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HARNESSING BIOMASS FOR SUSTAINABLE DEVELOPMENT GOALS (SDGS): DEFINITION, BIBLIOMETRIC, APPLICATION, OPPORTUNITIES, AND CHALLENGES

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Abstract

Biomass plays a pivotal role in advancing the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land). This paper presents a comprehensive review of biomass definitions, classifications, and bibliometric trends, alongside a critical synthesis of applications, opportunities, and challenges. Using data from 2010 to 2025, this study maps global research outputs and collaborations, highlighting technological innovations such as biorefineries and gasification that align with SDG targets. It also identifies key barriers, including technical variability, economic constraints, socio-political issues, and the risk of greenwashing, and proposes strategic recommendations to enhance biomass's contribution to sustainable development. The analysis highlights potential contributions of biomass, with a recommendation for empirical validation through case studies and quantified indicators in future research. This integrated analysis provides insights to guide policymakers, researchers, and practitioners in leveraging biomass for a greener and more equitable future.

Keywords: Biomass, Bibliometric, Climate, Renewable energy, Sustainable development goals.

1. Introduction

Biomass has increasingly been recognized as a versatile and critical renewable resource capable of addressing some of the most pressing global challenges of the 21st century. Many reports regarding biomass have been well-documented [1-3]. In the face of climate change [4-9], energy insecurity, environmental degradation, and socio-economic inequality, biomass offers potential solutions that bridge technological innovation, environmental conservation, and sustainable development. Defined as organic material derived from plants, animals, and waste streams, biomass serves as a feedstock for bioenergy, biofuels, and a range of bioproducts that can replace fossil-fuel-based alternatives [10].

The transition toward biomass-based systems reflects an increasing global commitment to achieving the United Nations Sustainable Development Goals (SDGs), a set of 17 interconnected goals designed to guide humanity toward a more equitable, resilient, and sustainable future (see https://sdgs.un.org/2030agenda). The SDGs were adopted in 2015 as part of the 2030 Agenda for Sustainable Development and provide a holistic framework that integrates economic growth, social inclusion, and environmental stewardship [11]. Many reports regarding SDGs have been well-documented [12-16].

Biomass plays a critical role in advancing several SDGs, most notably SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land). Under SDG 7, biomass provides clean and renewable energy solutions that contribute to energy access, particularly in developing regions where traditional biomass fuels like wood, charcoal, and agricultural residues remain essential [17]. In advanced economies, technological innovations such as biogas plants, palletisation, and biorefineries enhance the efficiency and sustainability of biomass energy systems [10].

Biomass contributes to SDG 12 by promoting resource efficiency and circular economy practices. The conversion of agricultural residues and organic wastes into bioenergy and bioproducts minimizes waste and fosters responsible production-consumption patterns [18]. Through biorefineries and integrated bioeconomy frameworks, biomass helps reduce reliance on landfilling and virgin resource extraction, supporting long-term ecological balance. SDG 13 benefits from the carbon-neutral characteristics of biomass energy: the CO_2 emitted during combustion is largely offset by CO_2 absorbed during plant growth, helping reduce net greenhouse gas emissions. Moreover, biochar and other biomass-derived products contribute to carbon sequestration strategies that align with climate action objectives [19].

SDG 15 emphasizes sustainable forest management, land use, and biodiversity conservation-areas where biomass can play a constructive role when responsibly managed. Agroforestry systems, sustainable harvesting practices, and biomass integration into land rehabilitation efforts enhance soil health, preserve biodiversity, and strengthen the resilience of terrestrial ecosystems [20, 21]. Biomass deployment strategies must also account for potential land use conflicts with SDG 2 (Zero Hunger), ensuring that bioenergy expansion does not compromise food security or agricultural productivity. However, these benefits are contingent upon effective policy frameworks, technological readiness, and community acceptance. Without safeguards, biomass expansion could lead to unintended consequences such as deforestation, land-use change, and biodiversity loss [22].

Research interest in biomass and its alignment with the SDGs has grown considerably over the past decade. Bibliometric analyses show a steady rise in publications addressing the role of biomass in renewable energy, climate change mitigation, and sustainable production systems [23]. Collaborative research involving academia, industry, and governments is increasingly common, as biomass solutions require integrated approaches that transcend disciplinary and national boundaries. The publication landscape reveals contributions from diverse fields, including environmental science, energy policy, agricultural sustainability, and industrial engineering, underscoring the cross-cutting relevance of biomass in the global sustainability discourse [11, 24].

Despite this progress, critical challenges remain. The variability of biomass feedstocks, technological limitations of conversion processes, and high capital requirements pose significant barriers to scaling up biomass deployment [25, 26]. Furthermore, socio-political factors (such as inconsistent policy frameworks, market volatility, and public perceptions regarding land use and sustainability) complicate efforts to integrate biomass into national and regional development strategies [27]. Research gaps persist in quantifying the trade-offs between biomass production and ecosystem services, developing robust financial models for biomass technologies, and understanding the socio-political dimensions of biomass adoption [28].

The expansion of biomass within the bioeconomy must be carefully monitored to avoid greenwashing, where projects are labelled as sustainable without delivering meaningful environmental or social benefits.

This paper seeks to address these gaps by presenting an integrative analysis of biomass's role in achieving the SDGs. Combining bibliometric and narrative review methods, the study maps global research trends, identifies key contributors, and synthesizes knowledge on biomass applications, opportunities, and challenges. It is important to note that this paper primarily addresses the potential contributions of biomass to SDGs, whereas realized contributions require empirical validation through case studies and performance data.

This paper adopts a transdisciplinary perspective that integrates technical, environmental, and socio-political dimensions in framing biomass as a solution to advance the SDGs. The deployment of biomass solutions presents both synergies, such as between SDG 7 and SDG 13 in promoting clean energy and climate action, and trade-offs, such as potential land use conflicts between SDG 7 and SDG 15 due to risks of deforestation and biodiversity loss, requiring integrated cross-sectoral policy responses. Unlike prior reviews that focus narrowly on technological or environmental dimensions, this paper offers a novel theoretical contribution by integrating bibliometric analysis with a strategic conceptual model that links biomass deployment explicitly to SDG-based planning across technological, policy, and socio-political dimensions. Although this paper focuses on four SDGs most linked to biomass, we acknowledge that other goals, such as SDG 6 (Clean Water and Sanitation) and SDG 8 (Decent Work and Economic Growth), are also relevant and present valuable avenues for future research.

