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Biomass energy as a catalyst for achieving global sustainability goals: technological advancements and policy implications

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Abstract

Biomass energy has emerged as a vital renewable energy source in the global transition towards sustainable development, aligning with the United Nations sustainable development goals (SDGs), particularly SDG 7 (affordable and clean energy) and SDG 13 (climate action). This study evaluates biomass energy's contributions by integrating real SI-unit-based data on energy usage in China, India, Denmark, Germany, Brazil, Namibia, and Ghana. An interpretative review was employed, incorporating primarily qualitative analysis and supplemented by the quantitative analysis of biomass energy deployment, cost assessments, and policy evaluations. The findings reveal that biomass contributes 8% to China's renewable energy mix (500 TWh), 12% in India (370 TWh), 20% in Denmark (43 TWh), and 27% in Brazil (160 TWh), yet its expansion faces economic, technological, and policy challenges. This study integrates cutting-edge catalysts (e.g., ZnO, TiO2, Ni) and nanotechnology applications (e.g., nanocatalysts, nanomembranes) to enhance biomass energy efficiency. A comparative technical analysis of combustion, anaerobic digestion, pyrolysis, and gasification highlights gasification as the most efficient process (70–85%), with the lowest carbon emissions (30–50 kg CO_2/GJ) but requiring higher capital investment (USD 0.07–0.14/kWh). This study concludes with policy recommendations, emphasizing targeted subsidies, international collaboration, and infrastructure investments to improve biomass energy adoption globally.

Keywords: *biomass energy, catalysts, energy transition, nanotechnology, policy frameworks, sustainable development goals, and technological advancement*

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1. Introduction

The global transition towards sustainable energy solutions has gained momentum as countries aim to combat climate change, lower carbon emissions, and bolster energy security [1, 2]. Biomass energy, which is sourced from organic materials such as agricultural residues, forestry waste, and municipal solid waste, has historically been a significant component of global energy systems [3, 4]. Prior to the industrial revolution, biomass was the primary energy source, providing heat, cooking fuel, and mechanical power. However, the rise of fossil fuels in the 19th and 20th centuries diminished its prominence, particularly in urban areas, while rural and developing regions continued to rely on traditional biomass sources [5].

Biomass energy has been a cornerstone of human civilization for thousands of years. In ancient societies, wood, crop residues, and animal dung were the primary energy sources, providing essential heat for survival and cooking. The reliance on biomass continued through the medieval period, where charcoal production for metallurgy played a pivotal role in economic development [6]. However, the transition from biomass to coal during the industrial revolution marked a significant shift in energy use. Steam engines powered by coal replaced biomass-based mechanical systems, leading to an era dominated by fossil fuels [7].

By the 20th century, oil and natural gas became dominant, further reducing biomass energy's share in global energy production. Nevertheless, biomass remained a vital energy source in developing countries where access to modern energy alternatives was limited. Over the past few decades, the resurgence of interest in biomass energy has been driven by the need for cleaner, renewable energy solutions and advancements in bioenergy technologies [8–10].

The concept of an energy transition ladder helps illustrate biomass's role in the shift from traditional to modern energy sources. In this framework, societies typically move from inefficient traditional biomass (such as firewood and dung) to more efficient forms of bioenergy (such as biogas and bioethanol), and eventually towards fully renewable and sustainable energy systems [2, 8–10]. Biomass serves as an intermediate step in this transition, particularly in regions where the rapid adoption of solar, wind, or hydropower is constrained by economic and infrastructural barriers.

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In countries such as China and India, biomass has been a steppingstone towards electrification and the expansion of renewable energy infrastructure. The introduction of improved cookstoves, biogas digesters, and biofuel programs has facilitated a gradual shift away from traditional biomass use while leveraging existing organic waste resources [3, 4, 11–13]. Similarly, in sub-Saharan Africa, modern biomass solutions have been promoted as a bridge towards energy access and sustainability, given that nearly 900 million people in the region still rely on traditional biomass for cooking and heating [8, 14, 15].

Despite advancements in renewable energy technologies, biomass remains a significant component of the global energy mix. As of 2023, biomass accounted for approximately 10% of global energy consumption, translating to around 55 exajoules, with various countries adopting distinct strategies for its integration [16]. Brazil has emerged as a global leader in bioethanol production, leveraging its vast sugarcane industry, whereas European nations such as Denmark and Germany have integrated biomass into district heating and combined heat and power (CHP) systems [17–32]. Thus, Denmark has shifted towards wind and solar energy, gradually reducing its reliance on biomass [25].

Conversely, developing countries such as Namibia and Ghana continue to depend on traditional biomass sources, highlighting the persistent energy divide between high-income and low-income nations [33–42]. While some regions have embraced wind and solar energy as primary renewable sources, others still see biomass as a more accessible and cost-effective solution for energy security. These variations underscore the influence of technological advancements, policy frameworks, and economic viability on the role of biomass in global energy transitions [17–42].

The evolution of biomass energy has been propelled by significant technological advancements. Modern biomass conversion technologies, including gasification, pyrolysis, and anaerobic digestion, have improved energy efficiency and reduced environmental impacts [43–48]. Gasification, for example, enables the production of synthetic gas (syngas) that can be used for electricity generation or as a feedstock for biofuels. Similarly, pyrolysis converts biomass into biochar, bio-oil, and syngas, offering a versatile approach to energy production and carbon sequestration [47, 48].

