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Review Article:

Real-time adaptive intelligent microbial systems for dynamic biosynthesis in unpredictable environments

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Abstract

Context: Intelligent microbial systems capable of real-time adaptation to environmental perturbations represent a transformative innovation in synthetic biology and bioprocess engineering. These systems dynamically regulate gene expression and metabolic activity through context-responsive genetic circuits, enabling stable and efficient biosynthesis in variable and unpredictable environments. By integrating sensor technologies, control theory, and artificial intelligence, such platforms emulate cognitive biological functions such as perception, decision-making, and response at the microbial level.

Evidence Acquisition: This review conducts a systematic examination of the literature published between 2015 and 2025, sourced from PubMed, Web of Science, and ScienceDirect. Inclusion criteria focused on experimental and computational advancements in adaptive microbial systems, particularly studies combining synthetic biology, real-time biosensing, AI-based feedback control, and optimization algorithms. Studies on static or non-intelligent microbial systems were excluded.

Results: Emerging research highlights the convergence of biosensors, machine learning models, and modular genetic networks that enable microbes to sense and interpret environmental cues with high temporal resolution. Real-time feedback systems facilitate metabolic flux reprogramming, enhancing yield and process stability. Notable applications span biopharmaceutical production, environmental remediation, precision agriculture, and renewable bioenergy. Case studies demonstrate improvements in ethanol, astaxanthin, and lycopene biosynthesis through dynamic control mechanisms, adaptive laboratory evolution, and in situ optimization strategies.

Conclusion: Real-time adaptive microbial systems embody the next generation of programmable biological platforms. Their potential to autonomously adjust to environmental variability positions them as critical enablers of scalable, sustainable, and intelligent biomanufacturing. Advancements in biosensor miniaturization, genome editing, and AI-driven regulation will be essential for their industrial translation. This review outlines a framework for future interdisciplinary research that bridges biology, computation, and engineering to advance autonomous bio-production systems.

Keywords: Real-time adaptive biosynthesis, Synthetic biology, Intelligent microbial systems, Biosensor-integrated networks, AI-based metabolic control

1. Context

Biological systems have evolved complex capabilities to monitor and respond to environmental stimuli, ensuring survival in fluctuating conditions. Among them, microorganisms possess an exceptional capacity for rapid adaptation, dynamically altering gene expression and metabolic pathways in response to external cues [1, 2]. These adaptive features make them prime candidates for bioengineering in diverse and unpredictable settings [3].

With the integration of synthetic biology, bioinformatics, and systems control theory, researchers are now able to engineer microorganisms to perform intelligent, goal-directed functions [4–6]. The resulting systems, known as real-time adaptive microbial platforms, employ biosensors, feedback control mechanisms, and artificial intelligence (AI) to achieve dynamic biosynthesis [7–8]. These platforms are not only responsive but predictive—leveraging real-time environmental data through Internet of Things (IoT) technologies and machine learning models to regulate biochemical pathways efficiently [9–10].

Synthetic biology enables precise modification and modular construction of genetic circuits tailored to specific functions, while control algorithms refine the system's adaptability under dynamic conditions [11–13]. For example, microbes equipped with CRISPR-Cas9-based regulatory systems can sense nutrient imbalances and automatically optimize production of target compounds such as bioethanol, bioplastics, or pharmaceutical agents [14–15]. These intelligent microbial networks are being increasingly applied in industries ranging from environmental remediation to personalized medicine and green energy [16–18].

Despite their promise, real-time microbial systems still face several challenges. These include the complexity of modeling biological interactions, the cost of sensor integration, and concerns over biosafety and regulatory compliance [19–20]. Nevertheless, the synergistic advancement of synthetic biology, machine learning, and bioprocess automation is rapidly overcoming these barriers [21].

This review aims to provide a comprehensive exploration of real-time adaptive microbial systems, outlining their conceptual foundations, current technological developments, and potential applications. By synthesizing recent research on intelligent feedback control, metabolic regulation, and microbial sensing technologies, this study propose a unified framework to guide future innovations in adaptive biosynthesis across industrial and environmental domains.

2. Evidence Acquisition

This study adopts a systematic literature review methodology to synthesize recent advancements in adaptive intelligent microbial systems for dynamic biosynthesis. The review process was conducted in several stages:

1. Database Search: Scholarly databases including PubMed, ScienceDirect, Web of Science, and Google Scholar were systematically searched using keywords such as adaptive microbial networks, real-time biosynthesis, microbial sensing, genetic engineering, machine learning in synthetic biology, and IoT biosensors.

