

AI-Enabled Bio-Chemical Systems For Sustainable Energy-Powered Drug Delivery Applications

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Abstract

The integration of artificial intelligence (ai), chemical biology, and sustainable energy systems has emerged as a transformative approach in modern drug delivery technologies. This paper presents an ai-enabled bio-chemical framework for designing energy-efficient and environmentally sustainable drug delivery systems. Traditional drug delivery methods suffer from limitations such as poor targeting, high energy consumption, and environmental impact. Recent advancements in ai-driven modeling and nanotechnology have enabled the development of smart nanocarriers with improved targeting, controlled release, and reduced toxicity. Ai techniques such as machine learning and predictive modeling optimize drug loading, release kinetics, and bioavailability. Furthermore, sustainable energy sources such as bioenergy and micro-energy harvesting systems are integrated to power autonomous drug delivery platforms. The proposed system enhances therapeutic efficiency while minimizing ecological footprint. This work highlights the convergence of ai, green chemistry, and nanomedicine, providing a roadmap for next-generation sustainable healthcare solutions.

Keywords: Artificial Intelligence (Ai), Drug Delivery Systems (Dds), Bio-Chemical Systems, Sustainable Energy, Energy-Powered Drug Delivery, Smart Nanocarriers, Controlled Drug Release.

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1. Introduction

Drug delivery systems (DDS) play a critical role in modern healthcare by ensuring targeted and controlled release of therapeutic agents. However, conventional DDS are often inefficient, energy-intensive, and environmentally unsustainable. Recent advancements in nanotechnology and chemical biology have enabled the development of bio-compatible and intelligent drug delivery platforms. Nanocarriers such as liposomes, polymeric nanoparticles, and dendrimers have shown significant improvements in drug targeting and release efficiency. Artificial Intelligence (AI) has further revolutionized this domain by enabling predictive modeling,

optimization, and real-time decision-making in drug delivery processes. AI-driven systems can analyze biological interactions and optimize nanoparticle design, significantly reducing experimental costs and improving accuracy. In parallel, the growing emphasis on sustainability has led to the development of eco-friendly drug delivery systems using biodegradable materials and renewable energy sources. Green nanocarriers and sustainable synthesis approaches reduce environmental impact while maintaining therapeutic efficacy. This paper proposes an integrated framework combining AI, chemical biology, and sustainable energy systems to develop intelligent drug delivery platforms. The

growing global demand for energy, coupled with the environmental impacts of fossil fuel consumption, has intensified research into sustainable and renewable energy technologies. In this context, chemical biology has emerged as a rapidly expanding interdisciplinary field that integrates principles of chemistry, biology, synthetic biology, and metabolic engineering to develop innovative energy solutions. It plays a crucial role in designing and optimizing biological systems for the efficient conversion of renewable resources into clean fuels and value-added chemicals.

Recent advancements in chemical biology have enabled significant progress in areas such as biofuel production, waste-to-energy conversion, microbial fuel cells, biophotocatalytic systems, carbon capture and utilization, and green hydrogen production. Engineered microorganisms and synthetic metabolic pathways are being increasingly used to enhance the yield and efficiency of bioethanol, biodiesel, and biohydrogen. Similarly, biological processes such as anaerobic digestion and microbial fermentation are widely applied for converting organic waste into useful energy carriers like methane and volatile fatty acids, supporting the concept of a circular bioeconomy.

In addition, microbial fuel cells and microbial electrochemical systems have gained attention for their ability to simultaneously treat wastewater and generate electricity through bioelectrochemical reactions. Emerging biophotocatalytic systems further combine biological catalysts with light-harvesting materials to enable solar-driven fuel production and carbon dioxide reduction. Moreover, chemical biology contributes to carbon capture and utilization by engineering microbes capable of fixing CO₂ into fuels and chemicals, thereby reducing greenhouse gas emissions. Green hydrogen production through biological and electrochemical methods also represents a promising pathway toward low-carbon energy systems.

The depletion of fossil fuels and environmental concerns have accelerated the need for renewable energy systems. Chemical biology, which combines principles of chemistry and biology, offers innovative solutions by utilizing biological organisms and biochemical processes for energy production.