Furthermore, advancements in catalytic processes and nanotechnology have enhanced the efficiency of biofuel production. Researchers are exploring second-generation and third-generation biofuels derived from non-food biomass sources such as algae and agricultural residues to mitigate concerns related to food security and land-use competition [9, 49, 50]. These innovations position biomass as a viable long-term player in the renewable energy landscape, complementing other sources such as solar and wind.

Despite its potential, biomass energy faces several challenges that must be addressed to ensure its sustainability. Key concerns include land-use conflicts, carbon neutrality debates, and economic feasibility. Large-scale bioenergy production can lead to deforestation, biodiversity loss, and competition with food crops, raising questions about its long-term environmental impact [51–53]. Moreover, while biomass is often considered a carbon-neutral energy source, the actual emissions depend on factors such as feedstock type, production methods, and land management practices.

Policy frameworks play a crucial role in shaping the future of biomass energy. Countries with well-defined bioenergy strategies have made significant progress in integrating biomass into their energy systems. For instance, the European Union's Renewable Energy Directive (RED II) has set ambitious targets for bioenergy deployment, emphasizing sustainability criteria and lifecycle emissions reductions [54, 55]. In contrast, many developing nations lack comprehensive policies to regulate biomass use, leading to inefficiencies and environmental concerns.

Given the pressing need for sustainable energy solutions, it is crucial to evaluate the role of biomass energy in achieving global sustainability goals. Biomass serves as both a historical and transitional energy source, bridging the gap between traditional fossil fuel dependence and modern renewable energy adoption. Understanding its evolution, technological advancements, and policy frameworks provides valuable insights into the pathways for [51–53] achieving a low-carbon future.

This study aims to investigate biomass energy adoption across selected countries, the impact of technological advancements, and the effectiveness of existing policy frameworks. By assessing the role of biomass in energy transitions, this research contributes to a deeper understanding of its significance in sustainable development and its future trajectory in the global energy landscape. As nations continue their pursuit of carbon neutrality, the strategic integration of biomass into energy portfolios remains a critical component of a diversified and resilient energy system.

2. Methodology

An interpretative review was employed for this study to uncover meaningful patterns that describe the phenomenon of biomass energy and its potential in achieving sustainability goals. By adopting an interpretive literature review, this study focused on interpreting "what other scholars have written" about biomass energy, specifically its role as a catalyst for sustainable development, and "to put them into specific perspectives" relevant to technological advancements and policy frameworks [56]. A key aspect of this method is its adherence to typical steps used in systematic reviews, following a qualitative communicative inquiry and quantitative case studies, incorporating elements of the preferred reporting items for systematic reviews and meta-analyses (PRISMA) approach to ensure rigorous data collection, analysis, and synthesis. In adopting this approach, it was important to clearly delineate how the literature data were sourced. However, we did not seek to draw conclusions from all the relevant sources or to identify their implications, as would be performed in a traditional critical literature synthesis. Therefore, we refer to our approach as interpretative or interpretive, reflecting our aim to explore the potential of biomass energy in driving sustainability while accounting for technological and policy factors comparatively [57].

2.1. Approach to the review

In this study, we aimed to gather mixed-method (qualitative and quantitative) information pertinent to understanding biomass energy and its potential to drive sustainability goals, with a particular focus on technological advancements and policy implications. This review was framed around interpreting research related to biomass energy as a catalyst for achieving sustainability, rather than critiquing existing views on the topic. This study sought to answer four main questions: (1) What role does biomass energy play in advancing sustainability goals? (2) What technological advancements have been made in biomass energy to enhance its efficiency and sustainability? (3) What are the policy implications of promoting biomass energy for sustainable development? (4) How can biomass energy be leveraged in the context of Africa's energy transition and sustainability goals? To address these questions, we identified relevant studies on biomass energy, focusing on both global and African contexts (China, India, Denmark, Germany, Brazil, Namibia, and Ghana), and conducted a systematic selection from the identified sources. These countries were chosen based on their unique biomass energy adoption models, policy frameworks, and contributions to global sustainability efforts.

The selection of study countries was grounded in their diverse energy landscapes, biomass potential, and policy orientations. China and India represented large-scale biomass energy adopters with significant governmental backing for renewable energy expansion. Germany and Denmark were included for their pioneering roles in sustainable energy policy and technological innovation in biomass conversion. Brazil was chosen due to its extensive bioenergy sector, particularly in bioethanol and biogas production. Namibia and Ghana provided insights into biomass energy in the African context, where resource constraints and policy frameworks shape energy sustainability transitions. This selection ensured a balanced examination of biomass energy adoption across varying economic, geographic, and policy environments. The process employed in this review is outlined in **Figure 1**. The methodology included four key steps: (1) identifying the sources for the literature search, (2) setting appropriate search terms, (3) defining selection criteria, and (4) extracting and synthesizing data. Each of these steps is explained in detail below.

Identifying the literature search sources: We began by recognizing Google Scholar as a primary source for accessing relevant academic research, alongside expert recommendations for additional resources. This led to a comprehensive search of scholarly articles, books, and conference papers related to biomass energy and sustainability, supplemented by the gray literature. These sources were identified through both Google Scholar and expert suggestions in the field of energy sustainability and biomass technologies.

