

Artificial Photosynthesis for Net-Zero Energy Integration in Commercial Buildings: A Systematic Literature Review

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Abstract

The transition toward net-zero energy commercial buildings has intensified interest in emerging sustainable technologies capable of enabling low-carbon and self-sustaining energy systems. Among these, artificial photosynthesis has gained growing attention due to its potential to convert solar energy into storable chemical fuels and integrate with building energy systems. This study presents a systematic literature review of research published between 2016 and 2026, examining the role of artificial photosynthesis in net-zero energy integration for commercial buildings. Guided by the PRISMA framework, a structured search was conducted across Scopus AI, ScienceDirect, Google Scholar, and Springer, resulting in the selection of 37 peer-reviewed journal articles for in-depth synthesis. The review analyses technological configurations, energy conversion pathways, system integration strategies and sustainability implications. Findings indicate that while artificial photosynthesis remains at an early developmental stage for building scale applications, it demonstrates strong potential when combined with photovoltaics, hydrogen systems and smart energy management. However, challenges related to efficiency, scalability, cost and policy support persist. The study contributes a consolidated knowledge base and identifies a future research agenda to inform technological development, policy formulation and net-zero energy strategies in commercial building contexts.

Keywords: Artificial photosynthesis, Commercial buildings, Net-zero energy buildings, Sustainable energy technologies, Systematic literature review.

1. Introduction

The transition toward net-zero energy buildings (NZEBS) has intensified in response to global decarbonisation commitments and the growing need to reduce operational and embodied carbon within the built environment (Hamzah & Go, 2023; Horzela-Miś et al., 2025). NZEBs are broadly defined as highly energy-efficient structures that generate as much energy on-site as they consume over an annual cycle, typically through the integration of renewable energy technologies (IEA, 2022; Marszal et al., 2011). The built environment sector accounts for approximately 37% of global energy-related carbon dioxide emissions, with commercial buildings representing a disproportionately large share due to their scale, operational intensity and continuous occupancy demands (IEA, 2022). Achieving net-zero performance in commercial buildings therefore requires not only passive design strategies, but also the deployment of advanced on-site energy generation and storage technologies capable of meeting residual energy needs across variable seasonal and diurnal conditions (Lv et al., 2025; Muthukumaran et al., 2024). While photovoltaic (PV) systems remain the dominant on-site renewable energy solution, their dependence on intermittent solar availability highlights the need for

complementary energy storage pathways (Song et al., 2019; Abbas et al., 2020).

Artificial photosynthesis (AP) is a bio-inspired process that replicates the mechanisms of natural photosynthesis to convert solar energy, water and carbon dioxide into hydrogen or other chemical fuels (Wang & Pornrungraj, 2025; Mohlaba et al., 2023). Unlike photovoltaic systems, which generate electricity instantaneously from solar irradiance, AP enables direct solar-to-fuel conversion, producing a storable chemical energy carrier capable of addressing the long-duration storage limitations that constrain current PV-dominant renewable energy strategies (Zou et al., 2025; Ganesh, 2023). Recent advances in photocatalytic materials and photoelectrochemical (PEC) systems have improved laboratory-scale performance, prompting growing interest in AP as part of integrated renewable-hydrogen energy systems (Wang & Pornrungraj, 2025; Li et al., 2021).

Despite increasing research activity, AP literature remains concentrated within materials science and electrochemical engineering, with limited consideration of commercial building applications (Ganesh, 2023; Wenten et al., 2024). Issues such as building integration, lifecycle costs, procurement, safety and regulatory requirements remain

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underexplored (Pillai et al., 2022; Lucchi et al., 2025). This study therefore examines how AP is positioned within net-zero energy research and identifies the technological, economic and implementation barriers affecting its future integration into commercial buildings through a systematic review of 37 peer-reviewed studies published between 2016 and 2026 (Abbas et al., 2020; Sonyy et al., 2026).