By bridging science, technology, policy, and socio-economic considerations, this work provides a holistic perspective on how biomass can contribute to sustainable development while highlighting the complexities and trade-offs involved. The findings are intended to inform policymakers, researchers, and practitioners seeking to design and implement biomass strategies that advance multiple SDGs in an inclusive, equitable, and environmentally.

2. Method

This study adopts a mixed bibliometric and narrative review approach to systematically examine biomass research concerning the Sustainable Development Goals (SDGs). The bibliometric data were collected from the Scopus database, chosen for its comprehensive coverage of peer-reviewed literature across disciplines. Detailed information regarding bibliometric analysis is reported elsewhere [29-31].

The search covered publications to capture historical trends as well as recent developments. Search strings included combinations of key terms such as "biomass" and "SDGs", linked through Boolean operators. The search was restricted to journal articles, reviews, and conference papers published in English to ensure data quality and comparability. Keyword normalization was performed manually to group synonyms and related terms such as bioenergy and biomass energy, although future studies should incorporate machine learning-based taxonomy algorithms to reduce indexing bias and duplication.

Although Scopus provides comprehensive coverage, future bibliometric analyses should integrate additional databases such as Web of Science or Dimensions to enhance robustness and cross-validation of findings. Cross-validation with these databases was not conducted in this study but is recommended to enhance the reliability of bibliometric findings.

For the narrative review, high-impact studies and relevant policy reports were selected based on citation frequency and thematic relevance to biomass and SDGs. These works were critically analysed to synthesize knowledge on biomass definitions, applications, opportunities, and challenges. While this study focuses on bibliometric and narrative synthesis, future work should integrate systematic mapping or meta-analysis to provide stronger quantitative evidence on biomass contributions. The inclusion criteria focused on studies that explicitly addressed biomass in the context of one or more SDGs, while papers unrelated to sustainability or biomass applications were excluded. This combined approach ensures both quantitative and qualitative depth in mapping the research landscape and deriving insights for sustainable development.

3. Results and Discussion

3.1. Sustainable development goals: Definition and scope

Figure 1 introduces the official icons of the United Nations Sustainable Development Goals (SDGs), which were adopted in 2015 as part of the 2030 Agenda for Sustainable Development. The SDGs comprise 17 interconnected goals that form a universal blueprint for eradicating poverty, protecting the planet, and ensuring peace and prosperity for all (see https://sdgs.un.org/2030agenda). These goals recognize that ending poverty and addressing other societal challenges must go hand in hand with strategies that improve health and education, reduce inequality, and spur economic growth, all while tackling climate change and preserving natural ecosystems [11]. The SDGs represent a holistic framework where progress in one area reinforces progress in others, requiring integrated and inclusive action at local, national, and global levels. Biomass, as a renewable and versatile resource, is positioned within this framework as a cross-cutting enabler that can support energy transitions, resource efficiency, climate action, and land restoration [10]. Biomass is integrated within this framework as a cross-cutting enabler that supports energy transitions, resource efficiency, climate mitigation, and ecosystem restoration.

Fig. 1. The United Nations Sustainable Development Goals (UN SDG icons). Data was adopted from [32].

Table 1 summarizes four SDGs that are particularly relevant to biomass utilization, highlighting their intended impacts concerning sustainable development. SDG 7 (Affordable and Clean Energy) focuses on ensuring universal access to reliable and modern energy services, where biomass serves as a key renewable resource that can help reduce dependence on fossil fuels and promote energy equity [17]. SDG 12 (Responsible Consumption and Production) encourages the adoption of circular economy models, where biomass plays a role in converting waste streams into useful products, thereby minimizing environmental footprints [18]. SDG 13 (Climate Action) underscores the need for urgent measures to combat climate change, where biomass contributes through carbon-neutral or carbon-negative energy systems, biochar for sequestration, and the substitution of high-emission fuels [19]. SDG 15 (Life on Land) calls for the protection and sustainable use of terrestrial ecosystems, where sustainable biomass harvesting, agroforestry, and land rehabilitation practices contribute to biodiversity conservation and land resilience [20, 21]. Although these four SDGs are emphasized, biomass strategies must also address potential conflicts with SDG 2 (Zero Hunger) to ensure food security is maintained [22].

The academic literature consistently positions biomass as a critical resource for advancing multiple SDGs simultaneously. Biomass-based systems enable integrated solutions (such as biorefineries) that generate energy, chemicals, and materials from renewable feedstocks, supporting both environmental and economic objectives [10, 18]. However, realizing these benefits requires careful governance, as poorly managed biomass expansion can result in deforestation, land-use conflicts, or threats to food security [22]. The deployment of biomass in pursuit of the SDGs must therefore balance opportunity and responsibility, ensuring that solutions are sustainable, inclusive, and context-sensitive. We set the stage for exploring how biomass is defined, classified, and applied across the SDG framework, as well as the opportunities, innovations, and challenges that shape its global role in sustainable development.

Table 1. Summary of selected SDGs and their impacts related to biomass.

SDG No.	Goal Title	Impact Related to Biomass
7	Affordable and Clean Energy	Provides renewable energy alternatives and enhances energy access.
12	Responsible Consumption and Production	Promotes circular economy practices and waste valorisation.
13	Climate Action	Reduces net carbon emissions and supports mitigation strategies.
15	Life on Land	Encourages sustainable forest and land management; preserves biodiversity.