Setting the search terms: To conduct a focused and systematic search, we defined specific search terms related to biomass energy, technological advancements, sustainability, and policy implications. This search was conducted between 9 and 29 October 2024, with Google Scholar being the preferred search engine due to its ability to index scholarly research across various databases, including peer-reviewed journals, academic books, and conference papers. The search terms used included keywords such as "biomass energy", "sustainability goals", "technological advancements in biomass", and "policy implications for biomass energy", specifically in the context of Africa's and non-Africa's energy transition (refer to **Table 1** for a detailed list of search terms).

Defining the search and selection criteria: Our initial inclusion considered abstracts focusing on biomass energy production and its role in sustainability goals in Africa or global contexts. In this regard, only two (n = 2) articles were found specifically addressing biomass energy and its implications for sustainability in Africa and global contexts. This is a clear indicator that, despite numerous theoretical discussions on biomass energy in some African and non-African countries, there remains a significant gap in research specifically focusing on biomass energy's contribution to sustainability goals in the African and global context. Our final inclusion considered variants of keywords, such as biomass energy technologies, biomass potential or efficiency for Africa/non-Africa, and biomass cost-effectiveness in sustainable development. Details on the literature search are presented in **Figure 2**.

The literature sources identified from Google Scholar numbered 517, while the sources identified through expert snowballing recommendations numbered 17, resulting in a total of n = 534 literature sources. These were screened based on unsuitable titles/abstracts,

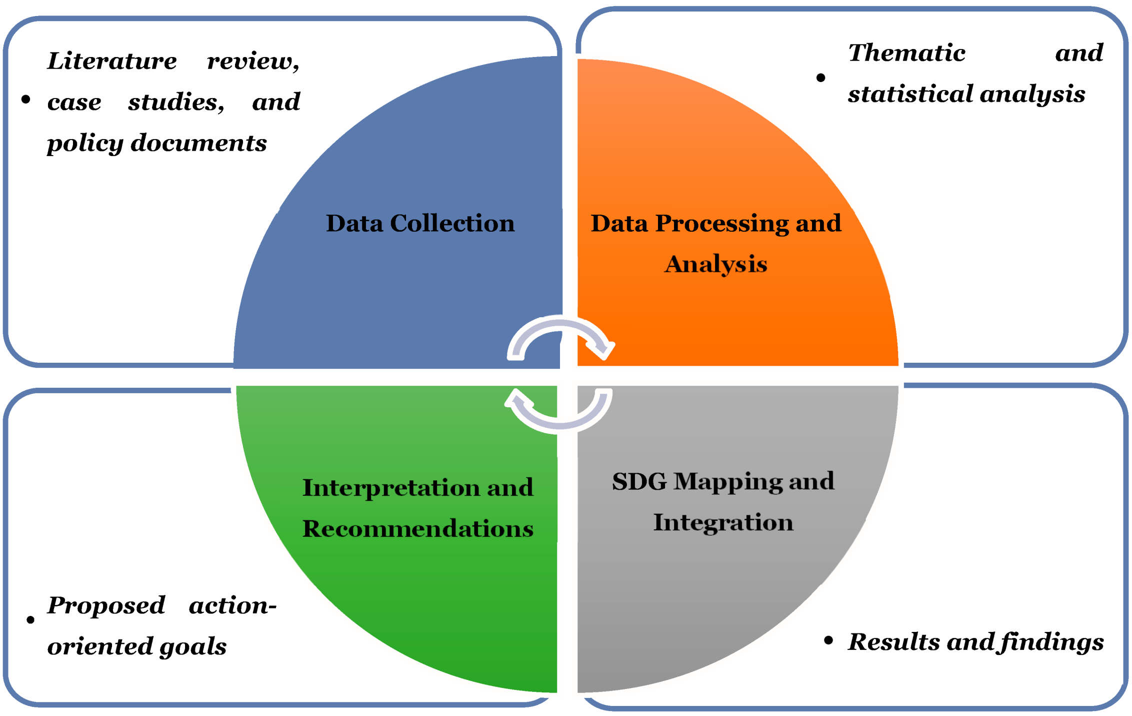

Figure 1 • The specific steps adopted in the interpretative literature review.

Table 1 • The combination of search terms or keywords used in the literature search.

Subject focus of the search *	Search terms or keywords
Biomass energy production	Biomass energy, biomass technology, bioenergy production, biomass energy potential, sustainable biomass energy
Technological advancement in biomass energy	Biomass technology advancements, innovations in biomass energy, efficiency in biomass energy, biomass technology improvements
Biomass energy in Africa/non-Africa (selected countries)	Biomass energy in Africa/non-Africa, renewable energy in Africa/non-Africa, biomass energy potential in Africa/non-Africa, Africa's/non-Africa's energy transition
Energy demand or sustainability in Africa/non-Africa	Energy demand in Africa/non-Africa, energy sustainability in Africa/non-Africa, renewable energy needs in Africa/non-Africa, energy consumption in Africa/non-Africa
Policy implications for biomass energy	Biomass energy policies, biomass energy policy frameworks, policy implications for renewable energy, biomass energy regulation in Africa/non-Africa
Biomass energy for sustainable development	Biomass energy and sustainable development, biomass energy for SDGs, biomass energy and green growth, sustainable energy in Africa/non-Africa

* The focus of the subject included terms, phrases, and expressions that address the main objectives and questions identified earlier for investigation in this study.