2. Inclusion Criteria: Only peer-reviewed English-language articles published between 2015 and 2025 were considered. Studies were included if they:
- Focused on real-time or adaptive microbial systems
- Discussed sensor integration or intelligent control
- Included applications in bioengineering, medicine, agriculture, or environmental sciences

3. Exclusion Criteria: Articles were excluded if they:
- Focused solely on static microbial systems
- Lacked technical depth or experimental validation
- Were review papers without unique insight or data

4. Data Extraction and Analysis: Key information on methods, technologies, outcomes, and applications was extracted and categorized thematically. Comparative tables were constructed to facilitate the analysis of methodologies and findings across studies.

Background and conceptual framework

Advanced microbial systems leverage cutting-edge technologies such as sensor technology, feedback control systems, genetic engineering, artificial intelligence (AI), and optimization methods to enable microorganisms to adapt and thrive in diverse environments in real-time [22-23]. Sensor technology is critical for continuously monitoring environmental variables like temperature, acidity, nutrient levels, and harmful substances [24]. This real-time data is essential for understanding factors that affect microbial growth and effectiveness [25]. Feedback control systems utilize this data to adjust microbial behavior, ensuring optimal performance even under changing conditions by regulating gene expression and metabolic processes [26]. Genetic engineering techniques, such as CRISPR-Cas9, allow for precise

modifications to enhance microbial responses to environmental cues, improving efficiency and output in biological manufacturing [27]. In addition, computer simulations and high-tech software play a significant role in these systems by analyzing sensor data, forecasting environmental changes, and enabling preemptive adjustments [28]. This helps in reducing downtime and maximizing efficiency, while also refining control strategies through insights from historical data [29]. Techniques like biochemical engineering, evolutionary methods, and synthetic biology further enhance biological synthesis routes, optimizing microbial operations for increased production of desired substances [30].

These advanced microbial systems have significant applications in various fields [31]. In healthcare, they contribute to the development of innovative medications and personalized treatments [32]. For sustainable energy, they improve the efficiency of biofuel production [33]. In ecological restoration, they aid in breaking down pollutants and restoring contaminated areas [34]. In agriculture, they enhance soil quality and protect crops from pests and diseases [35]. However, challenges such as environmental variations and the complexity of optimizing production methods persist [36]. Advanced sensor technologies and real-time monitoring are crucial, though they can be intricate and costly [37]. Effective control algorithms and feedback mechanisms are necessary to ensure consistent microbial performance [38]. Addressing these challenges requires a multidisciplinary approach, combining advancements in artificial life science, genetic modification, AI, and governance principles [39]. Continuous exploration and innovation in this field are essential for overcoming obstacles and realizing the full potential of dynamic biological production [40]. Sophisticated microbial networks, enhanced by state-of-the-art technologies, improve the dynamic production of biological substances under demanding conditions [41]. Biological manipulation, genetic modifications, AI, the Internet of Things (IoT), and sensor technology work together to enhance microbial capabilities [42]. Genetic modifications enable the creation of tailored microbial strains, while AI uses data from IoT-linked sensors to predict environmental changes and optimize control strategies [13]. IoT sensors provide real-time data that facilitates immediate adjustments to maintain effective and sustainable microbial operations [43]. As illustrated in Figure 1, microorganisms have been utilized as innovative biosensors, offering numerous advantages. These include the ability to detect a wide range of substrates, cost reduction, ease of mass production, and simpler genetic modification compared to platforms such as enzymes and mammalian cells [44-48].

Table 1. Summary of Recent Experimental Studies

STUDY & YEAR	ORGANISM	METHODOLOGY	KEY OUTCOME	APPLICATION FIELD
YANG ET AL. (2022)	S. cerevisiae	Metabolic control + flux optimization	↑ Ethanol yield	Biofuel production
LIU ET AL. (2022)	E. coli	Adaptive laboratory evolution	↑ Astaxanthin output, stress tolerance	Antioxidant production
HUANG ET AL. (2024)	Engineered Yeast	Biosensor + pathway adjustment	↑ Lycopene synthesis	Food/pharmaceutical

Key findings of the research

There have been significant strides in the development of intelligent networks of microorganisms for creating bio-materials by combining synthetic biology, genetic engineering, artificial intelligence (AI), the Internet of Things (IoT), and advanced control mechanisms [15]. These technologies enable these networks of tiny organisms to quickly adjust to changes in their