2. Research Methodology

2.1. Literature Search Strategy

This study employed a systematic literature review (SLR) approach to synthesise research on artificial photosynthesis for net-zero commercial building integration. Given the early developmental stage of AP technologies and the absence of operational building-scale applications, an SLR was selected as the most appropriate methodological approach, enabling rigorous synthesis of fragmented knowledge across disciplines, including materials science, energy engineering and built environment research, without requiring primary empirical data that does not yet exist at building scale (Nena et al., 2022; Moher et al., 2014). Therefore, a systematic phase-based search was conducted in four selected bibliographic databases (Scopus, Springer, ScienceDirect and Google Scholar) from 2016 to 2026. The search strategy was performed using Boolean operators (Nena et al., 2022) and the following terms were used as search strings: “Artificial photosynthesis” AND “built environment”, “Artificial photosynthesis” AND “net zero”, “Sustainable energy materials” AND “commercial buildings”,

“Electrochemical energy systems” AND “construction”, “Building-integrated energy systems” AND “carbon reduction”.

2.2. Study Selection Process

Following initial database searches, titles and abstracts were screened to remove irrelevant publications, with remaining studies assessed through full-text screening, resulting in a final dataset of 37 studies. The process was documented using a PRISMA flow diagram (Figure 1) to ensure transparency (Moher et al., 2014).

2.3. Data Extraction and Quality Assessment

2.3.1. Data Extraction

Data extracted from each study included publication year, geographical origin, methodological approach, technological focus and key findings. The data were analysed using descriptive statistics and thematic synthesis to identify recurring patterns relating to technology development, system integration, economic feasibility and implementation challenges.

3. Findings and Discussion

3.1. Findings

3.1.1. Temporal Distribution Overview

Publication frequency between 2016 and 2026 demonstrates a consistent upward trend, with significant growth after 2020 reflecting expanding global interest in hydrogen-based renewable systems

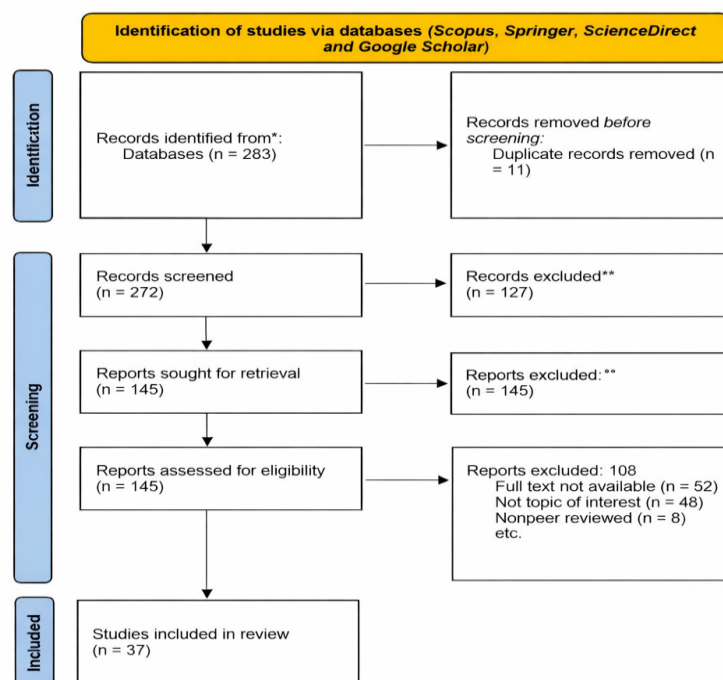


Figure 1: PRISMA Flow Diagram

and solar fuel technologies, peaking between 2022 and 2026 (Figure 2).

3.1.2. Geographical Distribution of Reviewed Studies

China accounts for the highest share of publications (23 studies), followed by India (6), South Africa and Switzerland (3 each), with smaller contributions from several European and Asian countries, concentrated in regions with active hydrogen economy development and strong materials science research infrastructure (Figure 3).

3.1.3. Descriptive Characteristics of Reviewed Studies

The reviewed studies were classified according to study type and technological focus to identify dominant research methodologies and technological orientations, as presented in Table 1 in Appendix 1.