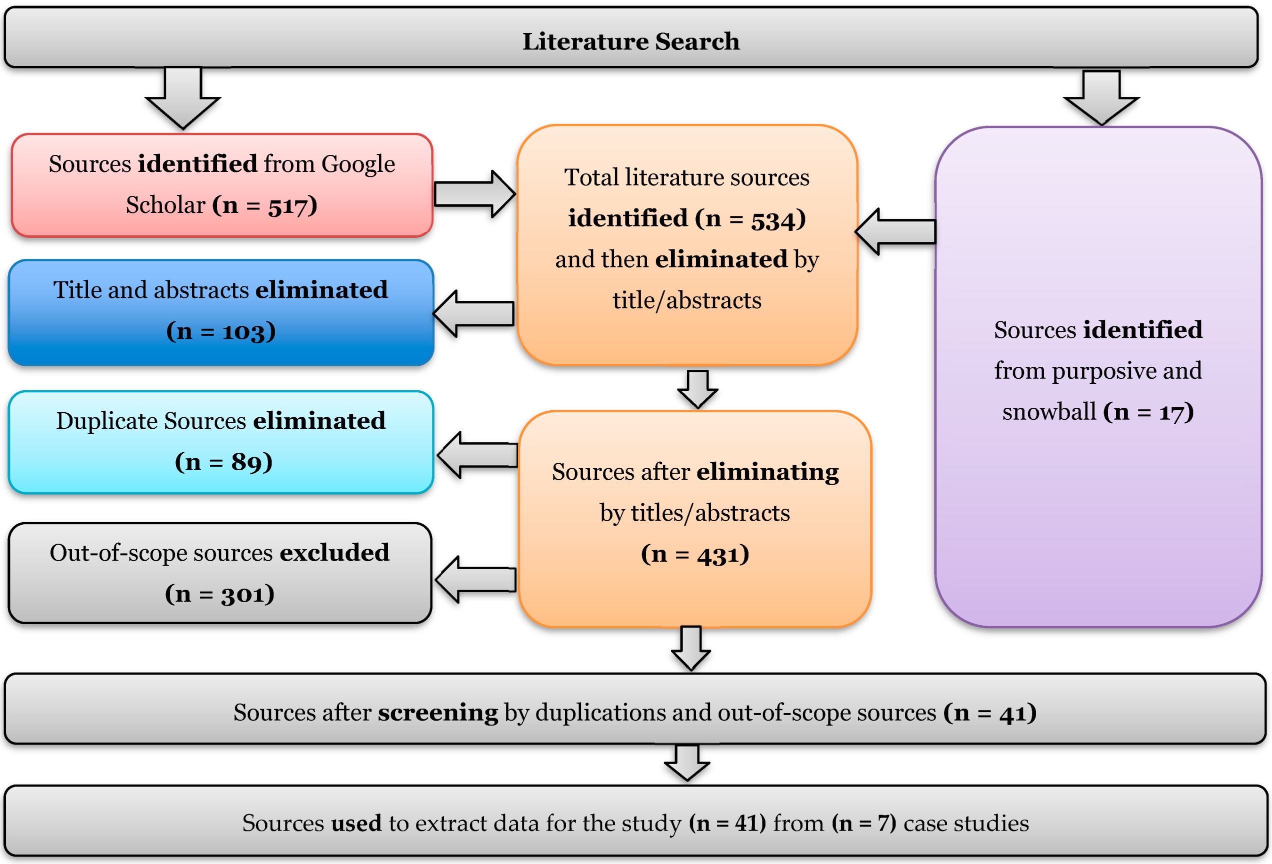

Figure 2 • The flowchart of the literature search process from 7 case study profiles.

duplications, and out-of-scope sources. The screening process identified 103 unsuitable titles/contents, 89 duplications, and 301 out-of-scope contents. Screening by titles/abstracts reduced the initial total of 534 identified documents to 431. However, further screening based on duplicates and out-of-scope contents reduced the total accepted literature resources to 41, which were then used for this study.

Extracting and synthesizing data: The final step involved a thematic and comparative statistical analysis of the selected literature. This process included reading and extracting data from the abstract, introduction, findings, and conclusion sections of each selected study. We adhered to Ahmadov and McMullin's [58, 59] notetaking methodology, and then grouped, synthesized, and built descriptive narratives and performed meta-data analysis comparatively around the four key questions under investigation, particularly focusing on how biomass energy technologies contribute to achieving sustainability goals and the policy implications for the energy transition in global and African contexts. The following sections present an interpretation of the studies within the context of the four questions explored, particularly regarding the technological advancements and policy implications related to biomass energy.

2.2. General characteristics

The preferred literature period used for this study spanned from 2015 to October 2024 (≤10 years old). A ten-year timeframe was selected due to the observed surge in research publications on biomass energy technologies and sustainability policy in the past five years (2019–2024). However, this review extended back an additional five years (2015–2024) to capture earlier contributions that may provide foundational insights into biomass energy advancements. Consequently, the literature examined fell within a 5–10-year range. As this study employed an interpretive approach rather than a conventional systematic review or scoping study, journal names, methodologies, or emerging theoretical frameworks were not the primary focus.

This approach aligned with this study's objective of synthesizing descriptive narratives and practical developments in biomass energy deployment, particularly within 7 selected countries globally. Emphasis was placed on research exploring biomass energy innovations, policy frameworks, and their role in achieving sustainability goals. A notable limitation of this approach was the predominance of sources that document government-backed renewable energy initiatives and international investments, primarily in English-language publications.

The interpretive review framework enabled a descriptive narrative and comparative case study analysis, rather than a strictly analytical synthesis of biomass energy contributions to sustainability. Publications were assessed based on authors, thematic relevance, and the research gaps they addressed concerning biomass energy as a catalyst for sustainable development. The selected literature (n = 41) spanned diverse subject areas and geographic contexts. Instead of evaluating each study based on standalone research gaps, priority was given to sources that directly or indirectly addressed this study's research questions.