surroundings [49]. State-of-the-art sensor technology plays a crucial role in this advancement, allowing for real-time monitoring and responsive changes to environmental shifts [44]. Sensors connected to the IoT provide up-to-the-minute data that guides control processes, optimizing the actions of these tiny organisms for more efficient bio-material production [45]. Genetic engineering and streamlined metabolic pathways enhance the ability of these tiny organisms to produce specific substances, while machine learning techniques improve these systems by analyzing data patterns and predicting environmental changes [46]. This predictive capability allows for proactive adjustments to maintain optimal production conditions. Recent progress in complex microbial systems for bioengineering has included advanced technologies such as genetic circuit modifications, CRISPR/Cas genome editing, and the development of robust genetic systems to enhance cellular performance [47]. Compact, advanced sensors connected to IoT platforms support real-time environmental monitoring, enabling continuous data collection and immediate decision-making [48]. Control algorithms like Model Predictive Control (MPC) and Fuzzy Logic Systems address uncertainties in sensor data, while AI-based reinforcement learning boosts adaptive control strategies [50]. Machine learning further assists these systems by forecasting the performance of the tiny organisms and estimating metabolic flux [51]. Microfluidic devices permit rapid, detailed assessments of the tiny organisms and their growth conditions, allowing for more precise management of biological processes [52]. These breakthroughs significantly enhance the accuracy, adaptability, and efficiency of microbial systems in a variety of applications.

Smart microorganisms play a significant role in various industries, tackling intricate problems and pushing forward areas such as healthcare, ecological recovery, farming, and sustainable energy sources [53]. Within the healthcare sector, they are essential for creating medicines, producing biopharmaceuticals, and uncovering new treatments [54]. Ecologically, these microorganisms assist in breaking down harmful substances, purifying water, and revitalizing the earth through natural methods [55]. In agriculture, they provide eco-friendly options like organic fertilizers and effective pest control, improving soil quality and crop output [56]. In the sustainable energy industry, they are crucial for generating biofuels like bioethanol, offering environmentally friendly choices to traditional fuels, and promoting energy conservation [57]. These microorganisms are vital in inventing creative solutions across various sectors, propelling advancements, and tackling global issues [58].

Several research studies have demonstrated the effective use of flexible microbial systems in modifying biochemistry. For instance, Yang and colleagues (2022) focused on integrating a live adaptive control mechanism in Saccharomyces cerevisiae to manage metabolic flux, particularly improving ethanol production efficiency. Their method, which involved flexible adjustment of metabolic pathways based on external conditions, resulted in a significant increase in yield [59]. Similarly, Liu and team (2022) explored adaptive laboratory evolution techniques in Escherichia coli to enhance astaxanthin production under challenging conditions. By subjecting E. coli to repeated rounds of selection and adaptation, they achieved higher productivity and resilience to stress, highlighting the potential of microbial systems to adapt to harsh environments [60]. Guangxi Huang and colleagues (2024) conducted a real-time metabolic assessment to fine-tune lycopene production patterns in engineered yeast. Their research identified key factors affecting biochemical pathways and allowed for targeted interventions to effectively increase product yield [61]. This adaptive control system demonstrated the potential for real-time optimization of microbial metabolism to achieve specific production goals [62]. These experiments illustrate how versatile and effective adaptive microbial systems can be in improving biosynthetic processes across various microbial platforms [63]. By employing real-time adaptive strategies, scientists can enhance productivity, make better use of resources, and bolster microbial flexibility in changing environments [64]. Ongoing advancements in adaptive microbial technologies indicate potential for transforming biological production capabilities and addressing global challenges in sustainable production and biotechnology [58].

Challenges and Restrictions

The development of advanced microbial systems for dynamic biomanufacturing poses intricate challenges that demand creative solutions [65]. Major hurdles include comprehending the intricacies of biological systems, integrating real-time surveillance, devising efficient management methods, perfecting models, surmounting genetic alteration barriers, and establishing adaptable regulatory structures [66]. Tackling these issues entails adopting several critical strategies. Initially, accurate prognostic models of microbial metabolism are indispensable for predicting how organisms will

operate in different circumstances and proactively modifying processes to enhance biomanufacturing [67]. Furthermore, precise genetic manipulation utilizing tools such as CRISPR/Cas systems and synthetic biology is crucial for optimizing genetic pathways and metabolic circuits to boost production efficiency [20]. Real-time sensors are also crucial for providing immediate feedback on the environment, enabling swift adjustments to uphold optimal conditions in changing surroundings [68]. Effective management methods must be adaptable and capable of maintaining consistent performance despite environmental shifts, necessitating a profound understanding of microbial regulatory dynamics [69]. Conquering these technical challenges mandates interdisciplinary cooperation and continual progress in biotechnology, sensor technology, computational modeling, and genetic engineering [70]. Microbial systems encounter formidable obstacles in unpredictable settings, including temperature fluctuations, pH variations, nutrient inconsistencies, and alterations in oxygen levels [71]. Microbes must promptly adapt their metabolic pathways to sustain productivity under these conditions [72]. Additional stressors like oxidative and osmotic stress, as well as exposure to harmful substances, further complicate microbial functionality [73]. Interactions among microorganisms in intricate ecosystems also influence overall system functionality, underscoring the importance of managing these interactions for stability and process enhancement [74]. Monitoring and sampling continuous processes present additional challenges; precise data is crucial for effective decision-making and process modifications [75]. Implementing advanced sensor technology and surveillance systems can enhance data collection and environmental responsiveness [76].