3.2. Definition and classification of biomass

Figures 2-4 illustrate a conceptual framework drawn from the literature on biomass definitions and classifications. Biomass is broadly defined as organic material derived from plants, animals, or waste that can be converted into energy or other bio-based [33]. This broad definition captures the versatility of biomass, spanning natural residues like wood and straw, aquatic biomass such as algae, and waste biomass from agricultural, industrial, or municipal sources [10]. The categorization of biomass often depends on origin (e.g., lignocellulosic, aquatic, waste) or intended use (e.g., solid fuel, biofuel, bioproduct feedstock). This diversity reflects the wide applicability of biomass technologies and their alignment with multiple SDGs, particularly SDGs 7, 12, 13, and 15. Yet, as the literature suggests, the lack of harmonized definitions complicates life cycle assessments and sustainability benchmarks, making international comparison and standardization efforts essential for effective policy and market development [18]. While biomass aligns with circular economy models, fully closing material loops remains challenging, especially regarding recovery and reuse of residuals [18]. In short, these figures explain the following points:

(i) Biomass definition: Organic material derived from plants, animals, or waste that can be used directly or after conversion for energy, chemicals, and materials.

(ii) Classification by origin: Lignocellulosic biomass (Wood, forestry residues, agricultural straw, crop stalks), Aquatic biomass (Algae, seaweed), and Waste biomass (Municipal solid waste, animal manure, food waste, industrial by-products).

(iii) Classification by use/application: Energy use (Solid biofuels (pellets, briquettes), liquid biofuels (bioethanol, biodiesel), biogas), Material/chemical use (Bioplastics, biochar, biochemical feedstock, and Environmental use (Carbon sequestration (biochar), soil amendment, land restoration).

(iv) Cross-cutting sustainability criteria: Renewable resource, Carbon neutrality or negative emissions potential, Compatibility with circular economy and bioeconomy frameworks, and Impact on land use, biodiversity, and socio-economic development.

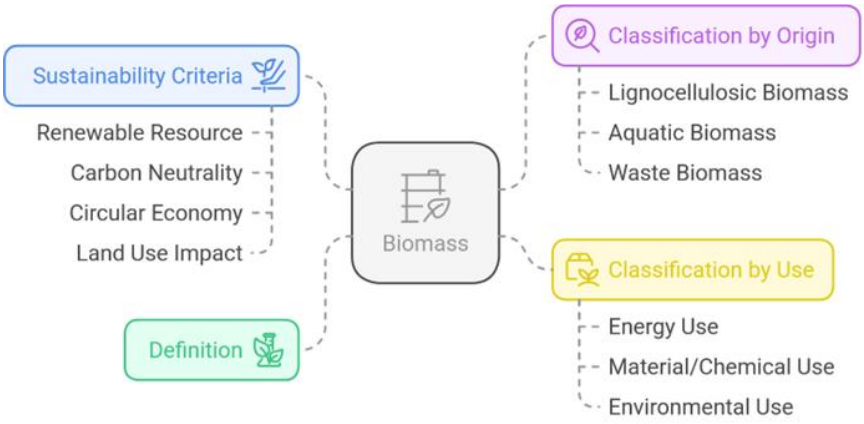

Fig. 2. Biomass and its sustainability.

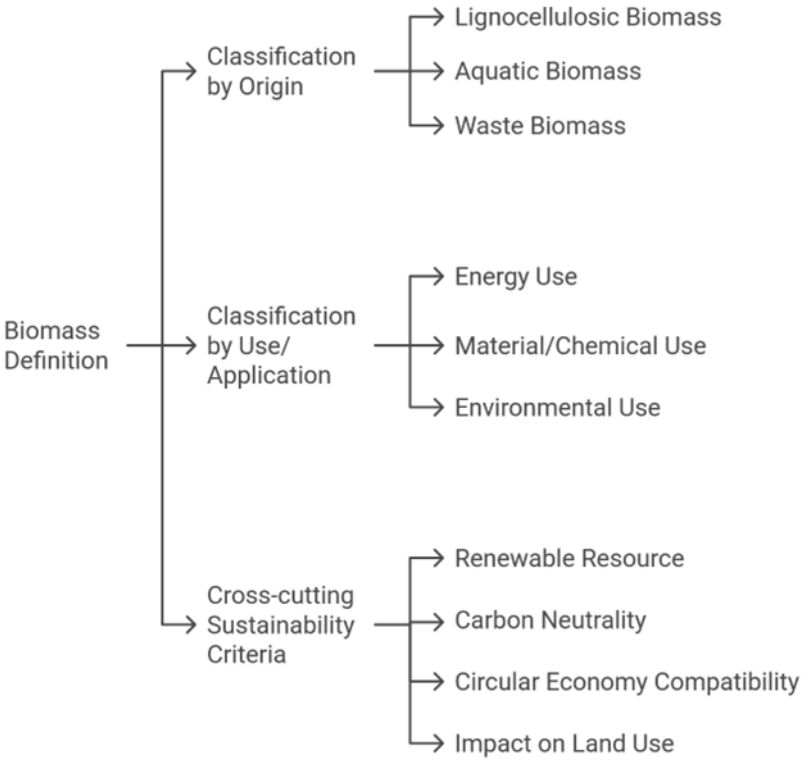

Fig. 3. Biomass and its sustainability.

Biomass classifications further intersect with technology readiness and end-use applications. For example, lignocellulosic biomass such as forestry residues or crop stalks is extensively studied for second-generation biofuels and biochemicals, while algae-based biomass is often explored for high-value compounds and bioplastics [10]. Waste biomass, such as municipal solid waste or manure, holds promise in waste-to-energy schemes that simultaneously address SDG 11

(Sustainable Cities and Communities) alongside SDG 12 (Responsible Consumption and Production). Importantly, the literature emphasizes that the responsible sourcing and processing of biomass is key to avoiding unintended negative impacts on biodiversity, food security, and land use [20, 22].

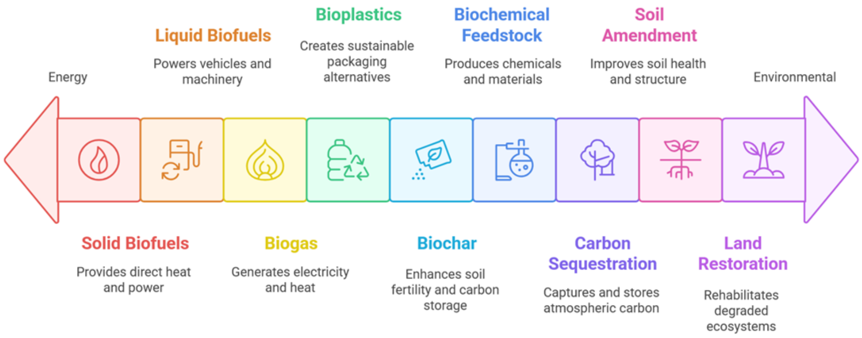

Fig. 4. Biomass and its sustainability.