This facilitated a structured interpretation of research within the broader context of technological advancements in biomass energy and its policy implications. The descriptive narration (argumentation) and meta-data comparison (statistical case study) employed in this study provided a lens through which biomass energy's role in achieving sustainability goals—particularly in relation to energy access, carbon reduction, and economic resilience—was examined, as denoted in **Table 2**. Additional literature and policy documents were cited where it is necessary to substantiate findings and provide readers with further insights into the evolving discourse on biomass energy, technology, and policy integration.

To strengthen methodological rigor, this study incorporated a comparative analysis framework for biomass conversion techniques, including combustion, anaerobic digestion, pyrolysis, and gasification. Each method was assessed based on efficiency, emission levels, cost implications, and scalability in different socio-economic and geographic contexts. Comparative analysis enhanced the understanding of how each country utilizes specific biomass technologies to address its unique energy needs and sustainability goals [57].

A key feature of this methodology is its focus on technological and policy linkages. This study examined how policies in each selected country influence biomass technology adoption and sustainability transitions. Policies such as China's renewable energy law, India's national bioenergy mission, Denmark's green energy strategy, Germany's act on renewable energy sources, Brazil's bioethanol policies, and Africa's biomass energy regulations were critically assessed. By integrating policy analysis with technological assessment, this study provides a holistic understanding of biomass energy's potential as a sustainable energy source.

The methodological framework also acknowledges limitations related to data availability and geographic scope. While the selected literature provides comprehensive insights into biomass energy developments, gaps remain in empirical studies, particularly for Namibia and Ghana. To address this, supplementary data from the gray literature, government reports, and international energy organizations were incorporated to provide a more robust analysis of biomass energy's role in Africa's energy transition.

3. Literature and theoretical review

Biomass energy, derived from organic materials such as agricultural residues, forestry waste, municipal solid waste, and dedicated energy crops, has emerged as a pivotal solution for achieving global

Table 2 • Table of the publications from which the interpretations were derived.

Research questions *	References	Subject and countries
What role does biomass energy play in advancing sustainability goals?	[17–42, 60–68]	Bioenergy consumption, sustainability, carbon neutrality
What technological advancements have been made in biomass energy to enhance its efficiency and sustainability?	[17–42, 60–66, 69–81]	Biofuel technologies, negative emissions, energy transition
What are the policy implications of promoting biomass energy for sustainable development?	[17–42, 60–66]	Policy frameworks, bioenergy adoption, sustainability policies
How can biomass energy be leveraged in the context of countries' energy transition and sustainability goals?	[17–42, 60–66, 69–81]	Renewable energy strategies, bioenergy implementation

* The focal point of enquiry was directly on the research questions.

sustainability goals [3, 4]. The transition towards renewable energy systems, in alignment with SDG 7 and 13, highlights the critical role of biomass energy in reducing carbon emissions, promoting energy security, and fostering socio-economic development [82]. In other words, technological advancements and supportive policy frameworks are essential for optimizing biomass energy's potential and mitigating associated challenges, such as land-use competition and carbon leakage. This literature review examines existing research on biomass resources, conversion technologies, and theoretical frameworks that inform the deployment of biomass energy systems.

3.1. Biomass energy transition

A growing body of research highlights the importance of integrating biomass energy within national energy transition strategies. Biomass is often viewed as part of an energy transition ladder, progressing from traditional forms such as wood and charcoal combustion to modern bioenergy technologies, including biogas, bioethanol, and bioelectricity [2, 8–10]. The transition is driven by advancements in catalytic conversion processes, which have significantly improved energy efficiency and emissions reduction. Studies emphasize that effective biomass deployment requires a comparative analysis with other renewable energy sources, including wind, solar, and hydroelectric power, to identify synergies and optimize energy mix strategies [83]. While biomass has advantages in terms of dispatchability and rural economic benefits, challenges such as supply chain inefficiencies and environmental trade-offs remain [84].

Existing research also explores key biomass feedstocks and their sustainability implications. Agricultural residues, such as corn stover, wheat straw, and rice husks, constitute a substantial portion of bioenergy production due to their abundance and renewability [85, 86]. Studies demonstrate that agricultural biomass can be effectively converted into biofuels and biochar through thermochemical and biochemical processes. However, seasonal variability and logistical inefficiencies pose significant barriers to scalability [86, 87]. Forestry residues, including sawdust, bark, and wood chips, present another critical biomass resource, particularly in combined heat and power applications [88]. Advanced thermochemical methods, such as gasification, have demonstrated the ability to enhance energy efficiency while minimizing emissions. However, sustainable forest management remains a prerequisite for preventing resource overexploitation [89].

Municipal solid waste (MSW) and organic municipal waste (OMW) are increasingly recognized for their potential in bioenergy production. Anaerobic digestion remains a dominant technology for converting biodegradable waste into biogas, which can be refined into biomethane [87, 90]. Scholars argue that leveraging OMW within urban energy systems can enhance waste-to-energy initiatives, particularly in developing cities struggling with waste management challenges [91]. Nevertheless, the success of such interventions depends on regulatory incentives, public participation, and advancements in waste segregation technologies [92, 93]. Dedicated energy crops, including miscanthus, switchgrass, and poplar, offer a reliable and high-yield biomass feedstock. Research suggests that these crops contribute to carbon sequestration and soil restoration [94]. However, concerns related to land-use competition, food security, and water resource depletion must be carefully managed through strategic land allocation and sustainable farming practices [94].

