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Comprehensive Review of Strengths and Weaknesses of Solar-Biomass Hybrid Power Systems: A Systematic Literature Approach

Fitri Setiabudi[1*], Muhammad Syukri Nur[2], Aep Saepul Uyun[3], As Natio Lasman[4]

[1,2,3,4] Renewable Energy Enginering Graduate Program, Universitas Darma Persada
Jalan Taman Malaka Selatan, Pondok Kelapa, Duren Sawit, Jakarta Timur 13450, Indonesia

[*]Korespondensi penulis: fitri.setiabudi@gmail.com

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Abstrak. Sistem pembangkit listrik hibrida surya-biomassa (Solar-Biomass Hybrid Power Systems/SBHPS) menawarkan solusi yang menjanjikan terhadap tantangan energi dan iklim global dengan mengintegrasikan dua sumber energi terbarukan yang saling melengkapi. Studi ini menyajikan tinjauan literatur sistematis (Systematic Literature Review/SLR) berdasarkan 543 artikel yang diperoleh dari Scopus dan Web of Science (periode 2014 hingga 2024), dengan 76 teks lengkap disaring, 26 memenuhi kriteria inklusi, dan 18 di antaranya memperoleh skor ≥4/5 berdasarkan kerangka kerja CASP dan MMAT. Analisis ini mengidentifikasi keunggulan utama SBHPS, termasuk peningkatan efisiensi energi, keandalan pasokan, pengurangan emisi gas rumah kaca, dan pemanfaatan sumber daya lokal. Sebaliknya, hambatan yang dihadapi mencakup biaya modal yang tinggi, ketergantungan terhadap sumber daya, kompleksitas teknis, dan keterbatasan kebijakan. Keunikan tinjauan ini terletak pada sintesis multidimensi yang terintegrasi, mencakup aspek teknis, ekonomi, lingkungan, dan sosial, yang mengisi kesenjangan yang belum dijangkau oleh tinjauan SBHPS sebelumnya. Temuan ini memberikan wawasan praktis bagi perencana energi, pengembang teknologi, dan pembuat kebijakan yang ingin menerapkan sistem hibrida yang berkelanjutan dan sesuai dengan kondisi regional.

Kata kunci: pembangkit listrik hibrida, energi matahari, energi biomassa, efisiensi energi, keberlanjutan energi.

Abstract. Solar-biomass hybrid power systems (SBHPS) offer a promising solution to global energy and climate challenges by integrating two complementary renewable sources. This study presents a systematic literature review (SLR) based on 543 articles retrieved from Scopus and Web of Science (2014 to 2024), with 76 full texts screened, 26 meeting the inclusion criteria, and 18 scoring ≥4/5 in quality based on CASP and MMAT frameworks. The analysis identifies key advantages of SBHPS, including improved energy efficiency, supply reliability, greenhouse gas emission reduction, and local resource utilization. Conversely, barriers include high capital costs, resource dependency, technical complexity, and policy constraints. The novelty of this review lies in its integrated, multi dimensional synthesis across technical, economic, environmental, and social aspects, filling a gap left by earlier SBHPS reviews. The findings offer practical insights for energy planners, technology developers, and policymakers aiming to implement sustainable and regionally adapted hybrid systems.

Keywords: hybrid power plant, solar energy, biomass energy, energy efficiency, energy sustainability.

INTRODUCTION

The global energy crisis and the threat of climate change represent two interrelated and pressing challenges that must be urgently addressed [1]. The world's dependence on fossil fuels has led to increased greenhouse gas emissions, exacerbating global warming, disrupting ecological balance, and causing various environmental disasters [2]. In addition, the depletion of fossil fuel resources and the volatility of global energy prices contribute to uncertainty in energy supply, directly impacting both national and global energy security.

In this context, renewable energy emerges as a strategic solution offering sustainability, energy security, and significant environmental benefits [3]. Among the renewable energy sources with high development potential are solar energy and biomass. Solar energy is widely available, particularly in tropical regions such as Indonesia, while biomass offers the opportunity to utilize organic waste from the agricultural, forestry, and household sectors as a renewable and sustainable fuel source [4].

