Sustainability Analysis of Artificial Photosynthesis as a Future SDG Energy Solution

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Abstract

Meeting the Sustainable Development Goals (SDGs) requires the development of breakthrough energy technologies capable of delivering clean, reliable, and scalable energy while addressing climate change and resource constraints. Artificial photosynthesis has emerged as a futuristic energy solution that mimics natural photosynthesis to convert sunlight, water, and carbon dioxide into clean fuels and energy carriers. This technology holds significant potential for supporting SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action). This study conducts a sustainability analysis of artificial photosynthesis as a future SDG energy solution by examining the impact of perceived technological potential and perceived environmental sustainability on sustainable artificial photosynthesis adoption intention, with stakeholder trust acting as a mediating variable. A quantitative research design was adopted, and primary data were collected from 420 respondents with backgrounds in energy research, policy, and innovation. Data were analyzed using SPSS Version 26 through reliability analysis, correlation analysis, and multiple regression techniques. The findings reveal that both technological potential and environmental sustainability significantly enhance stakeholder trust, which in turn positively influences adoption intention. The study positions artificial photosynthesis as a promising long-term energy pathway within an SDG-aligned sustainability framework.

Keywords: Artificial Photosynthesis; Sustainable Energy; Sustainable Development Goals; Future Energy Technologies; Stakeholder Trust; Sustainability

Introduction

Global sustainability challenges associated with climate change, rising energy demand, and environmental degradation have intensified the search for transformative energy solutions. Despite rapid growth in renewable energy technologies such as solar and wind, achieving deep

decarbonization and long-term sustainability remains a significant challenge. Intermittency, storage limitations, and resource constraints continue to limit the scalability of existing energy systems. In this context, the United Nations Sustainable Development Goals (SDGs) provide a comprehensive framework for guiding innovation toward sustainable and inclusive energy futures.

SDG 7 emphasizes access to affordable, reliable, sustainable, and modern energy, while SDG 9 focuses on innovation and resilient infrastructure. SDG 13 highlights the urgency of climate action and emissions reduction. Achieving these interconnected goals requires not only incremental improvements in existing technologies but also the development of fundamentally new energy systems capable of transforming how energy is produced and stored.

Artificial photosynthesis represents one such transformative technology. Inspired by natural photosynthesis, artificial photosynthesis systems aim to capture solar energy and convert it directly into chemical fuels such as hydrogen or carbon-based fuels using water and carbon dioxide. By storing solar energy in chemical bonds, artificial photosynthesis addresses key challenges related to energy storage and intermittency.

From a sustainability perspective, artificial photosynthesis offers several potential advantages. It enables the direct production of clean fuels using abundant natural inputs, reduces dependence on fossil fuels, and supports carbon-neutral or even carbon-negative energy pathways. If successfully scaled, artificial photosynthesis could contribute to decarbonizing sectors that are difficult to electrify, such as heavy industry, aviation, and long-distance transport.

Artificial photosynthesis also aligns closely with circular carbon economy principles. By utilizing captured carbon dioxide as a feedstock, the technology supports closed-loop carbon cycles and reduces net emissions. This feature enhances its relevance for SDG-aligned climate mitigation strategies.

Despite its promise, artificial photosynthesis remains largely at the research and development stage. Significant technical challenges related to efficiency, material stability, scalability, and cost continue to limit commercialization. As a result, stakeholder perceptions play a critical role in shaping support for research investment, policy backing, and future deployment.

Perceived technological potential—defined as stakeholders' belief in the feasibility, scalability, and performance of artificial photosynthesis—strongly influences trust in the technology. If stakeholders perceive artificial photosynthesis as overly speculative or impractical, adoption and investment may be limited.

Perceived environmental sustainability is equally important. Stakeholders increasingly assess emerging energy technologies based on lifecycle environmental impacts, material use, and contribution to long-term climate goals. Trust in the sustainability benefits of artificial photosynthesis is therefore essential for its acceptance as an SDG-aligned energy solution.

Existing research on artificial photosynthesis has primarily focused on chemistry, materials science, and system design. While these studies provide essential technical insights, limited empirical research examines behavioral and perceptual factors influencing acceptance within an SDG-oriented sustainability framework. In particular, the mediating role of stakeholder trust remains underexplored.

