I., Denaro, V., & Casu, M. (2024). Studying the effect of mindfulness, dissociative experiences, and feelings of loneliness in predicting the tendency to use substances in nurses. *Journal of Integrative Nursing and Palliative Care, 5*, 1–7. doi:10.51847/LASijYayRi

Bergeron, S., Boopathy, R., Nathaniel, R., Corbin, A., & LaFleur, G. (2024). A review of the reasons for increasing the presence of antibiotic-resistant bacteria presence in drinking water. *World Journal of Environmental Biosciences, 13*(2), 6–12. doi:10.51847/xXkJ6gfNwB

Chandrasekhar, K., Kumar, A. N., Raj, T., Kumar, G., & Kim, S. H. H. (2021). Bioelectrochemical system-mediated waste valorization. *Systems Microbiology and Biomanufacturing, 1*(4), 432–443. doi:10.1007/s43393-021-00039-7

Chandrasekhar, K., Raj, T., Ramanaiah, S. V. V., Kumar, G., Jeon, B. H. H., Jang, M., & Kim, S. H. H. (2022). Regulation and augmentation of anaerobic digestion processes via the use of bioelectrochemical systems. *Bioresource Technology, 346,* 126628. doi:10.1016/J.BIORTECH.2021.126628

Chaudhary, R., Nawaz, A., Fouillaud, M., Dufossé, L., Haq, I. U., & Mukhtar, H. (2024). Microbial cell factories: biodiversity, pathway construction, robustness, and industrial applicability. *Microbiology Research, 15*(1), 247–272. doi:10.3390/MICROBIOLRES15010018

Cho, J. S., Kim, G. B., Eun, H., Moon, C. W., & Lee, S. Y. (2022). Designing microbial cell factories for the production of chemicals. *JACS Au, 2*(9), 1781–1799. doi:10.1021/JACSAU.2C00344

Choi, K. R., Jang, W. D., Yang, D., Cho, J. S., Park, D., & Lee, S. Y. (2019). Systems metabolic engineering strategies: Integrating systems and synthetic biology with metabolic engineering. *Trends in Biotechnology, 37*(8), 817–837. doi:10.1016/J.TIBTECH.2019.01.003

Das, S., Sharma, K., Sharmmah, D., Sharma, S., Sevda, S., & Prabhu, A. A. (2024). Metabolic rewiring of microbial cell factories for improved production of succinic acid. *Biotechnology for Sustainable Materials, 11*(1), 1–21. doi:10.1186/S44316-024-00012-Z

Dattatraya Saratale, G., Rajesh Banu, J., Nastro, R. A., Kadier, A., Ashokkumar, V., Lay, C. H. H., Jung, J. H. H., Seung Shin, H., Ganesh Saratale, R., & Chandrasekhar, K. (2022). Bioelectrochemical systems in aid of sustainable biorefineries for the production of value-added products and resource recovery from wastewater: a critical review and future perspectives. *Bioresource Technology, 359,* 127435. doi:10.1016/j.biortech.2022.127435

Dehaghi, A. A., Dolatshahi, B., Taremian, F., Pourshahbaz, A., & Ansari, H. (2022). Acceptance and commitment therapy with Islamic aspects as a treatment for scrupulosity in a case study. *Journal of Organizational Behavior Research, 7*(2), 95–108. doi:10.51847/Fa3ED8HrzB

Ding, Q., & Ye, C. (2023). Microbial cell factories based on filamentous bacteria, yeasts, and fungi. *Microbial Cell Factories, 22*(1), 1–15. doi:10.1186/S12934-023-02025-1

Figueroa-Valverde, L., Marcela, R., Alvarez-Ramirez, M., Lopez-Ramos, M., Mateu-Armand, V., & Emilio, A. (2024). Statistical data from 1979 to 2022 on prostate cancer in populations of Northern and Central Mexico. *Bulletin of Pioneering Researches of Medical and Clinical Science, 3*(1), 24–30. doi:10.51847/snclnafVdg

Gondo, H. K., & Haryanti, E. (2024). Higher placental activin-a (ACV-A) and inhibin-A (INH-A) in the placenta of the mother compared to the placenta of a diabetic mother. *Journal of Advanced Pharmacy Education and Research, 14*(3), 15–17. doi:10.51847/QVCQHO6GxQ

Graefen, B., Hasanli, S., & Fazal, N. (2023). Behind the white coat: The prevalence of burnout among obstetrics and gynecology residents in Azerbaijan. *Bulletin of Pioneering Researches of Medical and Clinical Science, 2*(2), 1–7. doi:10.51847/vIIhM1UG2l