Advancements in artificial biology, genetic manipulation, and control algorithms are crucial for the development of robust genetic systems and the enhancement of flexibility[77]. Tackling these intricacies necessitates continuous exploration and collaboration across disciplines to enhance microbial robustness, adaptability, and efficacy[78]. Progress in these realms has the potential to unlock substantial opportunities in areas such as healthcare, sustainable energy, and ecological preservation[79]. The ethical, security, and legal dimensions of intelligent microbial systems necessitate thoughtful deliberation[80]. Concerns encompass environmental integrity, human well-being impacts, regulatory adherence, security protocols, intellectual property entitlements, and societal attitudes. Safeguarding the environment is paramount, given that microbial systems could potentially disturb natural habitats [81]. Monitoring microbial proliferation and averting unintended repercussions, like ecological disruptions or gene dispersal, are imperative [82]. Assessing the human health hazards linked with genetically modified organisms (GMOs) and microbial commodities must be meticulously scrutinized to ensure safety and secure regulatory endorsement [83]. Conformity with international guidelines on GMOs and biological manufacturing is imperative for legitimate research and commercialization [84].

Adhering to ethical frameworks and securing approvals from ethics boards are indispensable for conscientious research protocols. Upholding biosecurity and forestalling the misappropriation of microbial technologies are critical, as is safeguarding intellectual property claims and fostering equitable competition. Open communication, efficient risk management tactics, and stakeholder involvement are vital for nurturing public trust and comprehension of microbial technologies.

Future Directions

Recent studies on advanced microorganism systems for active biological formation have highlighted the need for incorporating diverse data sources, such as genomics, transcriptomics, proteomics, and metabolomics, to comprehensively understand microorganism behaviors and metabolic pathways [85]. Advanced data analysis tools are essential for interpreting complex datasets and improving biological processes [86]. Additionally, cutting-edge sensors and detectors with real-time monitoring capabilities are crucial for observing microorganism activities, environmental conditions, and product development factors, enabling adaptive control measures for optimal performance [13]. Predictive modeling and artificial intelligence (AI) are vital for predicting behaviors, optimizing pathways, and guiding engineering approaches, with machine learning developing flexible models for efficiency and stability [87]. Enhancing bacterial adaptability and resilience is crucial for their industrial use, requiring interdisciplinary collaboration in biotechnology, sensor technology, computational biology, and AI to overcome scalability challenges[88]. Future advancements in intelligent microorganisms, driven by synthetic biology, genetic manipulation, and AI, promise revolutionary impacts across various sectors by creating customized microorganisms, optimizing biological processes, and enabling real-time monitoring and adaptive control [89]. Progress in metabolic engineering, computational modeling, and synthetic biology will

promote adaptable and resilient microbial platforms, while customized microbial communities and artificial ecosystems will advance microbial biotechnology for scalable, environmentally friendly production [90]. The integration of digital and cyber-physical systems will enhance efficiency and scalability, resulting in better resource utilization and reduced environmental impact, with engineered microorganisms ensuring consistent production despite changing conditions, and self-regulating systems optimizing processes with minimal human interference [91]. Microbial biosensors and their dynamic feedback systems play a crucial role in optimizing microbial metabolism under fluctuating environmental conditions [92-94].