The hybrid power generation system that combines solar and biomass energy; **solar-biomass hybrid power system (SBHPS)**, has emerged as an innovative approach that leverages the strengths of both sources. Solar energy can generate electricity during the day when solar radiation is at its peak, while biomass can provide continuous energy supply, including at night or during cloudy weather. This synergy makes SBHPS more reliable than single-source renewable systems by reducing variability and improving the continuity of electricity supply [5].

Previous studies have highlighted various advantages of SBHPS. These include higher energy conversion efficiency, energy source diversification that enhances energy security, and a significant reduction in greenhouse gas emissions [6]. Moreover, SBHPS facilitates the use of local resources; especially biomass from domestic waste or agricultural industry by-products; which supports the circular economy and creates new employment opportunities in the clean energy sector [7].

However, SBHPS also faces several challenges and limitations that need to be considered. One major challenge is the relatively high initial investment required, including the cost of solar panels, thermal capture systems, and biomass combustion or gasification infrastructure [4]. There is also a dependency on the continuous availability of biomass supply and adequate solar irradiation, making system design and logistics management crucial factors in determining the plant's operational feasibility [3]. The technical complexity of integrating two different technologies and the need for intensive maintenance are additional weaknesses that must be considered [8].

To provide a more comprehensive and evidence-based understanding of the strengths and weaknesses of SBHPS, this study adopts a Systematic Literature Review (SLR) approach. The SLR method is used to systematically identify, evaluate, and synthesize relevant research findings that discuss SBHPS in the context of its advantages and disadvantages; covering technical, economic, environmental, and social aspects [9][10]. This approach not only maps the existing literature but also enables the drawing of objective, evidence-based conclusions with academic accountability.

This study is expected to contribute significantly to the development of renewable energy strategies and policies, particularly in promoting the adoption of solar-biomass hybrid systems as part of a sustainable energy transition. By systematically identifying the strengths and challenges of SBHPS, this article also aims to serve as a valuable reference for technology designers, policymakers, and investors engaged in the development of resilient and efficient renewable power generation systems.

While previous studies have discussed various aspects of renewable energy systems, there remains a lack of comprehensive reviews focusing specifically on solar–biomass hybrid power systems (SBHPS) from an integrated perspective. Unlike prior reviews that focused primarily on technical optimization or single-case feasibility studies, this review offers a comprehensive, multi-dimensional synthesis of SBHPS. It integrates technical, economic, environmental, and regulatory perspectives by analyzing peer-reviewed articles published between 2014 and 2024 from both developed and developing countries. This broader scope allows for a deeper understanding of implementation challenges and opportunities across diverse contexts, which have been underexplored in earlier studies.

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THEORETICAL REVIEW

Renewable Energy and Its Role in the Energy Transition

Renewable energy refers to energy derived from natural resources that are naturally and sustainably replenished, such as sunlight, wind, water, biomass, and geothermal heat. This type of energy plays a crucial role in reducing greenhouse gas emissions and enhancing energy security, particularly amid the challenges of climate change and the depletion of fossil fuels. Among the various types of renewable energy, solar and biomass energy hold strategic positions due to their abundant availability, especially in tropical countries like Indonesia [11], [12].

Solar energy harnesses sunlight radiation, which can be directly converted into electricity using photovoltaic (PV) panels or indirectly through thermal systems such as parabolic trough collectors or solar towers [11]. Meanwhile, biomass is an energy source derived from organic materials such as agricultural waste, forestry residues, and other organic matter. Biomass can be converted into energy through various technologies, including direct combustion, gasification, or biofuel production [12].

A Solar-Biomass Hybrid Power System (SBHPS) integrates two renewable energy sources solar photovoltaic (PV) and biomass-based power-into a single system to improve energy reliability and efficiency [5]. Typically, solar panels supply electricity via inverters, while biomass is processed through gasification or combustion to drive generator [13]. These components are managed by a hybrid controller that balances power flow to the load and, in some configurations, to a battery bank or the utility grid.

The general structure of SBHPS is illustrated in figure 1.