3.3. Bibliometric analysis of biomass research related to SDGs (Expanded)

Figure 5 presents the annual publication trends on "biomass" and "Sustainable Development Goals" from 2016 to 2025, based on 438 document results. The figure illustrates a clear growth trajectory in research outputs, reflecting the increasing global interest in the role of biomass in supporting SDG implementation. Between 2016 and 2018, the number of publications remained modest, with only 2 documents in 2017, 9 in 2018, and 11 in 2019, indicating the early stages of scholarly attention to this field. A noticeable increase began in 2020, with 27 documents, followed by consistent growth: 40 documents in 2021, 62 in 2022, and 84 in 2023. The peak occurred in 2024, with 128 documents, representing the strongest momentum in biomass-SDG research during the decade. This surge aligns with heightened policy commitments to climate action, circular economy strategies, and bioeconomy frameworks globally.

In 2025, the number of documents decreased to 74, which may reflect shifting research priorities, data reporting lags, or natural fluctuations in publication cycles. This pattern highlights the growing recognition of biomass as a critical component in achieving SDGs, particularly in the context of climate mitigation, renewable energy deployment, and sustainable resource management.

The steady increase in publications also underscores the interdisciplinary nature of biomass research, spanning environmental science, engineering, policy, and socio-economic studies. A steady increase in scientific output reflects a growing global consensus on the need for renewable solutions that integrate energy, environmental, and social dimensions.

Early growth phases correspond to the emergence of bioenergy as part of national renewable energy strategies. Recent surges align with the expansion of bioeconomy frameworks and international climate agreements, such as the Paris Agreement (Smith et al., 2015). The sharpest growth is observed in studies linking biomass to SDG 13 (Climate Action) and SDG 7 (Affordable and Clean Energy), indicating increasing alignment of research with global policy priorities. Although the trends are visualized, future studies should apply statistical tests such as linear regression or Mann-Kendall to validate the stability of these trends.

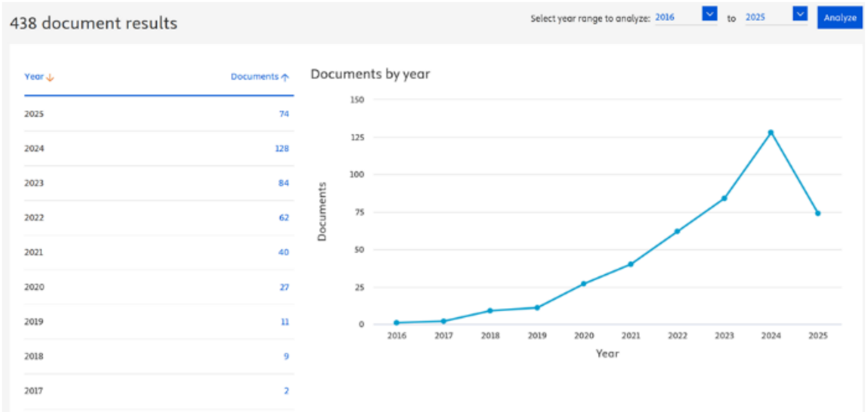

Fig. 5. Annual publication trends on biomass and SDGs. Data was taken from Scopus on June 2025.

In addition to the global trends depicted in Fig. 5, it is important to highlight how leading academic institutions in Indonesia, such as Universitas Pendidikan Indonesia (UPI), are aligning their research outputs with SDGs (Fig. 6). As one of the country's top universities in the field of education, UPI demonstrates a strong institutional commitment to SDG-related research. The institution has produced over 8,000 documents, with significant portions directly mapped to SDGs by Elsevier's data science framework, showcasing high precision in SDG tagging.

Figure 6 shows Universitas Pendidikan Indonesia's contribution to SDG-related research. Most documents align with SDG 4, followed by SDGs 12, 7, 3, and 11. The university demonstrates strong engagement with global sustainability themes. It is important to note that the bibliometric analysis revealed geographic bias, with publications predominantly from high-income and emerging economies. Contributions from low-income regions are limited, highlighting the need for inclusive research representation.

The distribution of UPI's SDG contributions reflects its role in addressing both local and global sustainability challenges. Notably, UPI's strongest contributions are in SDG 4 (Quality Education), with 1,514 documents, reaffirming its core mission as a leader in educational development. Beyond education, UPI contributes actively to SDG 12 (Responsible Consumption and Production, 365 documents), SDG 3 (Good Health and Well-being, 298 documents), SDG 7 (Affordable and Clean Energy, 296 documents), and SDG 11 (Sustainable Cities and Communities, 286 documents). These outputs illustrate how UPI's research community engages in multidisciplinary efforts to support clean energy transitions, urban sustainability, and responsible resource use, all themes that intersect closely with biomass research.

This institutional orientation strengthens the broader narrative of biomass as a strategic enabler for SDG achievement. The increasing publication trends combined with proactive university-level contributions, such as those by UPI, highlight the importance of academia in generating solutions that integrate renewable energy, climate action, and sustainable development. UPI's active participation further underscores how Indonesian higher education institutions are positioning themselves at the forefront of the SDG agenda, ensuring that national and regional research priorities align with global sustainability frameworks.