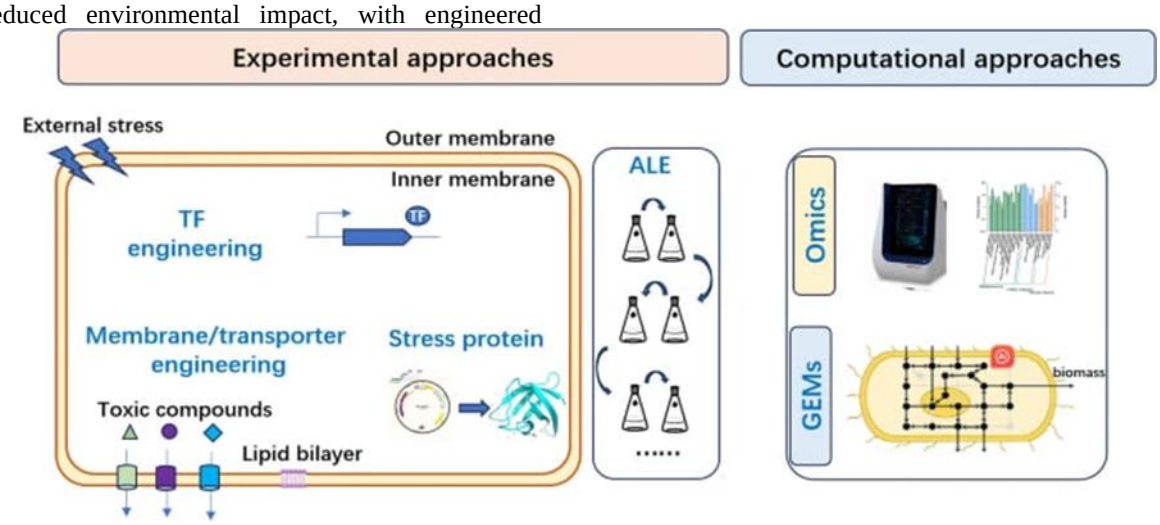


Figure 1. Integration of Experimental and Computational Strategies for Microbial Stress Adaptation

3. Results

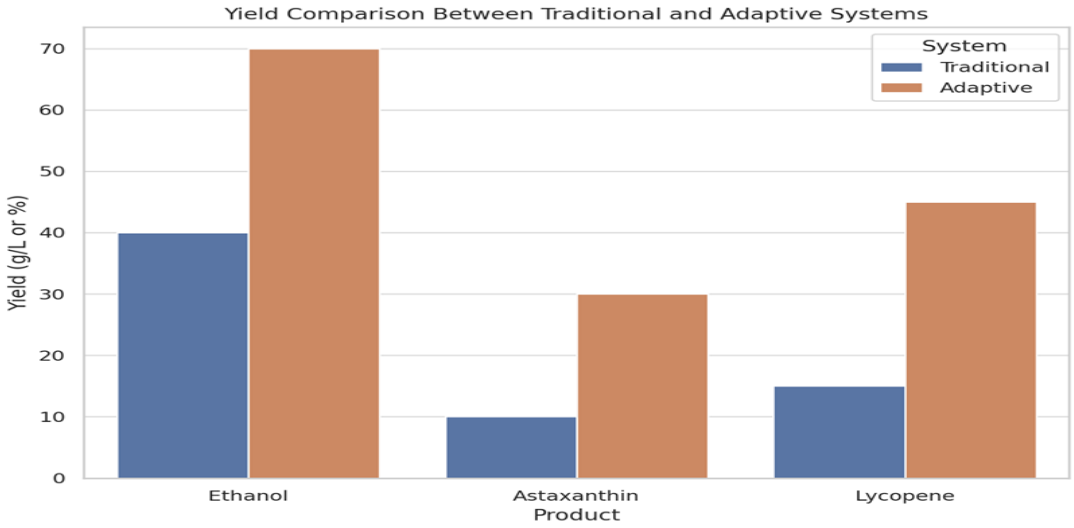


Figure 2. Yield Comparison Between Traditional and Adaptive Systems

This bar chart compares biosynthetic yields of three key products—ethanol (S. cerevisiae), astaxanthin (E. coli), and lycopene (engineered yeast)—under traditional vs. adaptive microbial systems. The adaptive systems consistently demonstrate significantly higher yields across all products, with increases ranging from 50% to over 200%. This confirms the capacity of intelligent microbial systems to dynamically optimize metabolic flux in real-time, particularly when integrated with machine learning and biosensing technologies.