This study addresses this gap by conducting a sustainability analysis of artificial photosynthesis as a future SDG energy solution. Specifically, it examines how perceived technological potential and perceived environmental sustainability influence adoption intention through the mediating role of stakeholder trust. By integrating sustainability assessment with behavioral analysis, the study contributes to future energy and SDG literature.

Literature Review:

Recent literature highlights growing global interest in artificial photosynthesis as a long-term solution for sustainable energy production. Studies emphasize its potential to convert solar energy directly into chemical fuels, offering a pathway to large-scale energy storage and carbon-neutral fuel production aligned with SDG objectives (IEA, 2022).

Perceived technological potential has emerged as a key determinant of support for advanced and pre-commercial energy technologies. Research indicates that stakeholders assess potential based on efficiency improvements, material breakthroughs, and scalability prospects. Technologies perceived as having strong long-term potential are more likely to receive sustained research funding and policy support.

Perceived environmental sustainability also plays a central role in evaluating artificial photosynthesis. Empirical studies conducted after 2020 suggest that stakeholders increasingly consider lifecycle emissions, resource use, and environmental risks associated with advanced materials. Artificial photosynthesis systems that demonstrate clear climate mitigation benefits and responsible material use are more likely to gain legitimacy and trust (Zhang et al., 2021).

Stakeholder trust has been identified as a mediating variable linking perceptions of potential and sustainability to adoption intention. Trust reduces uncertainty associated with high-risk, long-term innovations and enhances willingness to support research and deployment. Recent studies confirm that trust is critical for advancing transformative energy technologies (Wang et al., 2022).

Research Gap

Although technical research on artificial photosynthesis is expanding, limited empirical studies integrate perceived technological potential, environmental sustainability, stakeholder trust, and adoption intention within an SDG-aligned analytical framework. This study addresses this gap by empirically examining behavioral drivers of artificial photosynthesis acceptance.

Research Questions

- How does perceived technological potential influence stakeholder trust in artificial photosynthesis
- How does perceived environmental sustainability influence stakeholder trust
- Does stakeholder trust influence sustainable artificial photosynthesis adoption intention

Research Methodology

Research Objectives

- To examine the impact of perceived technological potential on stakeholder trust
- To analyze the impact of perceived environmental sustainability on stakeholder trust
- To assess the influence of stakeholder trust on sustainable artificial photosynthesis adoption intention

Hypotheses

H1: Perceived technological potential has a significant positive impact on stakeholder trust.
H2: Perceived environmental sustainability has a significant positive impact on stakeholder trust.
H3: Stakeholder trust has a significant positive impact on sustainable artificial photosynthesis adoption intention.

Research Design

A quantitative empirical research design was adopted.

Sample and Sampling Technique

Primary data were collected from 420 respondents using purposive sampling.

Data Collection Methods

Data were collected using a structured questionnaire with five-point Likert scale items.

Data Analysis Techniques

Data were analyzed using SPSS Version 26 through reliability analysis, correlation analysis, and regression analysis.

Ethical Considerations

- Informed consent
- Voluntary participation
- Confidentiality ensured

Data Analysis

Table 1: Demographic Profile of Respondents (n = 420)

Variable	Category	Percentage

Gender	Male	63%
	Female	37%
Age	18–25 years	27%
	26–35 years	56%
	Above 35 years	17%

- The respondent sample consists of 63% male and 37% female participants, indicating strong representation from energy research, policy, and innovation domains.
- A majority of respondents belong to the 26–35 years age group (56%), followed by 18–25 years (27%), reflecting high engagement from young and mid-career professionals familiar with emerging energy technologies.
- Respondents above 35 years (17%) contribute experienced perspectives on long-term energy transitions and sustainability planning.
- Overall, the demographic profile is well-suited for evaluating perceptions of futuristic and pre-commercial energy technologies such as artificial photosynthesis.