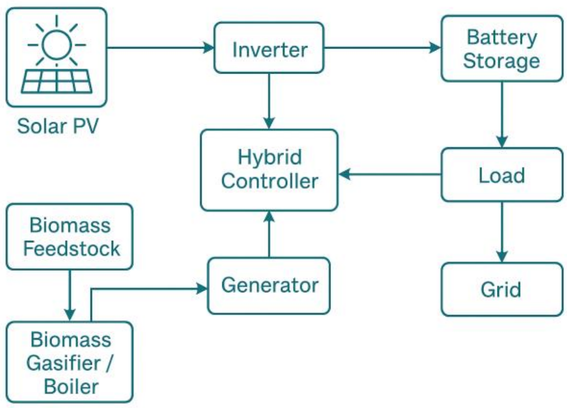

FIGURE 1. General schematic of a solar–biomass hybrid power system (SBHPS).

Concept and Principles of Solar-Biomass Hybrid Power Plants

A hybrid power plant is a system that combines two or more energy sources to improve efficiency and reliability of electricity supply. In the context of a solar-biomass system, solar energy is utilized during the day when solar irradiation is at its peak, while biomass serves as a complementary energy source that can operate continuously, including at night or during unfavorable weather conditions [14], [15], [16].

The key advantage of this system lies in the complementary nature of the two energy sources. Solar energy provides clean electricity during daylight hours, while biomass ensures system stability with its ability to operate continuously. This combination helps reduce output variability, which is often a major challenge in single renewable energy systems [16].

Common configurations of solar-biomass hybrid systems include the use of solar collectors (such as parabolic troughs or solar tower heliostats) to generate heat, which is then combined with steam from biomass combustion in a boiler to drive a steam turbine [17]. Electricity generation thus occurs through an integrated dual thermal process.

Key Technologies in Solar-Biomass Hybrid Systems

The technologies used in solar-biomass hybrid power generation systems involve several main components:

- **Solar Collectors**

Used to capture thermal energy from sunlight. Types of collectors include parabolic troughs, solar towers with heliostats, and Fresnel lenses. Each technology has different characteristics and efficiencies depending on site conditions and power generation objectives [17].

- **Biomass Boilers**

These use biomass fuel to generate steam. Common boiler technologies include fluidized bed combustion (FBC) and cooled grate burners, both designed to enhance combustion efficiency and reduce emissions [11], [18].

- **Steam Turbines and Generators**

Steam generated from both heat sources is used to drive steam turbines, which in turn power generators to produce electricity. The system can use condensing turbines for high efficiency or backpressure turbines for cogeneration in industrial applications [19].

- **Control and Integration Systems**

Advanced control systems are required to coordinate the operation of both energy sources and ensure power quality and output stability [16].

Technical and Operational Challenges

Although SBHPS systems offer many advantages, integrating two distinct technologies also presents several challenges. Design and operational complexity are a key issue, particularly in synchronizing energy output from two sources with different characteristics. Additionally, fluctuations in biomass supply and daily weather variability require storage systems or adaptive operational strategies [4], [20].

Other challenges include the large land area needed for biomass production, the need for a year-round sustainable biomass supply, and logistical issues in collecting and distributing biomass fuel [12], [21]. Therefore, the feasibility assessment of SBHPS systems must comprehensively consider geographical, technical, and social factors.

Comparison of SBHPS Technologies

Various configurations of SBHPS have been implemented globally, each with distinct technical and economic characteristics. Table 1 summarizes the comparison of selected SBHPS technologies based on key performance parameters as reported in the literature.

TABLE 1. Comparative synthesis of SBHPS technology configurations across technical and economic parameters.

Technology Configuration	CAPEX ($/kW)	OPEX ($/year)	Efficiency (%)	GHG Emissions (gCO_2/kWh)	Study / Source
PV + Biogas Engine	2,000-2,500	80-150	22-28	100-150	[6], [22], [23]
PV + Biomass Gasifier	2,500-3,200	120-180	25-35	90-130	[4], [13], [21]
PV + Direct Combustion Boiler	2,200-2,700	100-160	20-30	120-170	[1], [2], [16]
PV + Biomass CHP	3,000-3,800	150-200	30-40	70-100	[3], [24], [25]

As shown in table 1, systems incorporating gasifiers tend to offer higher electrical efficiency but come at higher CAPEX and operational complexity. In contrast, biogas-based systems are relatively cost-effective and simpler to maintain but may exhibit lower overall efficiency.

METHODS

This study employed the Systematic Literature Review (SLR) approach as the primary method to identify, evaluate, and synthesize scientific literature related to the strengths and weaknesses of solar-biomass hybrid power systems (SBHPS). This approach was chosen for its ability to produce a comprehensive, evidence-based, and unbiased understanding of the topic under investigation [9], [10].