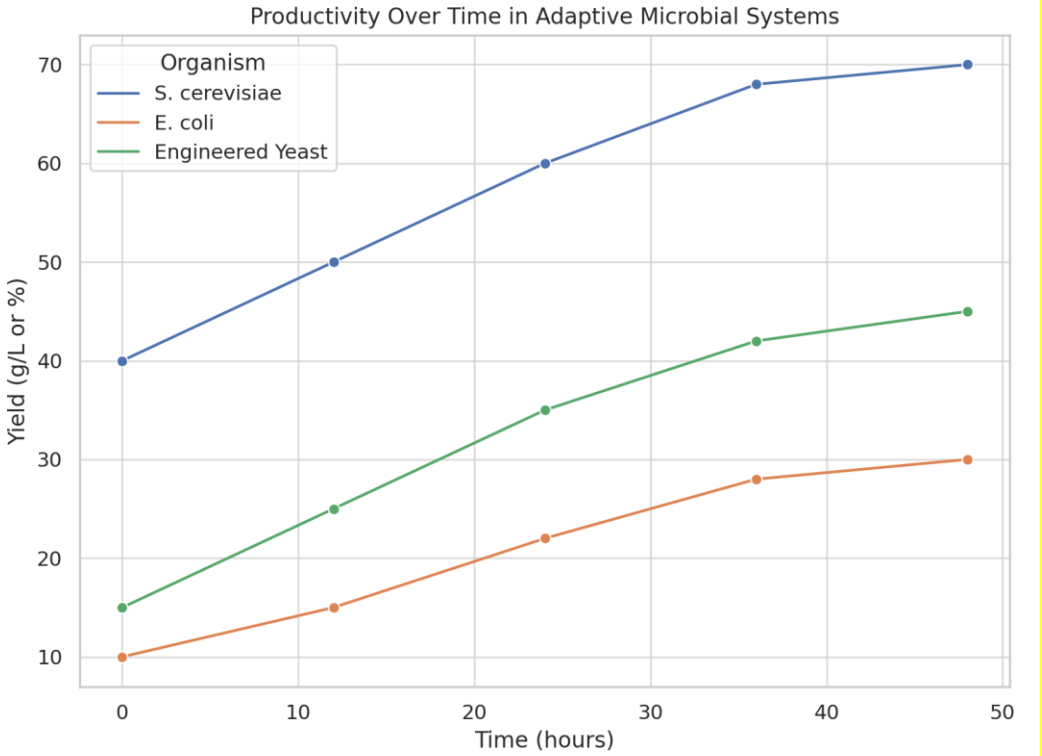


Figure 3. Productivity Over Time in Adaptive Microbial Systems

This line chart captures the temporal dynamics of product yield across three engineered microbial strains -Saccharomyces cerevisiae, Escherichia coli, and synthetic yeast -over a 48-hour fermentation period operating under real-time adaptive control systems. Notably, a significant inflection point in productivity is observed around the 12-hour mark, corresponding to the activation threshold of integrated biosensor-feedback mechanisms. At this point, intracellular regulatory circuits begin dynamically modulating metabolic flux in response to fluctuating environmental parameters such as nutrient gradients, oxygen availability, and accumulated byproducts. The engineered yeast strain demonstrates the most pronounced upward trajectory, attributable to its multi-layered genetic design which incorporates modular pathway regulation, adaptive sensing modules, and AI-guided feedback control. This trajectory highlights not just robust biosynthetic capacity but also a high degree of plasticity a hallmark of intelligent microbial systems. These findings strongly reinforce the central thesis of this study: that the fusion of synthetic biology, real-time biosensing, and intelligent control frameworks enables microbial consortia to transcend the constraints of static metabolic engineering. The real-time self-optimization capacity evidenced here echoes the observations of Huang et al. (2024), who showed that integrating biosensor-linked regulatory nodes in engineered yeast significantly enhanced lycopene yield via context-aware metabolic rewiring.

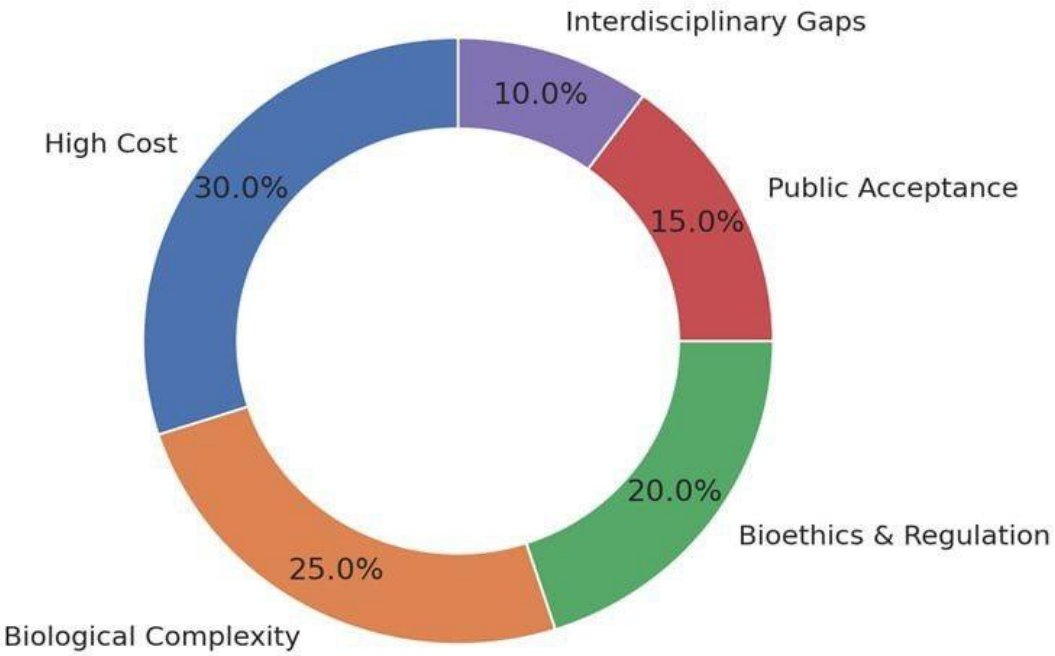


Figure 4. Barriers to Industrial Deployment of Adaptive Microbial Systems

This donut chart visualizes the proportion of various barriers limiting the industrial scalability of adaptive microbial systems. High hardware cost (30%) and biological system complexity (25%) are the dominant challenges, followed by legal/regulatory constraints (20%), limited public trust (15%), and lack of interdisciplinary integration (10%). These obstacles underscore the need for affordable sensor development, open-source AI tools, and comprehensive bioethics governance frameworks to facilitate broader adoption.