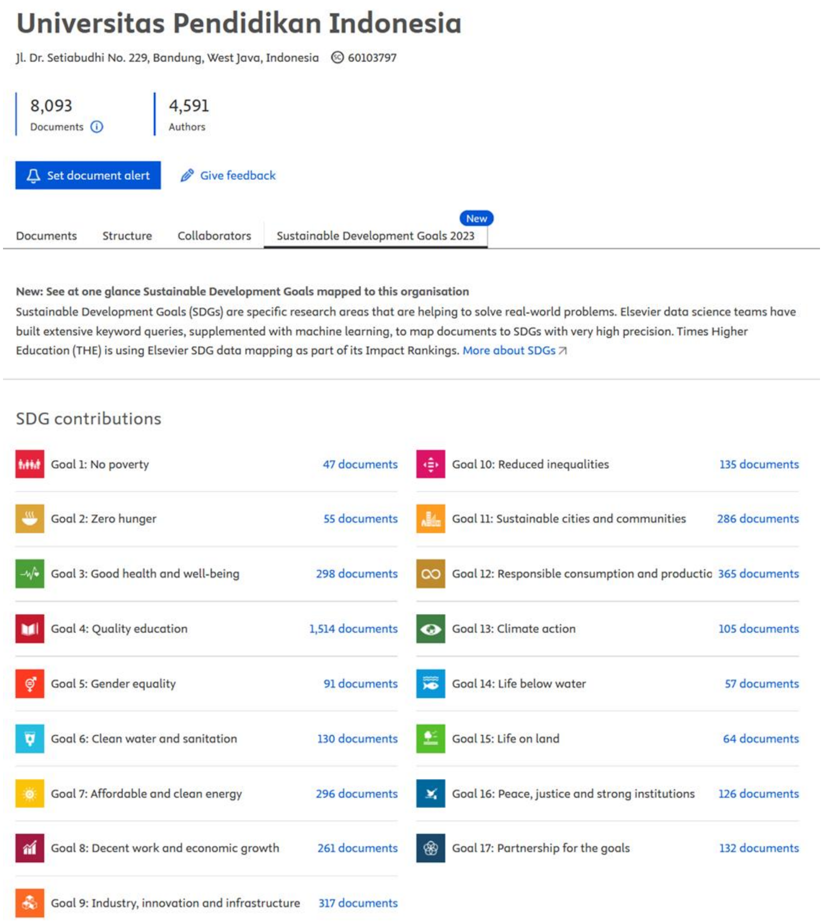

Fig. 6. Distribution of research contributions by Universitas Pendidikan Indonesia to the SDGs based on Scopus database taken June 2025, highlighting document counts per goal as mapped by Elsevier's SDG data framework.

3.4. Application of biomass in achieving SDGs

Figure 7 presents the percentage distribution of SDG-related keywords found in 438 biomass research papers published between 2016 and 2025 (see Scopus data in Fig. 5). The analysis reveals that nearly half of the papers (47.26%) address carbon, while climate and green themes appear in 40.87 and 36.30% of the papers, respectively. These results indicate that biomass research has been strongly aligned with carbon reduction, climate change mitigation, and green technology initiatives. Keywords such as renewable energy (19.41%), circular economy (16.67%), ecosystem (15.75%), mitigation (14.16%), and clean energy (10.96%) further reflect the diverse sustainability dimensions considered in biomass studies, emphasizing the sector's contribution to achieving multiple SDG targets.

Figure 8 illustrates the thematic evolution of biomass applications across SDG 1 (No Poverty), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land) from 2016 to 2025. Several key points were used to support the thematic analysis of biomass applications across the Sustainable Development Goals (SDGs). For SDG 1 (No Poverty), keywords such as poverty, low-income, social inclusion, income inequality, vulnerable groups, and basic needs were applied to identify research addressing poverty-related challenges. SDG 7 (Affordable and Clean Energy) was represented by terms including clean energy, renewable energy, energy access, affordable energy, sustainable energy, electricity access, and rural electrification, reflecting studies focused on expanding access to modern energy services. For SDG 12 (Responsible Consumption and Production), the analysis considered keywords like circular economy, sustainable consumption, sustainable production, waste management, resource efficiency, and lifecycle assessment, capturing efforts toward sustainable resource use. Lastly, SDG 15 (Life on Land) was linked to studies mentioning ecosystem, biodiversity, land restoration, forest, desertification, reforestation, and habitat conservation, emphasizing the role of biomass research in protecting terrestrial ecosystems.

Figure 8 shows thematic evolution over time, where interest has shifted towards clean energy, ecosystem restoration, and climate mitigation [23]. Future work should integrate quantitative indicators to measure biomass contributions to SDGs, enabling robust monitoring and policy evaluation.

The data reveal a growing research focus on SDG 7 and SDG 15, particularly peaking in 2024, addressing clean energy and land ecosystem themes. SDG 12 shows a notable rise in the later years, reflecting increasing attention to circular economy and sustainable production practices. SDG 1 remains the least represented, with only a few papers linking biomass studies directly to poverty-related goals. The overall trend highlights a shift in biomass research towards addressing climate action, energy transition, and ecosystem restoration as part of the broader SDG agenda. This is in line with current studies. early studies emphasized the role of biomass in achieving SDG 7 (Affordable and Clean Energy), particularly through rural electrification and the substitution of traditional fuels with modern bioenergy solutions [17]. Over time, the scope of research expanded to address SDG 12 (Responsible Consumption and Production) by integrating biomass into circular economy models that promote waste minimization and resource efficiency [18]. Recent trends show increased attention to SDG 13 (Climate Action) through carbon-neutral and carbon-negative technologies, such as biochar production and biomass energy with carbon capture and storage. SDG 15 (Life on Land) has also gained prominence, as biomass-based agroforestry systems and sustainable harvesting practices are recognized for their role in ecosystem restoration and biodiversity conservation [20, 21].

Biomass contributes significantly to SDG 7 by providing reliable, affordable, and sustainable energy solutions. Traditional biomass, such as wood and charcoal, continues to serve as a primary energy source in many low-income and rural regions, although it is often associated with health and environmental concerns [17]. Modern bioenergy technologies, including biogas, bioethanol, and biomass gasification, offer cleaner alternatives that can reduce household air pollution, enhance energy security, and support economic development. The integration of these technologies into national energy strategies, especially in developing countries, is seen as vital for achieving universal energy access while reducing dependency on fossil fuels [10].