Guan, W., Li, L., Zhang, C., Zhang, D., Xing, Q., Guo, D., Hongbing, O., & Zhang, H. (2024). Enhancing carbon fixation and suppressing bacterial chemotaxis through carbon matrix nano-selenium to mitigate emissions of antibiotic resistance genes and virulence factors from chicken manure. *Chemical Engineering Journal, 483,* 149076. doi:10.1016/J.CEJ.2024.149076

Gugel, I., Marchetti, F., Costa, S., Baldini, E., Vertuani, S., & Manfredini, S. (2025). Efficient downstream processing of second-generation lactic acid from lignocellulosic waste using aqueous two-phase extraction. *Bioresources and Bioprocessing, 12*(1), 1–13. doi:10.1186/S40643-025-00847-Y

Gurubasajar, N., Subhakar, A., Dadayya, M., Veeranna, S. H., & Basaiah, T. (2023). Isolation, characterization, and quantification of polyhydroxybutyrate-producing bacteria *Achromobacter xylosoxidans* KUMBNGBT-63 from different agroresidues. *World Journal of Environmental Biosciences, 12*(2), 35–42. doi:10.51847/YmLaQtfbzH

Ha, H. D., & Hang, H. T. T. (2024). The impact of transformational leadership on employee performance in the Vietnamese banking industry. *Journal of Organizational Behavior Research, 9*(2), 12–27. doi:10.51847/8COZGxs9s6

Hoang, T. T. V., Nguyen, T. H., Nguyen, T. T. T., Hoang, L. P. T., Ho, T. T. T., Nguyen, T. H. T., & Nguyen, T. T. M. (2022). Research factors affecting students' academic results in learning project subjects oriented CDIO at Vinh University. *Journal of Organizational Behavior Research, 7*(1), 14–28. doi:10.51847/SntPtYuASo

İlaslan, E., Adıbelli, D., Teskereci, G., & Cura, Ş. Ü. (2023). Studying the impact of clinical decision-making and critical thinking on the quality of nursing care. *Journal of Integrative Nursing and Palliative Care, 4*, 23–29. doi:10.51847/fsTLiDadY3

Jung, J. H., Ponnusamy, V. K., Kumar, G., Igliński, B., Kumar, V., & Piechota, G. (2024). Industrial–scale production of various bio-commodities by engineered microbial cell factories: Strategies of engineering in microbial robustness. *Chemical Engineering Journal, 502,* 157679. doi:10.1016/J.CEJ.2024.157679

Ko, Y. S., Kim, J. W., Lee, J. A., Han, T., Kim, G. B., Park, J. E., & Lee, S. Y. (2020). Tools and strategies of systems metabolic engineering for the development of microbial cell factories for chemical production. *Chemical Society Reviews, 49*(13), 4615–4636. doi:10.1039/D0CS00155D

Kondo, A., Ishii, J., Hara, K. Y., Hasunuma, T., & Matsuda, F. (2013). Development of microbial cell factories for bio-refinery through synthetic bioengineering. *Journal of Biotechnology, 163*(2), 204–216. doi:10.1016/j.jbiotec.2012.05.021

Krishnamoorthy, S., Kuppam, C., Mamilla, R., & C. R. (2024). Evaluation of carbon capture methodologies, mechanisms, and improvements for sustainable carbon dioxide mitigation using microalgae. *Industrial Biotechnology*, *20*(5), 186-203. doi:10.1089/ind.2024.0015

Kumar, P., Chandrasekhar, K., Kumari, A., Sathiyamoorthi, E., & Kim, B. (2018). Electro-fermentation in aid of bioenergy and biopolymers. *Energies, 11*(2), 343. doi:10.3390/en11020343

Kwatra, D., Venugopal, A., & Anant, S. (2024). Studying the efficacy of tolmetin radiosensitizing effect in radiotherapy treatment on human clonal cancer cells. *Bulletin of Pioneering Researches of Medical and Clinical Science, 3*(2), 22–28. doi:10.51847/Uuhjk0fMC8

Lee, S. Y., Kim, H. U., Chae, T. U., Cho, J. S., Kim, J. W., Shin, J. H., Kim, D. I., Ko, Y. S., Jang, W. D., & Jang, Y. S. (2019). A comprehensive metabolic map for the production of bio-based chemicals. *Nature Catalysis, 2*(1), 18–33. doi:10.1038/S41929-018-0212-4