Biomass energy conversion technologies have undergone significant advancements in recent years. Combustion-based systems, particularly modern fluidized-bed and grate-fired boilers, have achieved higher efficiency and lower emissions through improved flue gas treatment techniques [95, 96]. Pyrolysis has gained attention due to its ability to produce bio-oil with high energy density, although challenges related to feedstock heterogeneity remain [97, 98]. Recent developments in catalytic pyrolysis have introduced advanced catalysts such as nickel (Ni), cobalt (Co), iron (Fe), zinc oxide (ZnO), and titanium dioxide (TiO_2), which enhance bio-oil quality and increase conversion efficiency [87]. The literature also emphasizes the role of biochemical conversion technologies, including anaerobic digestion and enzymatic hydrolysis, in producing bioethanol, biogas, and other biofuels. Enzyme-based catalysis, particularly through genetically engineered microbial strains, has shown promising results in improving yield and cost-effectiveness [99–101].

The integration of artificial intelligence (AI) and internet of things (IoT) in biomass energy systems is an emerging area of research. AI-driven models are being deployed to optimize feedstock supply chains, enhance the predictive maintenance of bioenergy plants, and improve process efficiency [102, 103]. IoT-enabled sensors facilitate the real-time monitoring of biomass conversion systems, contributing to cost reductions and environmental impact mitigation. However, the adoption of AI-driven biomass management requires investments in digital infrastructure and cross-sectoral collaboration between energy and technology industries [104, 105].

From a theoretical perspective, biomass energy aligns with multiple frameworks that provide insights into its role in sustainable development. The circular economy theory highlights the potential of biomass energy to create closed-loop systems, where organic waste is repurposed into valuable energy products [106]. This reduces environmental footprints and supports resource efficiency. Energy transition theory provides a systemic perspective on the shift from fossil-based to renewable energy sources, positioning biomass as a key intermediary in this transformation [101, 107]. Biomass energy facilitates decentralized energy generation, particularly in rural and off-grid communities, thereby promoting energy access and resilience [108].

Another relevant framework is the sustainable livelihoods framework (SLF), which underscores the socio-economic benefits of biomass energy, including job creation and poverty alleviation [109]. Biomass energy projects can enhance rural economies by creating employment opportunities in feedstock cultivation, processing, and distribution. The SLF emphasizes that the success of biomass energy systems depends on institutional support, financial incentives, and community engagement [110].

Despite the progress in biomass energy research, several challenges persist. Regulatory uncertainties, financial constraints, and public perception issues continue to hinder large-scale deployment [111, 112]. Agricultural and forestry residues offer substantial bioenergy potential, but policy support and innovative financing mechanisms are necessary to overcome logistical and market barriers. Furthermore, sustainability concerns related to land-use change and biomass supply chain emissions must be addressed through integrated policy frameworks [110].

The interplay between technology, policy, and sustainability ultimately determines the success of biomass energy in global energy transitions (**Figure 3**). While technological innovations provide the means to enhance efficiency and reduce environmental impacts, their effectiveness relies on robust policy frameworks and institutional support. Policies that incentivize research and development (R&D), facilitate subsidies for bioenergy infrastructure, and enforce sustainable biomass sourcing are essential for long-term viability (IRENA, 2021). Socio-technical perspectives suggest that policy interventions should also consider social acceptance, equitable resource distribution, and participatory governance to prevent socio-economic disparities [113].

In conclusion, achieving sustainability in biomass energy systems requires a holistic approach that integrates technological advancements, policy mechanisms, and socio-economic considerations. The literature underscores the necessity of aligning biomass energy with circular economy principles, energy transition frameworks, and sustainable livelihood strategies to maximize its environmental and economic benefits. Addressing existing barriers through coordinated action among researchers, policymakers, and industry stakeholders will be critical for positioning biomass energy as a key contributor to a sustainable energy future.

4. Results and discussion

Having analyzed the research approach and theoretical insights, this section presents a detailed discussion of biomass energy deployment across diverse global contexts. The comparative case study analysis highlights success stories, challenges, and best practices in China, India, Denmark, Germany, Brazil, Namibia, and Ghana. This analysis directly addresses the research objectives by incorporating real-world numerical data, cost analysis, technological advancements, and policy implications.

4.1. Sustainable transition

The first step in addressing sustainability goals is to identify the role of biomass energy in African and non-African contexts. This section addresses the research question: what role does biomass energy play in advancing sustainability goals? The results reveal that biomass energy plays a pivotal role in achieving global sustainability goals, particularly SDGs 7, 8, 13, and 15. Thus, its contribution is observed through renewable energy generation, carbon emission reduction, rural–urban development, and improved energy access in both developed and developing countries. The findings across selected countries reveal the following:

- China is the leader in bioenergy adoption with substantial investment in biofuel technology and rural biomass projects, contributing significantly to carbon neutrality goals by 2060 [60–64].
- India's biomass contributes around 15% of its total energy consumption, particularly in rural areas, aiding energy equity and reducing reliance on traditional biomass fuels [65, 66].
- Denmark is a global leader in advanced bioenergy technologies and integrated biomass heating systems, achieving over 30% of national energy from bioenergy sources [25–27].
- Germany, a pioneer in bioenergy innovation with robust policy frameworks supporting biogas and biofuel sectors, contributes to Germany's renewable energy targets under Energiewende [28–32].