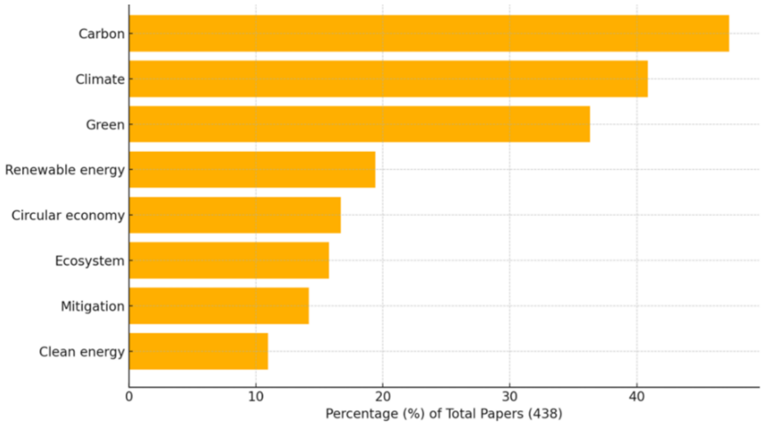

Fig. 7. Distribution of SDG-related key points in biomass applications from 2016 to 2025, based on an analysis of 438 research papers. The figure highlights the prominence of carbon, climate, and green themes, followed by renewable energy, circular economy, ecosystem, mitigation, and clean energy concepts in the literature. Data was extracted from Scopus database and analysed using a help of ChatGPT.

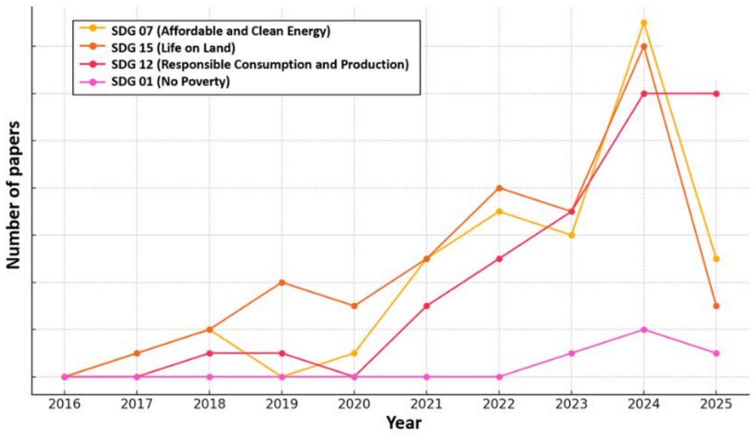

Fig. 8. Thematic evolution of biomass applications across SDGs from 2010 to 2025. Data was extracted from Scopus database and analysed using a help of ChatGPT.

In the context of SDG 12, biomass plays a crucial role in advancing responsible consumption and production patterns. Agricultural residues, forestry by-products, and organic municipal waste can be converted into energy, bio-based chemicals, or materials, contributing to circular economy objectives [18]. Biorefineries exemplify this approach by producing multiple value-added products from a single biomass feedstock, thereby maximizing resource efficiency and minimizing waste [10]. Such practices not only reduce the burden on landfills but also create new market opportunities for bio-based industries, fostering sustainable economic growth.

Biomass's role in SDG 13 is underscored by its potential to deliver low-carbon and carbon-negative energy solutions. When sustainably managed, the CO_2 released during biomass combustion is balanced by the CO_2 absorbed during plant growth, creating a near-carbon-neutral energy cycle. Furthermore, innovative applications like biochar production enable long-term carbon sequestration, contributing to negative emissions targets [19]. Substituting biomass for coal and other fossil fuels can reduce black carbon and greenhouse gas emissions, aligning energy systems with national and global climate commitments [34]. Biomass energy is also being explored as a component of bioenergy with carbon capture and storage (BECCS) systems, offering further potential for climate mitigation.

For SDG 15, biomass production systems such as agroforestry and integrated land management contribute to biodiversity conservation, soil health, and ecosystem restoration. Sustainable forest biomass harvesting, reforestation, and the use of fast-growing energy crops on degraded lands can enhance carbon stocks, prevent soil erosion, and provide habitat for wildlife [20, 21]. These practices support land resilience and productivity, helping to reverse land degradation and combat desertification. However, the benefits of biomass for SDG 15 depend heavily on responsible land-use planning and governance to ensure that biomass cultivation does not lead to deforestation, monoculture plantations, or loss of natural habitats [22].

Beyond these four SDGs, biomass intersects with other goals, such as SDG 8 (Decent Work and Economic Growth) through job creation in bioenergy sectors, and SDG 11 (Sustainable Cities and Communities) by contributing to urban waste management solutions. Integrated policies that align biomass strategies with multiple SDG targets can amplify positive outcomes while minimizing trade-offs [10]. As research and technology advance, the ability of biomass to deliver on these ambitions will hinge on sustained investment, innovation, and inclusive policy frameworks that address both global goals and local contexts.

3.5. Technological innovations in biomass utilization (Expanded)

Table 2 presents major technological innovations in biomass utilization and their relevance to specific SDGs. Advances in biomass conversion technologies have significantly enhanced efficiency, scalability, and environmental performance. Among these, torrefaction and palletisation improve the energy density and transportability of biomass, making logistics and storage more cost-effective. Integrated gasification combined cycle (IGCC) technologies enable the production of syngas for both electricity and heat, aligning with SDG 7's objectives for clean, modern energy [25]. Biorefineries represent a cornerstone innovation, capable of simultaneously producing fuels, chemicals, and materials from biomass, thus advancing SDG 12 by promoting resource efficiency and circular economy models [10]. Solar-enhanced drying systems, anaerobic digesters, and biochar reactors illustrate how innovations extend beyond energy to environmental management and soil health improvement, supporting SDG 15 [35].

Importantly, while these innovations offer substantial benefits, their widespread deployment is often constrained by cost, infrastructure needs, and technological maturity. Emerging solutions such as algal biomass conversion and synthetic biology-based biofuel production remain in early stages but hold potential for future contributions to SDG targets [10]. The integration of these technologies into national energy mixes depends on coherent policy support, financing mechanisms, and capacity building at the local level.