Levochkina, E. D., Belyaev, N. G., Tkach, A. I., Menadzhiev, A. S., Volkova, M. N., Akifeva, N. M., Zemcev, D. A., & Korotchenko, E. A. (2024). Data analysis of autoimmune bioindicators in the context of predicting cardiomyocyte damage. *Journal of Advanced Pharmacy Education and Research, 14*(3), 62–69. doi:10.51847/ilO1LTBQLt

Li, C. T., Yelsky, J., Chen, Y., Zuñiga, C., Eng, R., Jiang, L., Shapiro, A., Huang, K. W., Zengler, K., & Betenbaugh, M. J. (2019). Utilizing genome-scale models to optimize nutrient supply for sustained algal growth and lipid productivity. *npj Systems Biology and Applications, 5*(1), 1–11. doi:10.1038/S41540-019-0110-7

Linh, D. H., Hoa, T. T. V., Dan, N. K., Anh, T. T. P., Ngoc, D. H., & Hoang, P. N. (2024). The impact of green credit on a sustainable economy: an empirical study in Vietnam. *Journal of Organizational Behavior Research, 9*(2), 164–178. doi:10.51847/euzEogd4CX

Liu, L., Bilal, M., Luo, H., Zhao, Y., & Iqbal, H. M. N. (2019). Metabolic engineering and fermentation process strategies for L-tryptophan production by *Escherichia coli*. *Processes, 7*(4), 213. doi:10.3390/PR7040213

Liu, M., Tang, Q., Wang, Q., Xie, W., Fan, J., Tang, S., Liu, W., Zhou, Y., & Deng, X. (2022). Studying the sleep quality of first-time pregnant women in the third trimester of pregnancy and some factors related to it. *Journal of Integrative Nursing and Palliative Care, 3*, 1–6. doi:10.51847/K1PUWsJ24H

Makhoahle, P., & Gaseitsiwe, T. (2022). Efficacy of disinfectants on common laboratory surface microorganisms at R.S Mangaliso Hospital, NHLS Laboratory, South Africa.

Bulletin of Pioneering Researches of Medical and Clinical Science, 1(1), 1–12. doi:10.51847/d5bXpXAtcI

Mickevičius, I., Astramskaitė, E., & Janužis, G. (2023). Implant survival rate after immediate implantation in infected sockets: a systematic literature review. *Annals of Dental Specialty, 11*(2), 46–56. doi:10.51847/H2f8RrgSWB

Molas-Tuneu, M., Briones-Buixassa, L., Díaz, L., Pérez, H., Berrocoso, S., Naudó-Molist, J., Escribà-Salvans, A., Peraile, M. A., Barbero-Jambrina, S., & Lladó-Jordan, G. (2024). Perception of care and emotional impact of perinatal women during COVID-19: a multicenter study. *Journal of Advanced Pharmacy Education and Research, 14*(2), 1–10. doi:10.51847/AQbgFnHjf3

Najjar, A. A. (2023). Managing major foodborne mycotoxins: a therapeutic approach for safety and health. *World Journal of Environmental Biosciences, 12*(4), 46–53. doi:10.51847/fhNKVgnWUR

Naseri, B., & Sasani, S. (2024). Stem rust, planting date, wheat maturity, genetic resistance, weather, and productivity. *World Journal of Environmental Biosciences, 13*(4), 1–6. doi:10.51847/2njt2p8YQ0

Nastro, R. A., Kuppam, C., Toscanesi, M., Trifuoggi, M., Pietrelli, A., Pasquale, V., & Avignone-Rossa, C. (2025). Bio-electrosynthesis of polyhydroxybutyrate and surfactants in microbial fuel cells: a preliminary study. *Frontiers in Microbiology, 16,* 1372302. doi:10.3389/fmicb.2025.1372302

Navarrete, C., Jacobsen, I. H., Martínez, J. L., & Procentese, A. (2020). Cell factories for industrial production processes: current issues and emerging solutions. *Processes, 8*(7), 768. doi:10.3390/PR8070768

Nidheesh, P. V., Ganiyu, S. O., Kuppam, C., Mousset, E., Samsudeen, N., Olvera-Vargas, H., & Kumar, G. (2022). Bioelectrochemical cells as a green energy source for the electrochemical treatment of water and wastewater. *Journal of Water Process Engineering, 50,* 103232. doi:10.1016/j.jwpe.2022.103232