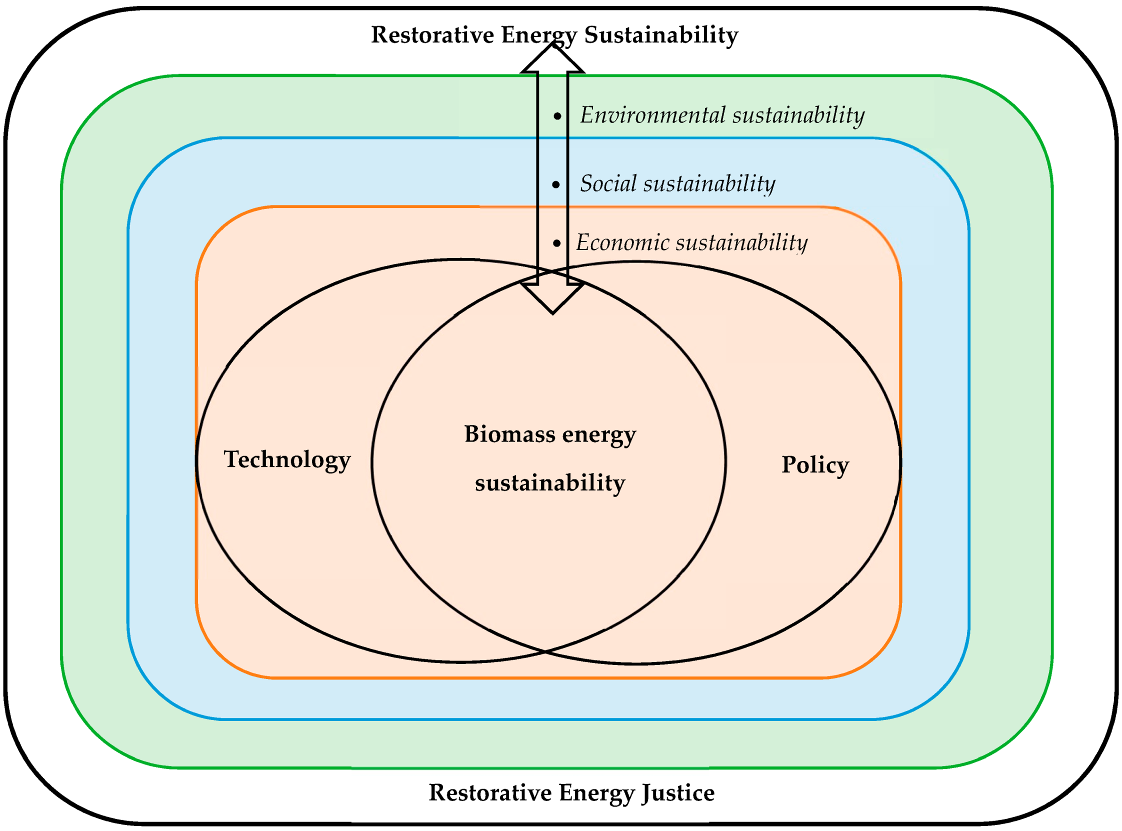

Figure 3 • The nexus between energy sustainability, technology, and policy.

- Brazil is the leading global producer of bioethanol, significantly reducing transportation emissions and supporting rural economic growth through sugarcane-based energy systems [17–24].
- Namibia's use of biomass from invasive bush species (bush-to-energy projects) addresses both environmental and energy challenges while supporting rural livelihoods [33–36].
- Ghana's biomass energy remains a dominant energy source for households, with ongoing projects aimed at modernizing traditional biomass usage and improving energy efficiency [37–42].

The data [17–42, 60–66] highlight a significant variation in biomass energy contributions to SDGs across the selected countries. For instance, biomass energy reduces greenhouse gas (GHG) emissions by replacing fossil fuels with renewable biofuels and biogas [67]. In Brazil, bioethanol from sugarcane has significantly reduced carbon emissions in the transport sector, while Namibia's bush-to-energy projects address land degradation and carbon sequestration simultaneously. Thus, environmental sustainability is achieved under SDG 13, i.e., climate action.

Furthermore, India's and Ghana's biomass energy has enhanced energy access, particularly in rural areas, contributing to poverty alleviation and rural economic development [40, 66]. Denmark and Germany exemplify how technological advancement in biomass utilization creates employment and boosts green economies [25–28]. This implies that the socio-economic developments of SDGs 7 (affordable and clean energy), 8 (decent work and economic growth), 13 (climate action), and 15 (life on land) are progressively achievable across the selected regions (**Table 3**). Further analysis revealed that energy security and policy frameworks play a vital role in biomass energy success stories. For instance, Denmark's renewable energy targets and Germany's Energiewende policy highlight the role of strategic governance in achieving SDGs. However, Namibia and Ghana face challenges such as inadequate infrastructure and policy gaps despite significant biomass potential. While biomass energy presents significant opportunities,

Table 3 • Contribution of biomass energy to achieving key sustainability goals in selected countries.