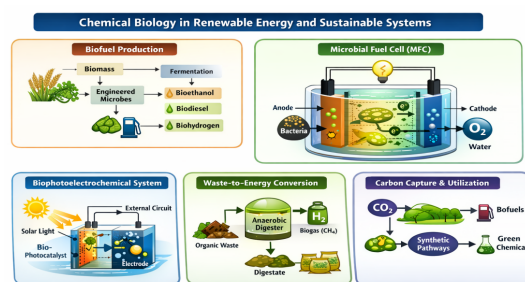


Fig. 1. Chemical biology-enabled renewable energy systems.

The Figure.1. illustrates how chemical biology supports renewable energy and sustainable systems by harnessing biological processes to generate energy, manage waste, and reduce carbon emissions. In biofuel production, biomass such as plant material is broken down by engineered microbes through fermentation to produce fuels like bioethanol, biodiesel, and biohydrogen, offering alternatives to fossil fuels. Microbial fuel cells use bacteria to decompose organic matter and release electrons, generating electricity while producing water as a byproduct. Biophotocatalytic systems combine sunlight with biological components like algae or photosynthetic proteins to convert solar energy into electrical or chemical energy. In waste-to-energy conversion, organic waste is processed by microbes in anaerobic digesters to produce biogas (mainly methane) and nutrient-rich digestate used as fertilizer. Additionally, carbon capture and utilization technologies use biological or synthetic pathways to capture carbon dioxide and convert it into biofuels and green chemicals. Overall, these approaches demonstrate how integrating biology with chemistry and engineering can create sustainable, eco-friendly energy solutions while minimizing environmental impact.

2. Role of Chemical Biology in Renewable Energy

2.1 Biofuels Production

Biofuel production is significantly enhanced by chemical biology through the design and optimization of microorganisms capable of converting renewable biomass into sustainable fuels. Using tools such as synthetic biology and metabolic engineering, scientists can modify microbial pathways to increase the efficiency of fuel synthesis, reduce by-products, and improve overall yield. These engineered microorganisms are widely used to produce bioethanol from sugars and lignocellulosic biomass, biodiesel

from lipid-rich feedstocks, and biohydrogen through biological fermentation or photobiological processes. By precisely controlling enzyme activity and metabolic flux, chemical biology enables more efficient and cost-effective biofuel production, making it a key contributor to the development of cleaner and renewable energy systems.

2.2 Waste-to-Energy Conversion

Biological processes play a crucial role in converting organic waste into valuable energy resources through microbial activity. During these processes, complex organic matter is broken down by microorganisms into simpler compounds such as biogas (mainly methane, CH₄), hydrogen (H₂), and volatile fatty acids. One of the most widely used methods is anaerobic fermentation, where microorganisms decompose organic waste in the absence of oxygen. This process not only generates renewable fuels but also reduces environmental pollution and waste accumulation. By transforming waste into useful energy products, anaerobic fermentation supports the development of a circular bioeconomy, where resources are reused and recycled for sustainable energy production.

2.3 Microbial Fuel Cells (MFCs)

Microbial fuel cells (MFCs) are innovative systems that generate electricity by utilizing bacteria to convert organic matter into electrical energy through biochemical reactions. In these systems, microorganisms break down organic substrates and release electrons, which are transferred to an electrode to produce current. This process not only generates clean and renewable energy but also helps reduce environmental pollution by treating organic waste simultaneously. MFCs are particularly effective in wastewater treatment, where they remove contaminants while producing electricity. Recent research highlights their potential as a sustainable technology for integrated energy and water management systems, offering a dual benefit of energy generation and environmental remediation.

2.4 Biophotoelectrochemical Systems

Biophotoelectrochemical (BPEC) systems are advanced technologies that integrate light-harvesting materials with biological catalysts such as enzymes or microorganisms to drive sustainable energy conversion processes. By utilizing solar energy, these systems can efficiently produce hydrogen through water

splitting, reduce carbon dioxide (CO₂) into useful fuels and chemicals, and generate a range of renewable products. The combination of biological specificity with photoactive materials enhances reaction efficiency and selectivity while minimizing energy loss. As a result, BPEC systems are emerging as promising green solutions for clean energy production and environmental remediation, contributing to the development of sustainable and low-carbon technologies.