Odeh, L. G. H., Jammal, L. E., Alenazi, A. A., & Ansari, S. H. (2024). Factors affecting the prognosis of dental implants: a systematic review. *Annals of Dental Specialty, 12*(2), 39–46. doi:10.51847/w0q1mO1V2r

Oran, İ. B., Ayboğa, M. H., Erol, M., & Yildiz, G. (2022). The necessity of transition from Industry 4.0 to Industry 5.0: SWOT analysis of Turkey's SCM strategy. *Journal of Organizational Behavior Research, 7*(2), 1–17. doi:10.51847/vrFR9HDvbh

Özatik, Ş., Saygılı, S., Sülün, T., & Alan, C. B. (2022). Semi-digital workflow of removable partial denture fabrication for scleroderma-induced microstomia patients: two clinical reports. *Annals of Dental Specialty, 10*(3), 1–6. doi:10.51847/CF2JBPvHvL

Padma, K. R., Don, K. R., Anjum, M. R., Sindhu, G. S., & Sankari, M. (2023). Application of green energy technology for environmental sustainability. *World Journal of Environmental Biosciences, 12*(4), 1–7. doi:10.51847/bAMKAPPZGe

Patra, P., Das, M., Kundu, P., & Ghosh, A. (2021). Recent advances in systems and synthetic biology approaches for developing novel cell-factories in non-conventional yeasts. *Biotechnology Advances, 47,* 107695. doi:10.1016/J.BIOTECHADV.2021.107695

Perwitasari, D. A., Candradewi, S. F., Purba, F. D., & Septiantoro, B. P. (2023). Mapping functions of cancer patients' quality of life in Indonesia: from EORTC-QlQ-C-30 to EQ-5D-5L. *Journal of Advanced Pharmacy Education and Research, 13*(3), 19–22. doi:10.51847/avg60W3aR5

Petronis, Z., Golubevas, R., Rokicki, J. P., Guzeviciene, V., Sakavicius, D., & Lukosiunas, A. (2023). Analysis of trigeminal neuralgia associated with neurovascular compression utilizing MRI: a systematic review and meta-analysis. *Annals of Dental Specialty, 11*(4), 1–8. doi:10.51847/rDJGquURHA

Petrova, P., & Petrov, K. (2020). Lactic acid fermentation of cereals and pseudocereals: ancient nutritional biotechnologies with modern applications. *Nutrients, 12*(4), 1118. doi:10.3390/NU12041118

Rangel, A. E. T., Gómez Ramírez, J. M., & González Barrios, A. F. (2020). From industrial byproducts to value-added compounds: The design of efficient microbial cell factories by coupling systems metabolic engineering and bioprocesses. *Biofuels, Bioproducts and Biorefining, 14*(5), 1228–1238. doi:10.1002/BBB.2127

Ranjel, E. S. M., Moreno, P. M. N., Córdova, M. G. D. G., Castillo, C. G. G., Flores, V. J. A., Conesa, J. G., & García, J. A. L. (2025). Bee propolis (*Apis mellifera*) as a growth promoter in tilapia (*Oreochromis niloticus*). *World Journal of Environmental Biosciences, 14*(2), 13–19. doi:10.51847/uDczvYfi37

Roy, S., Laha, I., Ray, D., & Choudhury, L. (2022). Influence of climate change & environmental toxicants on epigenetic modifications. *World Journal of Environmental Biosciences, 11*(3), 21–29. doi:10.51847/jku3EDOAkt

Roy, S., Schievano, A., & Pant, D. (2016). Electro-stimulated microbial factory for value-added product synthesis. *Bioresource Technology, 213,* 129–139. doi:10.1016/J.BIORTECH.2016.03.052

Saliev, T., Tanabayeva, S., Ussebayeva, N., Izmailova, S., Umbayev, B., Akhanov, G., Akhmad, N., & Fakhradiyev, I. (2024). In vitro cytotoxicity and antiviral activity of aminocaproic acid against SARS-CoV-2. *Journal of Advanced Pharmacy Education and Research, 14*(3), 1–8. doi:10.51847/ueSpVWAvbT

Shi, T. Q., Darvishi, F., Cao, M., Ji, B., & Ji, X. J. (2023). Editorial: Design and construction of microbial cell factories for the production of fuels and chemicals. *Frontiers in Bioengineering and Biotechnology, 11,* 1198317. doi:10.3389/FBIOE.2023.1198317/BIBTEX