3.2. Discussion

This discussion interprets the findings in relation to the two guiding research questions: (RQ1) how is artificial photosynthesis currently positioned within net-zero energy research for commercial buildings, and (RQ2) what technological, economic and implementation gaps currently limit its uptake in commercial building contexts. The discussion proceeds through a thematic synthesis of the literature, followed by direct responses to RQ1 and RQ2, with practical implications for built environment practice highlighted throughout.

3.2.1. Thematic Synthesis of Reviewed Literature

The thematic synthesis of the reviewed literature identified four dominant research themes within the field of renewable energy integration for net-zero commercial buildings, as shown in Table 2 in Appendix 1. The reviewed studies demonstrate a progression from fundamental technology development toward integrated energy system management and environmental evaluation. While a substantial proportion of the literature remains focused on laboratory-scale technological innovations, an increasing number of studies are exploring system-level optimisation, sustainability assessment and the integration of renewable technologies within built environment applications, signalling that AP is transitioning from a purely scientific research domain toward one with emerging relevance for building energy system design and procurement.

3.2.2. RQ1: Positioning of AP within Net-Zero Energy Systems

The reviewed literature indicates that AP is increasingly positioned within broader net-zero and renewable energy system research rather than being treated solely as an isolated chemical process. Research is primarily focused on solar-to-fuel conversion technologies, particularly photoelectrochemical systems and catalyst development aimed at converting solar energy into hydrogen or other chemical fuels

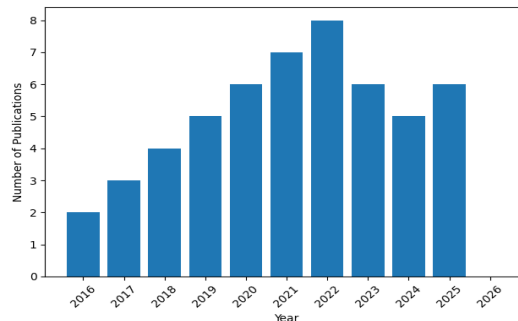


Figure 2: Publications per Year between 2016-2026

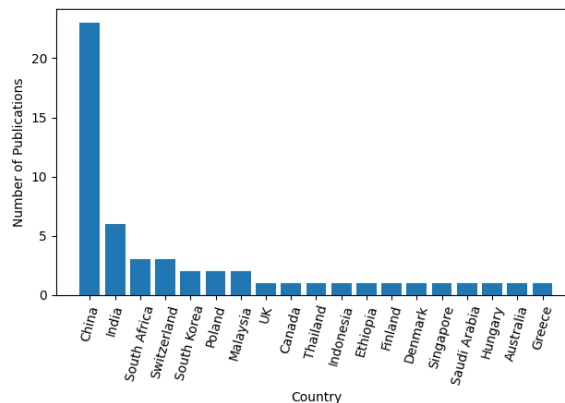


Figure 3: Publications per Country (2016-2026)

(Kuittinen et al., 2021; Temiz & Dincer, 2023; Wenten et al., 2024). These studies primarily originate from materials science and electrochemical engineering disciplines and concentrate on improving catalytic activity, conversion efficiency and long-term stability of artificial photosynthesis systems. Within the broader net-zero energy discourse, hydrogen produced through solar-driven processes is increasingly conceptualised as a long-duration energy storage solution capable of addressing renewable energy intermittency (Song et al., 2019; Li et al., 2021; Zhang et al., 2026). As a result, AP is progressively framed as part of an integrated renewable-hydrogen energy ecosystem that can complement PV electricity generation and energy storage within future building-scale energy systems (Wei & An, 2024; Liu et al., 2025; Hua et al., 2025). In response to RQ1, AP is best understood not as a replacement for PV but as a complementary long-duration storage pathway within integrated net-zero building energy systems, with practical implications for how energy system briefs are drafted, how multi-technology procurement packages are structured, and how lifecycle cost assessments are framed when both electricity generation and chemical fuel storage are involved.