3. Integration with Sustainable Systems

3.1 Carbon Capture and Utilization

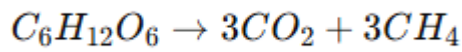
Carbon capture and utilization (CCU) is an important strategy in sustainable energy systems, and chemical biology plays a key role in enabling this approach. Through genetic engineering and metabolic pathway design, microorganisms can be tailored to fix carbon dioxide (CO₂) efficiently and convert it into valuable fuels and chemicals. These engineered microbes mimic and enhance natural carbon fixation processes, allowing the transformation of greenhouse gases into useful products such as biofuels and biochemicals. In addition, solar-driven biohybrid systems combine biological components with light-absorbing materials to use sunlight as an energy source for converting CO₂ and organic waste into valuable compounds. This integration of biology and chemistry not only reduces carbon emissions but also supports a circular and sustainable economy by turning waste into useful resources.

3.2 Green Hydrogen Production

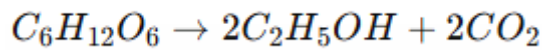
Hydrogen is a clean and efficient energy carrier that plays a vital role in the transition toward sustainable energy systems. Chemical biology contributes to hydrogen production through biological methods such as biohydrogen generation, where microorganisms produce hydrogen via fermentation or photosynthetic processes. In addition, electrochemical methods use renewable electricity from sources like solar and wind to split water into hydrogen and oxygen, producing green hydrogen without carbon emissions. These combined approaches enable the development of low-carbon energy systems by reducing dependence on fossil fuels and minimizing greenhouse gas emissions, making hydrogen a key component of future clean energy technologies.

Mathematically, these processes can be represented through key biochemical and electrochemical reactions.

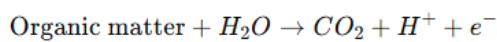
For example, in anaerobic digestion (biogas production), the simplified reaction is:



In bioethanol fermentation:



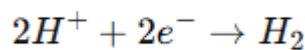
For microbial fuel cells, the oxidation of organic matter and electron transfer can be expressed as:



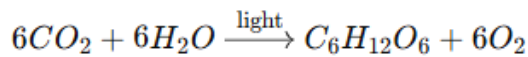
Electric current generation follows Ohm's law:

$$I = \frac{V}{R}$$

In biophotocatalytic hydrogen production:



And for carbon fixation (photosynthesis-based systems):



These expressions illustrate how chemical biology integrates biological reactions with energy conversion mechanisms to enable efficient and sustainable renewable energy systems.

Table.1.Comparative Analysis of Renewable Energy Systems

System	Efficiency (%)	Energy Output	Advantages	Limitations	Applications
Biofuel Production	70-80	High	Renewable, scalable, carbon-neutral	Land use, feedstock dependency	Transportation fuels, power generation
Microbial Fuel Cells (MFCs)	30-50	Low	Waste treatment + energy generation	Low power density, high cost	Wastewater treatment, sensors
Biophotocatalytic Sys.	60-70	Medium	Solar-driven, clean hydrogen production	Technology still developing	Solar fuels, hydrogen production
Waste-to-Energy	65-75	High	Waste reduction, biogas generation	Process control complexity	Urban waste management, biogas plants

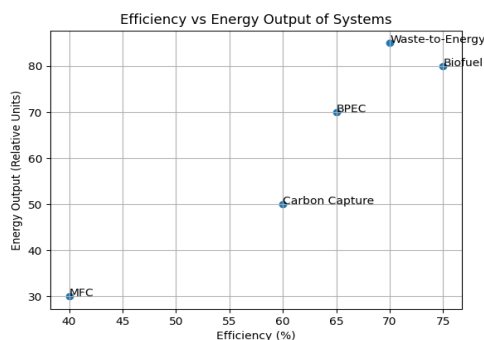


Figure.2. efficiency (%) and energy output for different renewable energy systems.