Sindhu, S., Maiti, S., & Nallaswamy, D. (2023). Factors affecting the accuracy of intraoral scanners: systematic review. *Annals of Dental Specialty, 11*(1), 40–52. doi:10.51847/izu17ACVUd

Singh, M., Mal, N., Mohapatra, R., Bagchi, T., Parambath, S. D., Chavali, M., Rao, K. M., Ramanaiah, S. V., Kadier, A., Kumar, G., et al. (2022). Recent biotechnological developments in reshaping the microalgal genome: a signal for green recovery in biorefinery practices. *Chemosphere,*

293, 133513. doi:10.1016/j.chemosphere.2022.133513

Singh, M., Mal, N., Trivedi, D., Krishnamoorthy, S., Behera, C., Krishnan, C., Naik, S., & Kuppam, C. (2025). An overview of the role of algae-fortified foods in nutraceutical industries: synthesis pathway of value-added bioproducts and co-products. *Food Bioscience, 63,* 105568. doi:10.1016/j.fbio.2024.105568

Soman, C., Hawzah, A. A. A. A., Alsomali, M. A., Alghamdi, S. A. K., & AlOsaimi, M. M. (2024). Salivary specimen in COVID-19 testing for dental settings: a meta-analysis comparing saliva, nasopharyngeal, and serum specimens. *Annals of Dental Specialty, 12*(1), 33–47. doi:10.51847/LNn8bSwowj

Son, V. T., Ha, B. T., Anh, N. Q., Mai, N. P., Trang, D. T., Lu, L. D., Anh, N. T. N., & Tam, L. T. (2023). Impact of enterprise risk management on firm value during the instability context: case of Vietnam. *Journal of Organizational Behavior Research, 8*(2), 236–250. doi:10.51847/x9nE6PL4i8

Tam, L. T., An, H. T. T., Linh, T. K., Nhung, L. T. H., Ha, T. N. V., Huy, P. Q., & Luc, P. T. (2022). Value co-creation activities of students on the Covid-19 pandemic: empirical evidence from economics students in Vietnam. *Journal of Organizational Behavior Research, 7*(2), 214–228. doi:10.51847/Nofw4ZK2wd

Thazha, S. K., Cruz, J. P., Alquwez, N., Scaria, B., Rengan, S. S., & Almazan, J. U. (2023). Studying the attitude and knowledge of nursing students towards the physical restraint use in patients. *Journal of Integrative Nursing and Palliative Care, 4*, 1–5. doi:10.51847/cFz2ew4AK8

Tural, A., & Şahan, G. (2023). Awareness towards human rights and democracy education: a mixed-method research. *Journal of Organizational Behavior Research, 8*(2), 107–128. doi:10.51847/odg5gU1i7S

Upchezhokov, M. A., Avagyan, A. T., Bagomedova, D. M., Kurbanov, A. E., Kadyrov, E. R., Bremov, I. M., Agabekov, A. A., & Shidakova, L. Z. (2024). The impact of weather and climatic conditions on the dental health of military personnel. *Annals of Dental Specialty, 12*(4), 39–46. doi:10.51847/JBHRQlFtfR

Veerapandian, B., Krishnan, S., Sivaraman, S., Immanuel, A., Shanmugam, S. R., Toksoy Öner, E., Venkatachalam, P., & Ulaganathan, V. (2025). Bacillus spp. as microbial factories for levan and fructooligosaccharide production – recent trends. *International Journal of Biological Macromolecules, 300,* 140252. doi:10.1016/J.IJBIOMAC.2025.140252

Winnifrith, A., Outeiral, C., & Hie, B. L. (2024). Generative artificial intelligence for de novo protein design. *Current Opinion in Structural Biology, 86,* 102794. doi:10.1016/J.SBI.2024.102794

Zhang, Y., Liu, M., Cai, B., He, K., Wang, M., Chen, B., & Tan, T. (2022). De novo biosynthesis of α-aminoadipate via multi-strategy metabolic engineering in Escherichia coli. *MicrobiologyOpen, 11,* e1301. doi:10.1002/MBO3.1301

Zharashueva, E. B., Mirzayeva, A. K., Iakovleva, A. N., Dyshnieva, N. A., Dudurgova, A. T., Utovka, O. V., Strelchuk, S. V., & Dekkusheva, R. M. (2024). Sanitary and hygienic assessment of the dressing material modified with silver nanoparticles. *Journal of Advanced Pharmacy Education and Research, 14*(3), 9–14. doi:10.51847/J10C8y3UWQ