3.2.3. RQ2: Limitations and Gaps in Commercial Building Integration of Artificial Photosynthesis

Despite promising developments, AP integration within commercial buildings remains constrained by technological immaturity, economic uncertainty and institutional barriers (Mohlaba et al., 2023; Wenten et al., 2024; Jachimowski et al., 2025). Key challenges include catalyst degradation, low conversion efficiencies, limited building-scale performance data, uncertain lifecycle costs and hydrogen infrastructure requirements (Kuittinen et al., 2021; Wang et al., 2024; Horzela-Miś et al., 2025). From an economic perspective, several studies identify uncertainties regarding capital costs, hydrogen production economics and the infrastructure requirements associated with hydrogen storage and distribution at the building scale (Song et al., 2019; Li et al., 2021; Wang et al., 2026; Zhang et al., 2026). From a quantity surveying standpoint, the absence of building-scale techno-economic data presents a significant constraint: without reliable cost benchmarks, lifecycle cost modelling and investment appraisal for AP integration cannot be undertaken with confidence. Implementation barriers are further compounded by safety

considerations relating to on-site hydrogen storage, regulatory constraints and the lack of large-scale demonstration projects integrating hydrogen-based energy systems within commercial buildings (Ganesh, 2023; Wei & An, 2024; Zou et al., 2025). In summary, RQ2 is answered by the convergent evidence that technological immaturity, economic uncertainty and institutional unpreparedness collectively constrain the near-term integration of AP in commercial buildings, requiring interdisciplinary collaboration across materials science, building engineering, quantity surveying and regulatory policy, as well as further research on techno-economic feasibility, system integration strategies and pilot-scale demonstrations within the built environment (Hua et al., 2025; Liu et al., 2025; Li et al., 2026).

4. Conclusion and Further Research

This review synthesised 37 studies examining the role of artificial photosynthesis in net-zero commercial building research. The findings indicate that AP is increasingly viewed as a complementary technology within renewable-hydrogen energy ecosystems rather than as a replacement for photovoltaic systems. Its principal contribution lies in its potential to support long-duration energy storage through solar-to-hydrogen conversion.

However, AP remains at an early stage of technological maturity. Key barriers include catalyst durability, conversion efficiency limitations, uncertain economic viability, hydrogen infrastructure requirements and underdeveloped regulatory frameworks. The literature also reveals a shortage of building-scale studies, demonstration projects and lifecycle cost assessments relevant to commercial building implementation.

Future research should prioritise pilot-scale demonstrations, techno-economic modelling, lifecycle cost benchmarking and regulatory development for hydrogen-integrated buildings. Greater engagement from construction business and project management researchers will be essential to ensure that emerging AP technologies can be effectively translated into practical built-environment applications.

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Appendix 1

Table 1: Descriptive Characteristics of Studies Included in the Systematic Review