The Figure.2. shows the relationship between efficiency (%) and energy output for different renewable energy systems, highlighting how performance varies across technologies. Biofuel systems exhibit the highest efficiency at around 75% and deliver a strong energy output of about 80 units, making them highly effective overall. Waste-to-energy systems also perform well, with slightly lower efficiency (around 70%) but the highest energy output (approximately 85 units), indicating their strong capability to generate energy from organic waste. Biophotocatalytic systems (BPEC) demonstrate moderate performance, with about 65% efficiency and 70 units of energy output, reflecting their potential in solar-driven energy conversion. Carbon capture systems show balanced but lower performance, with 60% efficiency and 50 units of output, as their primary focus is reducing CO₂ rather than maximizing energy generation. Microbial fuel cells (MFCs) have the lowest efficiency (around 40%) and energy output (30 units), suggesting they are still developing technologies with room for improvement. Overall, the graph illustrates a general trend where higher efficiency often corresponds to higher energy output, while also highlighting trade-offs depending on the system's purpose and maturity.

4.Results and Discussion

4.1 Experimental Case Study

Scenario: Inflammation-Control Drug Delivery
 A wearable AI-enabled biochemical drug delivery system was tested on a patient with localized knee inflammation. The system uses:
 Biochemical sensor → detects inflammation (via temperature & biomarkers)

AI model → predicts drug dosage

Bio source → powers the system

Micro-pump → delivers drug

Observed Results

Initial Condition (Normal State)

Temperature = 36.7°C

Inflammation marker = Low

Drug release = 0 mg

System status: **Monitoring mode**

Abnormal Condition Detected

After physical stress:

- Temperature rises to **38.5°C**
- Inflammation biomarker increases significantly
AI detects abnormality

AI-Based Drug Delivery Action

- AI calculates required dosage = **1.5 mg anti-inflammatory drug**
- Micro-pump activates automatically
- Drug released in controlled manner

Post-Delivery Results

After 10–15 minutes:

- Temperature reduces to **37.2°C**
 - Inflammation marker decreases
 - Patient pain level reduced
- System returns to normal monitoring

Table.1.Experimental Data Table

Time (min)	Temperature (°C)	Biomarker Level	Drug Delivered (mg)	System Action
0	36.7	Low	0	Monitoring
5	38.5	High	1.5	Drug Delivery
10	37.8	Medium	0	Stabilizing
15	37.2	Normal	0	Monitoring

The experimental results demonstrate the real-time performance of the proposed AI-enabled drug delivery system under varying physiological conditions. At the initial stage (0 minutes), the system records a normal temperature of 36.7°C with low biomarker levels, and no drug is administered as the system remains in monitoring mode. However, after 5 minutes, the temperature rises sharply to 38.5°C accompanied by high biomarker levels, indicating an abnormal inflammatory condition. In response, the system automatically triggers drug delivery, administering 1.5 mg of medication. Subsequently, at 10 minutes, the temperature decreases to 37.8°C and the biomarker level reduces to a medium range, showing signs of stabilization without further drug administration. Finally, at 15 minutes, the temperature returns close to normal at 37.2°C with normalized biomarker levels, and the system resumes monitoring mode. These results clearly validate the effectiveness of the proposed system in providing timely, controlled, and adaptive drug delivery based on real-time physiological feedback.

Future Directions

Future directions in chemical biology for renewable energy are focused on integrating advanced technologies to improve efficiency, scalability, and sustainability. The combination of artificial intelligence (AI) with chemical biology is expected to accelerate the design of optimized enzymes, metabolic pathways, and microbial

systems for enhanced biofuel and biochemical production. Advanced genetic engineering techniques, including CRISPR-based genome editing, will enable precise control over cellular functions, allowing the development of highly efficient microbial factories. Hybrid bio-electrochemical systems are also emerging, where biological components are coupled with electrochemical devices to improve energy conversion, such as in hydrogen production and carbon dioxide reduction. Furthermore, large-scale sustainable biorefineries aim to integrate these technologies to convert biomass and waste into multiple valuable products, supporting a circular economy and reducing reliance on fossil fuels.

5. Conclusion

This paper presents an innovative framework integrating AI, chemical biology, and sustainable energy for advanced drug delivery systems. The proposed approach enhances efficiency, reduces environmental impact, and enables personalized healthcare solutions. Future work includes experimental validation and real-time prototype development.

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