SLR Framework and Protocol

The SLR implementation in this study followed the PRISMA 2020 guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), which provide a systematic and transparent reporting framework across all stages of the review process [26]. The applied SLR framework consisted of five main phases:

1. formulation of the research question,
2. literature search strategy,
3. study selection,
4. data extraction, and
5. quality assessment.

Research Question Formulation

The research question was developed using the PICO framework (Population, Intervention, Comparison, Outcome), which helps focus the review and structure the search strategy effectively [27].

The primary research question addressed in this study is:

What are the strengths and weaknesses of solar-biomass hybrid power systems compared to conventional or other renewable power generation systems?

To guide the selection and data extraction process, the PICO framework was adapted as follows:

PICO Element

Population	:	Solar-biomass hybrid power systems (SBHPS).
Intervention	:	Integration of solar and biomass energy.
Comparison	:	Compared to conventional (fossil-based) or single-source power generation.
Outcome	:	Strengths and weaknesses in terms of efficiency, cost, reliability, emissions, and social impact.

Literature Search Strategy

The literature search was conducted using two leading academic databases: Scopus and Web of Science (WoS). Search strings were constructed using PICO elements and Boolean logic. Examples of the key search terms used include: (“hybrid” AND (“solar” OR “photovoltaic” OR “PV”) AND “biomass” AND (“power plant” OR “energy system”) AND (“advantages” OR “drawbacks” OR “efficiency” OR “sustainability”) AND (“comparison” OR “versus”)).

Search filters applied:

- Publication years: 2014 - 2024
- Language: English
- Document type: Peer-reviewed journal articles

Although the search range was set from 2014 to 2024, the majority of relevant and high-quality articles that met the inclusion criteria were published between 2019 and 2024

Inclusion and Exclusion Criteria

To ensure the quality and relevance of the analyzed literature, a filtering process was carried out based on the following criteria:

Inclusion Criteria	Exclusion Criteria
– Articles discussing solar and biomass hybrid power systems	– Proceedings, technical reports, or books

- Full-text availability
- Written in English
- Published in peer-reviewed scientific journals
- Published between 2014 and 2024

- Articles that do not explicitly discuss SBHPS
- Journal quality score below 4 out of 5

Selection Process and Quality Assessment

The selection process involved three stages:

1. Title and abstract screening
2. Full-text review
3. Duplicate identification across databases

Selected articles were assessed for quality using the Critical Appraisal Skills Programme (CASP) for qualitative studies and appropriate validity indicators for quantitative studies, such as clarity of research aims, data adequacy, and methodological alignment with the research question [26], [28].

Each article was scored using a 5-point relevance and quality checklist adapted from CASP and MMAT guidelines. Only articles scoring 4 or higher were retained. The coding process was cross validated by two reviewers to reduce subjectivity.

Final selection results:

- 26 articles were included for the research question on strengths and weaknesses of SBHPS.
- Each article was thematically analyzed to identify the main dimensions of advantages and disadvantages.

Analysis Techniques

The analysis was conducted using a qualitative-descriptive and thematic approach. Findings from the various journal articles were coded and categorized into the following key themes:

- Energy efficiency
- Reliability of power supply
- Environmental impact
- Economic and cost considerations
- Technological complexity
- Resource and regulatory constraints

Findings from different sources were compared and synthesized to develop a comprehensive understanding of both the positive and negative aspects of SBHPS.

Data Analysis Procedure

The article identification and selection process followed the general structure of the PRISMA guidelines. A total of 543 articles were initially identified through Scopus and WoS using the predefined keyword strategy. After removing duplicates and screening titles and abstracts, 76 articles remained.

Further screening based on full-text availability and relevance to the research question resulted in 26 articles. From these, 18 articles met the minimum quality score (≥4 out of 5) based on CASP and were selected for final thematic analysis.

Data from the selected articles were extracted and organized in analytical tables capturing recurring themes and insights, with specific focus on:

- Key advantages such as energy efficiency, emission reduction, and resource complementarity.
- Key disadvantages such as capital investment, biomass supply reliability, and system complexity.

The primary tool used for analysis was thematic coding, allowing the identification, comparison, and synthesis of recurring patterns across the literature. This method ensures that key insights into the strengths and weaknesses of SBHPS are systematically organized and interpreted.