Dimension: <i>Category</i>	Description of Evidence in Reviewed Studies	Sources (citations)
Study Type:		
Experimental	Laboratory experiments investigate the performance of photocatalytic materials, photoelectrodes and reactor designs used in AP.	Jachimowski et al., 2025; Horzela-Miś et al., 2025; Muthukumaran et al., 2024; Abbas et al., 2020; Zhou & Zhou, 2023; Li et al., 2021; Hua et al., 2025; Temiz & Dincer, 2023; Lv et al., 2025; Song et al., 2019; Zhang et al., 2024; Mohlabla et al., 2023; Zhai et al., 2025; Qiu et al., 2025;
Modelling	Computational prediction of energy conversion and system performance	Liu et al., 2025; Ganesh, 2023; Wenten et al., 2024; Zhao et al., 2025
Simulation	Numerical simulations analyse AP system behaviour, solar utilisation efficiency and integration with renewable energy systems.	Wang et al., 2025; Wenten et al., 2024; Rehman et al., 2021; Gebreabe et al., 2025; Wang et al., 2026; Dong et al., 2025; Wei & An, 2024; Zou et al., 2025
Techno-economic analysis	Evaluation of cost, scalability and lifecycle performance	Raman et al., 2024; Kuittinen et al., 2021; Zhang et al., 2026; Wang et al., 2024; Alharasees et al., 2024
Review	Review studies synthesise existing research to identify technological advances, limitations, and future research directions in artificial photosynthesis.	Ullhøi, 2021; Hamzah & Go, 2023; Sonny et al., 2026; Lu et al., 2025
Technology Focus:		
Photocatalytic systems	Photocatalytic systems use semiconductor catalysts to enable solar-driven water splitting or CO ₂ reduction, focusing on efficiency and material stability.	Jachimowski et al., 2025; Horzela-Miś et al., 2025; Muthukumaran et al., 2024; Abbas et al., 2020; Zhou & Zhou, 2023; Li et al., 2021; Hua et al., 2025; Temiz & Dincer, 2023; Lv et al., 2025; Mohlabla et al., 2023; Zhai et al., 2025
Photoelectrochemical (PEC) cells	Photoelectrochemical cells integrate light absorption and electrochemical reactions to improve solar energy conversion efficiency and durability.	Song et al., 2019; Zhang et al., 2024; Liu et al., 2025; Wang & Pornrungrroj, 2025; Ganesh, 2023; Arora et al., 2024; Wenten et al., 2024;
Hydrogen production	Many studies focus on solar-driven water splitting to produce hydrogen as a clean and sustainable energy carrier.	Wang & Pornrungrroj, 2025; Ganesh, 2023; Arora et al., 2024; Zhao et al., 2025; Wei & An, 2024; Zou et al., 2025
Hybrid PV-artificial photosynthesis systems	Hybrid systems combine photovoltaic technology with catalytic processes to enhance energy conversion efficiency and operational control.	Wang et al., 2025; Wenten et al., 2024; Rehman et al., 2021; Dong et al., 2025; Wei & An, 2024; Hur et al., 2023; Lu et al., 2025; Li et al., 2026

Table 2: Thematic Classification Matrix

Theme	Description of Theme	Key Findings from Reviewed Studies	Sources
Artificial Photosynthesis and Solar-to-Fuel Technologies	Studies focusing on the development of AP systems and photoelectrochemical processes for solar driven fuel production	Research focuses on catalyst development, conversion efficiency and scalability; most studies remain laboratory based.	Muthukumaran et al., 2024; Zhou & Zhou, 2023; Li et al., 2021; Hua et al., 2025; Temiz & Dincer, 2023; Lv et al., 2025; Song et al., 2019; Zhang et al., 2024; Mohlabi et al., 2023; Wang et al., 2025
Hydrogen Production and Energy Storage Systems	Research examining hydrogen generation, storage, and utilisation as part of renewable energy systems.	Hydrogen is viewed as a promising long-duration storage solution, although cost and infrastructure challenges remain.	Li et al., 2021; Lv et al., 2025; Zhang et al., 2024; Liu et al., 2025; Wang & Pornrungrroj, 2025; Ganesh, 2023; Arora et al., 2024; Mohlabi et al., 2023; Wang et al., 2025
Photovoltaic and Hybrid Solar Energy Systems	Studies investigating photovoltaic (PV), photovoltaic-thermal (PVT), and hybrid solar technologies for renewable electricity generation and building integration.	PV technologies remain more mature and possess established building-integration pathways.	Jachimowski et al., 2025; Horzela-Miś et al., 2025; Abbas et al., 2020; Wenten et al., 2024; Rehman et al., 2021; Gebreabe et al., 2025; Dong et al., 2025; Zhai et al., 2025; Zhao et al., 2025; Raman et al., 2024; Kuittinen et al., 2021
Energy Optimisation, Smart Systems, and Sustainability Assessment	Studies addressing digital energy management, optimisation techniques, and sustainability evaluation of renewable energy systems.	Machine learning, optimisation and lifecycle assessment are increasingly used to improve renewable energy performance.	Jachimowski et al., 2025; Abbas et al., 2020; Ganesh, 2023; Ulhøi, 2021; Zhang et al., 2026; Qiu et al., 2025; Wei & An, 2024; Wang et al., 2024; Hamzah & Go, 2023; Zou et al., 2025; Alharasees et al., 2024; Sonny et al., 2026; Hur et al., 2023; Lu et al., 2025; Li et al., 2026