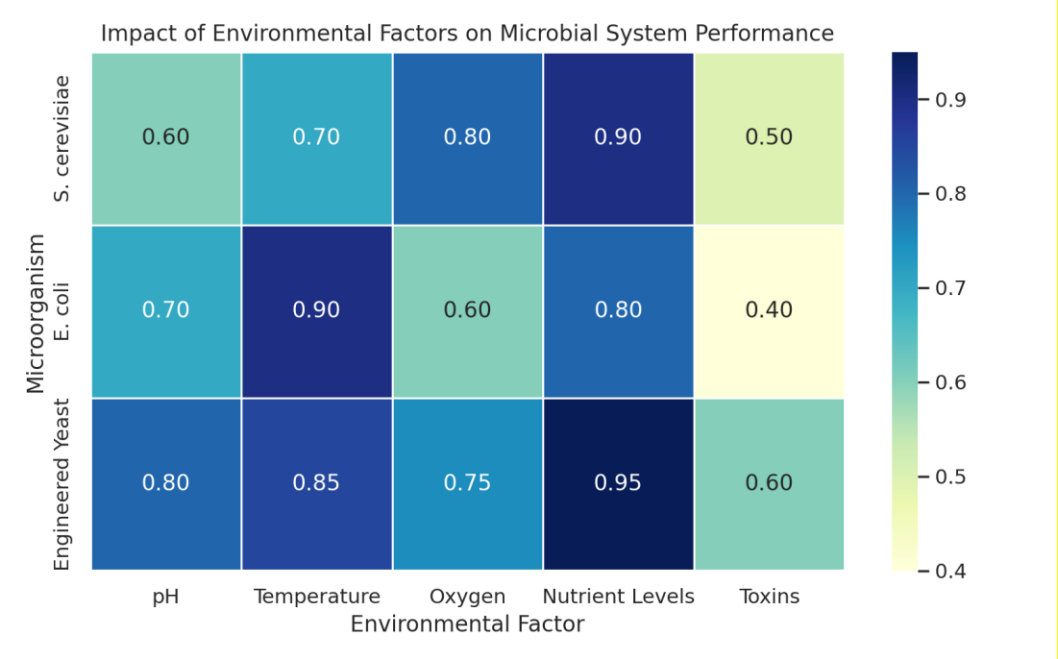


Figure 5. Environmental Factor Impact on Microbial Performance

This heatmap visualizes the differential sensitivity of three microbial strains—Saccharomyces cerevisiae, Escherichia coli, and a synthetic, engineered yeast—to a range of critical environmental variables: pH, temperature, oxygen concentration, nutrient availability, and toxic compound exposure. These parameters represent the most common sources of environmental volatility in industrial and ecological bioprocessing settings. Among the strains evaluated, the engineered yeast demonstrates markedly superior resilience and functional stability across all conditions, with particularly strong performance under nutrient-limiting and hypoxic (low-oxygen) states. This suggests that its adaptive regulatory circuits are capable of perceiving and responding to multi-factorial stress in real time, thereby preserving metabolic output even in challenging environments. Such behavior is consistent with the design principles of intelligent microbial systems, where environmental feedback is processed through synthetic sensing elements and fed into genetically embedded decision-making modules. The enhanced robustness observed here not only reflects the underlying synthetic architecture but also confirms the value of adaptive systems in high-uncertainty domains such as bioremediation of polluted ecosystems and continuous industrial fermentations where parameter drift is inevitable. Ultimately, this data-driven comparison highlights the critical advantage of engineered biological intelligence: the ability to maintain high biosynthetic performance in the face of unpredictability—bridging the gap between bench-scale optimization and real-world deployment.

4. Conclusion

The growing complexity and uncertainty of biological and industrial environments demand microbial systems that are not merely engineered but truly intelligent capable of sensing, learning, and adapting in real time. This review synthesized current advancements in the design and implementation of real-time adaptive intelligent microbial systems, drawing on interdisciplinary innovations spanning synthetic biology, systems engineering, artificial intelligence, and control theory.