TABLE 2. Quality assessment criteria.

Research Design	Assessment Criteria
Qualitative	QA1: Is a qualitative approach appropriate? QA2: Are data collection methods adequate? QA3: Are findings derived sufficiently from data? QA4: Are interpretations well supported? QA5: Is there coherence among data sources, analysis, and interpretation?
Quantitative (randomized controlled trials)	QA1: Was randomization done properly? QA2: Were groups comparable at baseline? QA3: Is outcome data complete? QA4: Were outcome assessors blinded? QA5: Did participants comply with assigned intervention?
Quantitative (nonrandomized)	QA1: Do participants represent the target population? QA2: Are measurements appropriate for outcomes/intervention? QA3: Is the data complete? QA4: Are confounders accounted for? QA5: Was the intervention delivered as intended?
Quantitative descriptive	QA1: Is the sampling strategy relevant? QA2: Does the sample represent the population? QA3: Are measurements appropriate? QA4: Is nonresponse bias low? QA5: Are statistical analyses appropriate?
Mixed methods	QA1: Is mixed methods justified for the research question? QA2: Are components well-integrated? QA3: Are integrated findings well interpreted? QA4: Are inconsistencies between qualitative and quantitative results addressed? QA5: Do components meet respective quality standards?

To ensure the validity and reliability of the findings, only articles meeting a minimum quality threshold of 4/5 based on the adapted CASP tool were included in the final analysis. Each selected article was cross-checked for data interpretation consistency and relevance to the main research objective.

TABLE 3. Journal quality assessment report.

Author	Category	QA1	QA2	QA3	QA4	QA5	Criteria	Sources
Buscheck & Upadhye (2021)	Quantitative Descriptive	X	V	V	X	V	3/5	Scopus
Chowdhury (2020)	Quantitative Descriptive	V	V	V	X	V	4/5	Scopus
Khosravi (2021)	Quantitative Descriptive	V	V	V	X	V	4/5	Scopus / WoS
Paraschiv (2023)	Quantitative Descriptive	X	V	V	X	V	3/5	Scopus
Jasim (2022)	Quantitative Descriptive	V	V	V	X	V	4/5	Scopus / WoS
Rehmani (2023)	Mixed Methods	V	V	V	V	V	5/5	Scopus
Ribó-Pérez (2020)	Qualitative	X	V	V	X	V	3/5	Scopus
Patibandla (2021)	Quantitative Descriptive	V	V	V	X	V	4/5	Scopus
Katsaprakakis (2022)	Mixed Methods	V	V	V	V	V	5/5	Scopus
Rahimi (2019)	Quantitative Descriptive	V	V	V	X	V	4/5	Scopus
Zhang (2019)	Quantitative Descriptive	X	V	V	X	V	3/5	Scopus / WoS
Gul (2023)	Quantitative	V	V	V	X	V	4/5	Scopus

	Descriptive							
Alturki & Awwad (2021)	Quantitative Descriptive	V	V	V	X	V	4/5	Scopus / WoS
Kharrich (2021)	Quantitative Descriptive	V	V	V	X	V	4/5	Scopus
Oyekale (2020)	Quantitative Descriptive	X	V	V	X	V	3/5	Scopus
El-Houari (2020)	Quantitative Descriptive	V	V	V	X	V	4/5	Scopus
Rashid (2021)	Quantitative Descriptive	V	V	V	X	V	4/5	Scopus
Tiwary (2019)	Quantitative Descriptive	V	V	V	X	V	4/5	Scopus
Hussain (2020)	Quantitative Descriptive	V	V	V	X	V	4/5	Scopus / WoS
Zajkowski (2023)	Quantitative Descriptive	V	V	V	X	V	4/5	Scopus / WoS
Goswami (2023)	Quantitative Descriptive	X	V	V	X	V	3/5	Scopus
Cui (2021)	Quantitative Descriptive	X	V	V	X	V	3/5	Scopus
Das (2023)	Quantitative Descriptive	V	V	V	X	V	4/5	Scopus
Konneh (2019)	Quantitative Descriptive	V	V	V	X	V	4/5	Scopus
Gutiérrez (2021)	Quantitative Descriptive	V	V	V	X	V	4/5	Scopus
Rapa (2020)	Quantitative Descriptive	X	V	V	X	V	3/5	WoS

RESULT AND DISCUSSION

The systematic literature review conducted in this study revealed various strengths and weaknesses of solar-biomass hybrid power systems (SBHPS). The analysis was based on 18 articles that met the inclusion and exclusion criteria and passed the quality assessment process. The findings are classified into two main categories "**strengths** and **weaknesses**" covering technical, economic, environmental, and social aspects. A summary of the results is presented in the following table 4.