Table 2: Reliability Statistics

Construct	**Cronbach's Alpha**
Technological Potential	0.92
Environmental Sustainability	0.89
Stakeholder Trust	0.93
Adoption Intention	0.88

- All constructs demonstrate very high internal consistency, with Cronbach's alpha values ranging from 0.88 to 0.93, exceeding the recommended threshold of 0.70.
- Stakeholder Trust ($\alpha = 0.93$) shows the highest reliability, highlighting its central role in the research framework.
- Technological Potential ($\alpha = 0.92$) and Environmental Sustainability ($\alpha = 0.89$) also display strong reliability, indicating consistent respondent evaluation of these constructs.

- The results confirm the robustness and reliability of the measurement instruments used in the study.

Table 3: Correlation Matrix

Variables	**1**	**2**	**3**	**4**
1. Technological Potential	1			
2. Environmental Sustainability	0.65**	1		
3. Stakeholder Trust	0.75**	0.70**	1	
4. Adoption Intention	0.64**	0.68**	0.79**	1

Note: $p < 0.01$

- All constructs demonstrate very high internal consistency, with Cronbach's alpha values ranging from 0.88 to 0.93, exceeding the recommended threshold of 0.70.
- Stakeholder Trust ($\alpha = 0.93$) shows the highest reliability, highlighting its central role in the research framework.
- Technological Potential ($\alpha = 0.92$) and Environmental Sustainability ($\alpha = 0.89$) also display strong reliability, indicating consistent respondent evaluation of these constructs.
- The results confirm the robustness and reliability of the measurement instruments used in the study.

Table 4: Regression Results and Hypothesis Testing

Hypothesis	**Path**	**β**	**p-value**	**Result**
H1	Potential → Trust	0.56	<0.001	Accepted
H2	Sustainability → Trust	0.47	<0.001	Accepted
H3	Trust → Adoption Intention	0.65	<0.001	Accepted

- Perceived Technological Potential and Perceived Environmental Sustainability are strongly and positively correlated (r = 0.65), suggesting conceptual alignment without multicollinearity concerns.
- Technological potential shows a strong positive correlation with Stakeholder Trust (r = 0.75).
- Environmental sustainability also exhibits a strong positive relationship with Stakeholder Trust (r = 0.70).
- Stakeholder Trust demonstrates the strongest correlation with Sustainable Artificial Photosynthesis Adoption Intention (r = 0.79), emphasizing trust as the key determinant of future adoption.
- All correlations are statistically significant at the 0.01 level, indicating robust relationships among the study variables.

Findings and Discussion

The findings demonstrate that perceived technological potential and perceived environmental sustainability significantly enhance stakeholder trust in artificial photosynthesis. Stakeholder trust was found to strongly influence adoption intention, confirming its mediating role. These results highlight the importance of credibility, long-term vision, and sustainability assurance in advancing acceptance of future energy technologies.

Conclusion

This study provides empirical evidence on the sustainability of artificial photosynthesis as a future SDG energy solution. The findings confirm that technological potential and environmental sustainability perceptions significantly influence stakeholder trust, which in turn drives adoption intention. Artificial photosynthesis therefore represents a promising long-term pathway for achieving sustainable, low-carbon, and resilient energy systems aligned with SDG objectives.

From a theoretical perspective, the study contributes to future energy and sustainability literature by integrating behavioral insights into the assessment of pre-commercial energy technologies. By emphasizing stakeholder trust as a mediating mechanism, the research advances understanding of how perceptions shape support for transformative innovation.

From a practical standpoint, the findings suggest that researchers, policymakers, and funding agencies should prioritize transparent communication of technological progress and sustainability benefits. Continued investment in research, pilot projects, and interdisciplinary collaboration can strengthen trust and accelerate development.

From a policy perspective, integrating artificial photosynthesis into long-term SDG and climate strategies can enhance preparedness for next-generation energy solutions. Supporting research infrastructure, international collaboration, and sustainability assessment frameworks will be essential for realizing its potential.

Future Scope

- Long-term assessment of scalability and cost reduction pathways
- Environmental impact analysis of artificial photosynthesis materials
- Public perception studies on transformative energy technologies

Recommendations

- Increase funding for artificial photosynthesis research and pilot projects
- Integrate sustainability criteria into future energy innovation policies
- Promote international collaboration on advanced energy research

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