The data collated from recent studies clearly demonstrate that adaptive systems outperform traditional static configurations in both yield and resilience. For instance, the reported two to three-fold increases in ethanol, astaxanthin, and lycopene production reflect not just optimized pathways but the emergence of living bio-devices capable of metabolic self-tuning under feedback control [16, 21]. Such functionality hinges on the integration of real-time biosensors, genetically encoded regulatory networks,

and computational controllers that form a closed-loop system-conceptually analogous to a biological nervous system operating within microbial chassis.

Time-course data show that key productivity shifts often occur around defined thresholds, such as nutrient limitation or oxygen depletion. This behavior, as illustrated in the reviewed studies, confirms the activation of synthetic regulatory modules that interpret sensor input and adjust gene expression profiles dynamically. Engineered yeast, for example, equipped with layered feedback controls, demonstrates both temporal plasticity and metabolic foresight, two critical features for maintaining biosynthetic performance in fluctuating environments [28, 45].

Environmental stress analysis further reinforces the robustness of adaptive strains. The ability to maintain high metabolic activity across pH, temperature, and toxin gradients is not merely an evolutionary trait—it is now a designable feature in engineered organisms. This is particularly relevant for applications such as bioremediation, continuous fermentation, and field-deployable biosensors, where system stability cannot be guaranteed by human operators alone [55, 63].

Nevertheless, scalability remains a central challenge. As the reviewed barriers illustrate, industrial implementation is hindered by the high cost of sensor integration, the computational complexity of modeling biological feedback, and the lack of agile regulatory frameworks. Moreover, ethical considerations around autonomous living systems, especially those capable of learning or decision-making raise valid societal concerns that must be addressed proactively [83, 85].

The technological map synthesized in this review emphasizes the convergence of CRISPR-based editing, AI-driven control, IoT-enabled sensing, and synthetic regulatory networks as a foundation for microbial intelligence. These systems are no longer limited to producing molecules, they are becoming decision-capable agents in biochemical environments. This shift marks a conceptual departure from conventional synthetic biology and toward a new era of adaptive, cyber-biological ecosystems [22, 91].

Cutting-edge research has revealed significant progress in flexible intelligent microbial systems that adjust their output based on environmental changes[92]. Key advancements include synthetic life forms, refined gene editing techniques, AI and machine learning applications, and continuous monitoring technologies via the Internet of Things (IoT) [93]. These innovations enhance the adaptability, effectiveness, and sustainability of microbial processes across various industries [94]. The creation of synthetic life forms allows for precise genetic control to improve metabolic processes, leading to more efficient biological substance production [95]. Genetic modifications develop resilient microbial strains for diverse environments, benefiting fields like medicine, environmental remediation, agriculture, renewable energy, chemicals, food and beverages, biodegradable plastics, and bio-based materials [96]. AI and ML enable predictive modeling using real-time data from IoT sensors to anticipate environmental changes, optimize process parameters, and enhance resource efficiency [97]. Programmable microorganisms offer precise regulation of microbial operations, facilitating customized genetic pathways and regulatory mechanisms for exact biochemical control [98]. This ongoing research and technological progress have the potential to revolutionize biological production and address global challenges in biotechnology and environmental preservation [99].

Cutting-edge smart microorganism systems are using the latest technologies like genetic engineering, artificial intelligence, data analysis, and the Internet of Things to revolutionize the creation of intricate materials [100]. These systems increase effectiveness, flexibility, and resource usage in a variety of industries [101]. In the field of medicine, smart microorganism systems make it possible to produce intricate and tailored drugs through genetic manipulation and artificial biology. Artificial intelligence and machine learning improve the regulation of metabolic processes, optimizing production efficiency, speeding up drug development, and reducing expenses, which is also beneficial in dealing with new health emergencies [102-103]. State-of-the-art microorganism networks, in conjunction with genetic alteration, artificial intelligence, data analysis, and the Internet of Things, have the potential to transform environmental cleanup, agriculture, and organic production. Tailored microorganisms can efficiently break down pollutants and cleanse polluted areas, while intelligent sensors allow for continual monitoring and adaptable microorganism behavior to enhance cleanup processes [104]. In agriculture, these systems enhance soil quality and safeguard plants using natural fertilizers and organic insecticides, reducing the need for synthetic chemicals [103]. The incorporation of these technologies into microorganism networks offers significant possibilities for tackling worldwide challenges, advancing economic development, and promoting environmental sustainability [105].

Ethical Considerations

Compliance with ethical guidelines

Not applicable

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Author's contributions

HMS conceived the study; MM designed the study design and wrote the first draft. RM performed language editing and suggested for quality improvement. HMS supervised the project and performed the final editing. HA and HMS performed literature search and collection and proofread the manuscript all authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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