TABLE 4. Summary of strengths and weaknesses of solar-biomass hybrid power systems.

No.	Author	Strengths							Weaknesses						
		1A	1B	1C	1D	1E	1F	1G	2A	2B	2C	2D	2E	2F	2G
1	Tiwary et al., 2019 [5]	V	V	V	V	V		V		V		V			V
2	Konneh et al., 2019 [7]	V	V	V	V	V	V			V				V	V
3	Al. Katsaprakakis et al., 2022 [29]	V	V	V	V	V	V		V	V					
4	Patibandla et al., 2021 [6]	V	V		V	V	V	V	V	V				V	
5	Jasim et al., 2022 [30]	V	V	V	V	V				V	V			V	
6	Hussain et al., 2020 [13]	V	V		V			V	V	V	V			V	
7	Chowdhury et	V	V	V	V	V		V	V	V				V	

	al., 2020 [22]														
8	El-houari et al., 2020 [24]	V	V	V	V	V		V	V					V	
9	Rashid et al., 2021 [31]	V	V	V	V	V		V	V	V		V	V		
10	Kharrich et al., 2021 [32]	V	V	V	V	V	V	V	V	V					
11	Khosravi et al., 2021 [4]	V	V	V	V	V	V	V	V	V	V	V	V		
12	Chakraborty et al., 2023 [3]	V	V	V	V	V		V		V	V		V		
13	Das et al., 2023 [8]	V	V	V	V	V		V	V	V	V	V		V	
14	Ariae et al., 2019 [2]	V	V	V	V	V		V							
15	Alturki & Awwad, 2021 [33]	V	V	V	V	V		V		V				V	
16	Gutiérrez et al., 2021 [34]	V	V	V	V	V		V	V	V	V				
17	Rehmani et al., 2023 [25]	V	V	V	V	V				V		V	V	V	V
18	Gul et al., 2023 [1]	V	V	V	V	V	V	V	V	V	V				

Notes: systematic Literature Review of 26 journal articles, with 18 meeting inclusion and quality criteria.

Strengths

1A. Higher efficiency in resource utilization - 100.0%
1B. Improved power supply reliability due to dual energy source combination - 100.0%
1C. Significant reduction of greenhouse gas emissions - 88.9%
1D. Energy diversification enhancing energy security - 100.0%
1E. Utilization of local biomass resources - 94.4%
1F. Technological advancement and innovation development - 33.3%
1G. Long-term energy cost savings potential - 77.8%

Weaknesses

2A. Relatively high initial investment costs - 61.1%
2B. Dependence on biomass supply and solar irradiance - 88.9%\
2C. Higher technical complexity and maintenance requirements - 38.9%
2D. Challenges in biomass waste management - 27.8%
2E. Land limitations for large-scale installation - 22.2%
2F. Variability in energy output performance - 50.0%
2G. Regulatory and policy challenges - 16.7%

A total of 18 selected articles were thematically analyzed. The strengths and weaknesses were extracted, coded, and categorized into seven sub-dimensions for each group (1A–1G for strengths, 2A–2G for weaknesses). The frequency of each sub-dimension's occurrence was also recorded to highlight key concerns in the literature.