Biochar production faces high production costs that limit scalability, while torrefaction technology struggles with process efficiency and product uniformity. This paper provides qualitative synthesis; future studies should quantify biomass technology impacts using empirical data and modelling, including CO_2-equivalent reductions and energy output [19].

Table 2. Major technological innovations in biomass utilization and their SDG relevance.

Technological Innovation	Description	Relevant SDGs
Torrefaction and palletisation	Enhances energy density, improves transport and storage efficiency	SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production)
Integrated gasification combined cycle (IGCC)	Converts biomass into syngas for electricity and heat generation	SDG 7, SDG 13 (Climate Action)
Biorefineries	Produce multiple outputs (fuels, chemicals, materials) from biomass	SDG 12, SDG 9 (Industry, Innovation, and Infrastructure)
Anaerobic digestion	Converts organic waste to biogas and digestate for energy and soil health	SDG 7, SDG 12, SDG 15 (Life on Land)
Biochar production	Produces carbon-rich material for soil improvement and carbon sequestration	SDG 13, SDG 15
Solar-enhanced drying systems	Uses solar energy for biomass drying, reducing energy input requirements	SDG 7, SDG 12
Algal biomass conversion technologies	Emerging technologies for producing biofuels, bioplastics, and chemicals	SDG 9, SDG 13

3.6. Opportunities and potential of biomass in the green economy (Expanded)

Table 3 outlines the main opportunities for biomass within green economy strategies and associated policy instruments that have been identified in the literature. Biomass offers unique potential to link climate action, energy security, and inclusive economic growth. It supports rural livelihoods by creating jobs in harvesting, processing, and conversion industries while providing decentralized energy solutions that can reduce poverty and enhance local resilience [10]. In regions with abundant agricultural or forestry residues, biomass represents a means of turning waste liabilities into economic assets.

Table 3. Opportunities and policy instruments supporting biomass for SDGs in selected regions.

Opportunity	Region/Example	Supporting Policy Instruments
Rural employment and local economic development	Sub-Saharan Africa, Southeast Asia	Rural energy subsidies, bioenergy development programs
Renewable energy diversification	European Union, United States	Renewable portfolio standards, feed-in tariffs, and carbon pricing
Waste-to-energy initiatives	Urban centres in Latin America, Asia	Municipal waste management policies, public-private partnerships
Sustainable forestry and land restoration	Scandinavia, Canada	Sustainable forestry certification, reforestation incentives
Bioeconomy industrial innovation	Germany, Finland	National bioeconomy strategies, innovation funding schemes
Smallholder inclusion in supply chains	Indonesia, Brazil	Agroforestry grants, inclusive value chain initiatives
Climate mitigation through negative emissions	Japan, United Kingdom	BECCS (bioenergy with carbon capture and storage) funding pilots
Technology transfer and capacity building	Developing countries (general)	International cooperation agreements, technical assistance programs

From a policy perspective, instruments such as renewable energy targets, feed-in tariffs, carbon pricing, and public-private partnerships can accelerate biomass adoption [23]. Additionally, integrating biomass into bioeconomy strategies facilitates synergies across energy, agriculture, and environmental sectors. These integrated approaches foster innovation, support technology diffusion, and strengthen the competitiveness of domestic bio-based industries. International collaboration in technology transfer, knowledge sharing, and capacity building further enhances these opportunities, particularly in developing economies.

Sensitivity analyses are needed to assess how fluctuations in feedstock prices affect economic viability. Similarly, feasibility of green bonds or blended finance should be tested through simplified financial simulations to strengthen policy recommendations [28].

3.7. Challenges in biomass development and implementation (Expanded)

Table 4 summarizes key challenges that hinder the widespread deployment of biomass solutions, grouped into technical, economic, and socio-political categories. Technically, biomass faces challenges such as heterogeneous feedstock composition, seasonal availability, and low bulk energy density, which complicate processing and transport logistics. Advanced conversion technologies often require consistent, high-quality feedstock inputs, posing difficulties for supply chains that depend on diverse and variable resources.

Economically, biomass projects are often capital-intensive, with high upfront investment costs for infrastructure such as biorefineries and gasification plants [26]. Biomass feedstock prices can be volatile, influenced by competing demands (e.g., food, materials export markets), and market structures that lack long-term procurement contracts [36]. Without supportive policy frameworks (such as subsidies, tax incentives, or carbon credits), biomass systems may struggle to achieve cost parity with fossil fuel alternatives [28].

Socio-political challenges include policy inconsistency, where renewable energy goals are not always matched by enabling legislation or land-use regulations. In some contexts, concerns about deforestation, land conversion, and food security lead to public resistance to biomass expansion, particularly when projects are perceived to threaten local ecosystems or livelihoods [37]. Overcoming these challenges requires integrated governance, participatory decision-making, and transparent communication strategies to build social license and community trust.

Policy failures, such as inconsistent regulatory frameworks or weak enforcement, can undermine biomass adoption and should be addressed through coherent and stable governance structures. Effective biomass deployment requires transition policies that directly address fossil fuel technology lock-in, including incentives for switching infrastructure and phasing out fossil subsidies. Large-scale biomass deployment raises ethical considerations, including fair benefit distribution, avoidance of marginalization of vulnerable groups, and ensuring intergenerational equity. Effective biomass strategies must address role conflicts among stakeholders such as private sector, government, and local communities to prevent power imbalances and ensure social equity. Institutional capacity in developing countries needs to be strengthened to effectively implement biomass recommendations and support sustainable transitions.

3.8. Strategic recommendations for future research and policy

Figure 9 presents a conceptual model synthesizing the contributions of biomass to the Sustainable Development Goals (SDGs) and outlining strategic recommendations for future action. The model emphasizes the need for integrated policy frameworks that align energy, climate, and land-use objectives. It illustrates how biomass serves as a dynamic resource that connects to key SDG clusters, including SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land). This integration reflects the multifaceted role of biomass in advancing energy security, climate mitigation, circular economy practices, and ecosystem restoration [10]. Biomass can play a significant role in achieving SDGs if its deployment is guided by evidence-based policies, robust technologies, and inclusive governance. This study provides a synthesis of opportunities and challenges, but further efforts are needed to translate these into actionable strategies. Policy recommendations in this study are based on literature and bibliometric synthesis. Future research should incorporate empirical data, including case studies, to strengthen evidence-based policy guidance.