Strengths of the PV-Biomass Hybrid System (SBHPS)

a. High Energy Efficiency - SBHPS can improve energy conversion efficiency by combining two complementary renewable energy sources. Solar energy is utilized during periods of high sunlight intensity, while biomass serves as a continuous energy source at night or during cloudy weather. This combination provides more stable operational efficiency compared to single-source systems [29].

b. Power Supply Reliability - By using biomass as a backup or supplementary energy source, SBHPS offers greater power supply reliability. This is especially important in remote areas or regions with limited grid access, as it reduces dependence on a single energy source [30].

c. Greenhouse Gas Emissions Reduction - Most reviewed journals noted that SBHPS can significantly reduce carbon emissions compared to fossil-fuel-based plants. When managed properly, the use of biomass waste also supports the principles of the circular economy and climate change mitigation [8], [31].

d. Energy Diversification and Utilization of Local Resources - SBHPS enables energy diversification while also making use of local resources such as agricultural waste, forestry residues, or organic waste. This local utilization positively impacts regional economic development and adds value to previously worthless waste [23], [34].

e. Potential for Long-Term Cost Reduction - Several studies state that while the initial investment is high, the operational costs of SBHPS are relatively low since biomass fuel can often be sourced locally at low or no cost. Long-term efficiency and energy cost reduction are key advantages [1], [25].

2. Weaknesses of the PV-Biomass Hybrid System (SBHPS)

a. High Initial Investment Costs - Most studies highlight that one of the main barriers to SBHPS implementation is the high initial capital required. This includes the procurement of solar panels, thermal collectors, biomass combustion systems, and fuel processing and distribution infrastructure [2].

b. Dependence on Solar Irradiance and Biomass Availability - The performance of SBHPS heavily depends on two fluctuating energy sources: solar irradiance and biomass supply. If either is insufficient or of low quality, system output may be disrupted [3].

c. Technological Complexity and Maintenance - Integrating two different generation systems (solar thermal and biomass boiler) creates technical challenges in design, control, and maintenance. Control systems must regulate the operation of two sources with differing characteristics, requiring skilled labor and advanced technology [16].

d. Waste and Land Management Challenges - Large-scale biomass use requires proper management of ash waste and emissions, as well as land for cultivating energy crops such as woody plants. Some studies also mention that land use for biomass may compete with agricultural or residential land [21].

e. Regulatory and Policy Uncertainty - SBHPS still faces policy-related challenges, particularly regarding renewable energy incentives, environmental permits, and the lack of support for biomass supply chain development. Such uncertainties can hinder investment and large-scale adoption of the technology [25], [33].

Despite these challenges, SBHPS remains a promising approach for reducing carbon emissions compared to fossil-fuel-based systems. Several studies provide estimates of CO_2 reduction potential under different SBHPS configurations. Table 5 summarizes the reported values from selected studies.

TABLE 5. Estimated CO_2 emission reductions from selected SBHPS configurations.

Study	Configuration	Estimated CO_2 Reduction (kg/kWh)	Reference
Chakraborty et al., 2023	PV + Biomass (Remote India)	0.65	[3]
El-houari et al., 2020	Off-grid SBHPS (Morocco)	0.42	[24]
Rehmani et al., 2023	Rural Microgrid (Developing Country)	0.58	[25]

These data points reinforce the environmental advantages of SBHPS systems, particularly in regions where biomass resources are abundant and fossil fuel alternatives are carbon intensive.

3. Thematic Synthesis of Findings

Table 4 in the thesis results groups the strengths into seven key indicators and the weaknesses into seven indicators as well, including efficiency, reliability, emissions, diversification, cost, complexity, and regulation. These findings are consistent with international literature, which emphasizes that SBHPS systems should ideally be developed in local contexts, taking into account resource availability and technological readiness [5].

Regional Variations in SBHPS Performance - The effectiveness of SBHPS varies significantly across regions, depending on factors such as solar irradiation levels, biomass

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feedstock availability, infrastructure readiness, and policy support. For instance, tropical regions like Southeast Asia benefit from abundant solar resources and agricultural residues, while arid or colder regions may face seasonal limitations. Studies e.g., [1], [29], [30] highlight that geographic and climatic conditions strongly influence both technical feasibility and cost-effectiveness.

Trade-offs between System Complexity and Reliability - While combining solar and biomass improves energy reliability, it also increases system complexity. Hybrid configurations require synchronization between PV generation, biomass processing (e.g., gasification), and storage systems. These technical requirements can lead to higher initial costs and maintenance burdens. The trade-off between operational reliability and technical simplicity must be considered in project planning and system design e.g., [4], [28], [32].

Technology Trends and Innovation - Recent literature reflects growing interest in advanced technologies to optimize SBHPS. These include improvements in biomass gasifiers, hybrid controllers with AI-based load management, and real-time monitoring systems. Innovations aim to reduce emissions, improve conversion efficiency, and lower life-cycle costs e.g., [5], [27], [33]. Such trends demonstrate the potential for SBHPS to evolve into more scalable and commercially viable systems.

These findings offer a comprehensive understanding of SBHPS, yet further research is needed to explore implementation across different geographical and socio-political contexts.

One key limitation of this review is the potential publication bias toward successful or positive implementations of SBHPS. Negative case studies or unsuccessful pilot projects may be underreported in literature, limiting the ability to fully understand challenges and real-world constraints.

Integrated Conceptual Framework

To better illustrate the multifaceted interaction among key factors influencing the development and implementation of Solar-Biomass Hybrid Power Systems (SBHPS), a conceptual framework is presented in Figure 2.

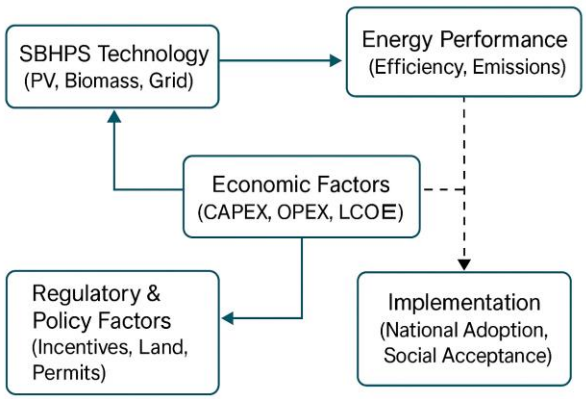

FIGURE 2. Conceptual framework of interactions influencing the implementation of SBHPS.

This framework highlights the interdependence between technical, economic, environmental, and regulatory aspects. Technical feasibility including system design, grid integration, and storage—is shaped by economic factors such as investment cost, operation and maintenance, and return on investment. Both of these dimensions are strongly influenced by regulatory policies and government incentives, while environmental and social considerations act as cross-cutting factors affecting all other domains. This integrated model serves as a tool for policymakers, developers, and stakeholders to identify leverage points and barriers in the adoption of SBHPS technology.

CONCLUSION

This study aimed to identify and analyze the strengths and weaknesses of solar-biomass hybrid power systems (SBHPS) using a systematic literature review (SLR) approach. Based on the analysis of 18 relevant scientific articles, several key findings were obtained. SBHPS offers notable advantages, including higher energy efficiency due to the complementary integration of solar and biomass sources, improved electricity supply reliability, and strong potential for reducing greenhouse gas emissions. Additionally, SBHPS enables the use of local resources, supports energy diversification, and presents opportunities for long-term cost savings. However, several weaknesses also emerge, such as high initial investment costs, technical and operational complexity, dependency on biomass supply and solar availability, and challenges related to waste management and land use. Moreover, limited policy and regulatory support continues to hinder broader adoption. Considering these factors, SBHPS holds significant promise in supporting the global energy transition, particularly in developing regions rich in solar and biomass resources. To fully unlock this potential, an integrated design approach coupled with robust policy interventions will be essential.

Recommendations

Based on the findings, several strategic recommendations can be proposed to support the development of Solar-Biomass Hybrid Power Systems (SBHPS). First, it is essential to optimize system design by developing adaptive and efficient technologies that align with local characteristics such as biomass availability, solar radiation intensity, and community energy demands. Second, enhancing technical capacity through targeted training is necessary to ensure that human resources are equipped to operate and maintain these complex hybrid systems effectively. Third, governments should strengthen policies and incentives by offering fiscal support, expediting permitting procedures, providing technology subsidies, and ensuring competitive electricity pricing to attract investment. Fourth, sustainable biomass supply must be ensured through circular economy models that utilize agricultural and forestry waste, alongside land-use policies that preserve ecological balance. Finally, further research and region-specific case studies are required to evaluate the real-world feasibility of SBHPS, which will contribute to developing replicable business models. Overall, SBHPS represents a promising pathway toward sustainable energy systems, provided that technical, economic, and policy challenges are addressed through multi-stakeholder collaboration involving governments, academia, industry, and local communities.

Solar-biomass hybrid power systems offer a promising pathway for sustainable energy in regions with abundant solar and biomass resources. To accelerate adoption, governments should incentivize investment and local capacity building. A cost-benefit analysis across deployment scales remains essential for future implementation

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