At the core of the model, biomass is categorized into various feedstocks (such as lignocellulosic materials, aquatic biomass, and organic waste) that contribute to clean energy systems, carbon-neutral or carbon-negative technologies, and bio-based materials. The figure highlights technological pathways like biorefineries, biochar production, anaerobic digestion, and integrated gasification combined cycle systems, each offering specific contributions to different SDGs [10, 19]. Technological innovation remains vital. Governments and industry should invest in research and development to improve conversion efficiencies, reduce costs, and commercialize emerging technologies such as algae-based biofuels and advanced biorefineries [10]. Integrating biomass studies with scenario models such as TIMES or MESSAGE would provide detailed projections of biomass roles in national and global energy planning.

Research priorities, as indicated in the model, include improving the efficiency and cost-effectiveness of emerging biomass technologies, quantifying trade-offs between biomass production and biodiversity conservation, and developing robust life cycle assessment methodologies that capture full sustainability impacts [22]. These priorities are critical to ensuring that biomass deployment maximizes environmental benefits while minimizing unintended ecological or social harms. A key recommendation is to integrate biomass planning with circular economy and bioeconomy policies to enhance resource efficiency and value creation [18]. Policy coherence at national and regional levels is critical to ensure alignment between biomass development and broader sustainability goals. Overcoming fossil fuel lock-in requires transition policies that directly address infrastructure inertia and fossil fuel subsidy reform.

In addition to technological innovation, financial mechanisms must be strengthened to enable large-scale and equitable biomass deployment. The model advocates for novel financing approaches, such as climate-aligned financing, green bonds, and blended finance, which can de-risk investments and mobilize private sector participation in biomass projects [28]. These mechanisms are essential to bridge funding gaps, particularly in low- and middle-income countries where capital constraints often limit renewable energy adoption. Financing models must be diversified. Green bonds, blended finance, and public-private partnerships can mobilize capital for biomass projects. While financial instruments such as green bonds and blended finance are discussed narratively, future research should stimulate their feasibility through simplified financial models such as cash flow projections or sensitivity analyses.

The outer layers of the model underscore the importance of international cooperation in scaling best practices, harmonizing sustainability standards, and supporting capacity building. Collaborative research, technology transfer, and regional policy alignment can accelerate biomass innovation and adoption globally, ensuring that sustainability gains are shared across borders [37]. International cooperation is essential to share best practices, transfer technology, and build capacity in low-income regions. This will help address the geographic bias identified in the current research landscape.

Furthermore, the model emphasizes the need to foster community involvement in biomass planning and deployment. Engaging local stakeholders (including smallholder farmers, Indigenous communities, and civil society organizations) can enhance social acceptance, promote equitable benefit distribution, and ensure that biomass strategies are context-appropriate and culturally sensitive [37]. Participatory governance approaches are vital to building trust, reducing conflicts over land use, and aligning biomass initiatives with local development goals. Social equity should be at the heart of biomass strategies. Policies must ensure fair benefit distribution, protect vulnerable groups, and enable active participation of local communities [27]. Institutional capacity in developing countries needs to be strengthened to effectively implement biomass recommendations and support sustainable transitions.

Figure 9 encapsulates four strategic pillars essential for realizing biomass's potential in supporting the SDGs:

(i) Technological innovation and diffusion: Advancing and disseminating biomass technologies suited to diverse local contexts.
(ii) Integrated policy frameworks: Aligning sectoral policies to create a coherent enabling environment.
(iii) Financial and market instruments: Mobilizing funding and creating stable markets for bio-based solutions.
(iv) Stakeholder engagement and capacity building: Ensuring inclusive, equitable, and sustainable biomass systems through participatory approaches.

By presenting this holistic view, the conceptual model offers a roadmap for decision-makers, researchers, and practitioners seeking to harness biomass as part of an integrated strategy for sustainable development. Finally, this adds new information regarding SDGs, as reported elsewhere [38-43].

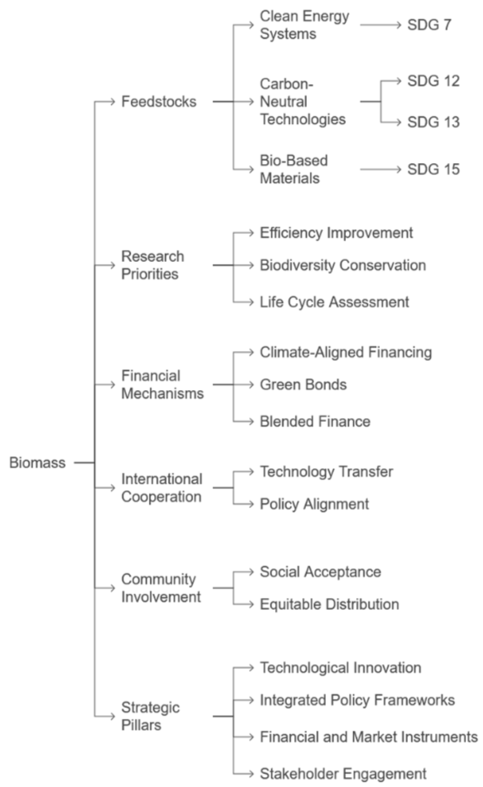

Fig. 9. Conceptual model of biomass contributions and strategic recommendations for SDGs.

4. Conclusions

This paper has provided an integrative review of biomass's role in achieving the Sustainable Development Goals, combining bibliometric and narrative analyses to map global trends, technologies, opportunities, and challenges. Biomass offers significant potential to contribute to clean energy, resource efficiency, climate action, and sustainable land use. It is important to note that this paper primarily addresses the potential contributions of biomass to SDGs, whereas realized contributions require empirical validation through case studies and performance data. While technological, socio-economic, and environmental challenges remain, targeted policies, inclusive governance, and sustained innovation can enable biomass to become a cornerstone of sustainable development. Biomass strategies should be designed to remain adaptive beyond 2030, supporting the evolving global sustainability agenda and future post-SDG frameworks.

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