Variables: (1) country, (2) biomass strategy and initiatives, (3) SDG contribution, and (4) challenges
1—China; 2—Bioenergy from crop residues; national biomass plan and rural bioenergy; 3—SDGs 7, 8, and 13 (high contribution to rural electrification; supports job creation in rural areas; reduction in carbon emissions); biomass contributes ~8% (~500 TWh) to renewable energy mix; 4—Technological costs and land competition.
1—India; 2—Agricultural biomass feedstock; national bioenergy mission; 3—SDGs 7, 8, and 13 (expansion of biomass power plants; employment in energy production; reduction in reliance on coal); biomass accounts for ~12% (~370 TWh) of energy needs; 4—Feedstock supply chain and rural infrastructure.
1—Denmark; 2—Advanced bioenergy technologies; advanced biomass co-firing in power plants; 3—SDGs 7, 8, and 13 (35% of energy from biomass; supports green job creation; carbon-neutral bioenergy systems), biomass covers ~20% (~43 TWh) of the total energy demand; 4—Dependency on imported biomass feedstock.
1—Germany; 2—Integration into national grid; renewable energy act (EEG) incentives; 3—SDGs 7, 8, and 13 (25% energy from biomass ethanol biofuels; green employment opportunities; reduced fossil fuel resilience); biomass contributes ~9% (~110 TWh) to energy production; 4—Land-use conflicts and sustainability concerns.
1—Brazil; 2—Sugarcane ethanol program; ethanal production from sugarcane; 3—SDGs 7, 8, and 13 (ethanol biofuels dominate transport energy; sugarcane industry employment; lower greenhouse gas emissions); biomass contributes ~27% (~160 TWh) of total energy; 4—Environmental degradation from monoculture crops.
1—Namibia; 2—Encroacher bush biomass; bush-to-biomass initiative; 3—SDGs 7, 8, 13, and 15 (rural electrification via biomass; jobs through bush harvesting; reduction in deforestation; biodiversity conservation); biomass potential remains largely untapped (~10 TWh); 4—Limited technical capacity and policy gaps.
1—Ghana; 2—Charcoal and firewood biomass; promotion of clean cookstoves; 3—SDGs 7, 8, and 13 (household energy reliance on biomass; rural job creation; potential carbon savings); biomass accounts for ~40% (~30 TWh) of energy consumption; 4—Inefficient technologies and lack of financing.

~ is used to estimate figures.

challenges such as unsustainable harvesting, technological barriers, and policy fragmentation persist in both developed, emerging economies, and developing contexts [17–42, 60–66]. Lessons from Denmark's integrated biomass systems and Brazil's bioethanol sector provide scalable solutions for addressing these challenges globally.

The analysis further reflects varied progress in the biomass energy transition toward achieving sustainability goals. For instance, Denmark and Germany are still below their planned biomass shares, with Denmark producing ~43 TWh and Germany ~110 TWh, focusing on other renewable sources like biowaste and biogas. China and India have made significant strides with China producing ~500 TWh and India ~370 TWh, largely from agricultural resides and crop waste. Brazil has met its biomass share target, producing ~160 TWh from sugarcane ethanol, a notable success in biofuels. In contrast, Namibia and Ghana are reliant on traditional biomass sources like bush biomass, firewood, and charcoal, with Ghana meeting its target but needing more sustainable methods. Namibia lags, producing only ~10 TWh, due to infrastructure limitations. While developed economies are working on scaling down their traditional biomass share in achieving SDGs 7 and 13, emerging and developing countries show varying degrees of success and challenges in meeting their biomass energy targets (**Table 4**).

The data from the 2024 UN-SDG report provide insights into the contributions of biomass energy toward achieving four key SDGs (7, 8, 13, and 15) across China, India, Denmark, Germany, Brazil, Namibia, and Ghana [68]. **Table 5** illustrates that Denmark (85%) emerges as a global leader, showcasing robust biomass infrastructure, efficient policies, and technological innovations. Brazil (80%) excels in climate action through the extensive use of bioenergy, while Germany (75%) and Ghana (75%) demonstrate moderately improving trends, reflecting ongoing efforts despite persistent challenges. Emerging countries like Namibia (70%), China (65%), and India (65%) exhibit steady progress but still face infrastructural, financial, and policy hurdles in fully realizing biomass energy's potential.

Counties scoring 80–100% provide valuable lessons and best practices for others, while those in the 60–80% range require targeted policy interventions, investments, and technological advancements (**Figure 4**). This analysis underscores the importance of global collaboration and knowledge sharing to bridge gaps and accelerate biomass energy's contribution to achieving sustainability goals.

4.2. Conversion processes

Having analyzed the role of biomass energy in achieving sustainability, this research now proceeds to address the following question: what technological advancements have been made in biomass energy to enhance its efficiency and sustainability? The findings reveal that biomass energy technologies have evolved significantly in recent decades, driven by advancements in bioenergy research, engineering innovations, and increased investment in renewable energy sectors [69, 70]. Globally, countries are adopting diverse technological approaches to improve the efficiency, cost-effectiveness, and environmental sustainability of biomass energy systems. The results revealed four conversion approaches: (1) thermochemical conversion, (2) biochemical conversion, (3) biofuel production, and (4) hybrid systems. This approach is therefore categorized into two categories: technologies such as pyrolysis, gasification, and combustion dominate thermochemical conversion processes, while anaerobic digestion and fermentation denote biochemical conversion processes. Thus, a comparative analysis of conversion techniques, including efficiency, cost, emissions, and scalability, is presented in **Table 6**.

An extensive interpretive review illustrates that gasification, as the most efficient technology (70–85%) with low emissions and high energy yields but requiring higher capital investment, has seen rapid adoption in Germany and Denmark, producing cleaner syngas for

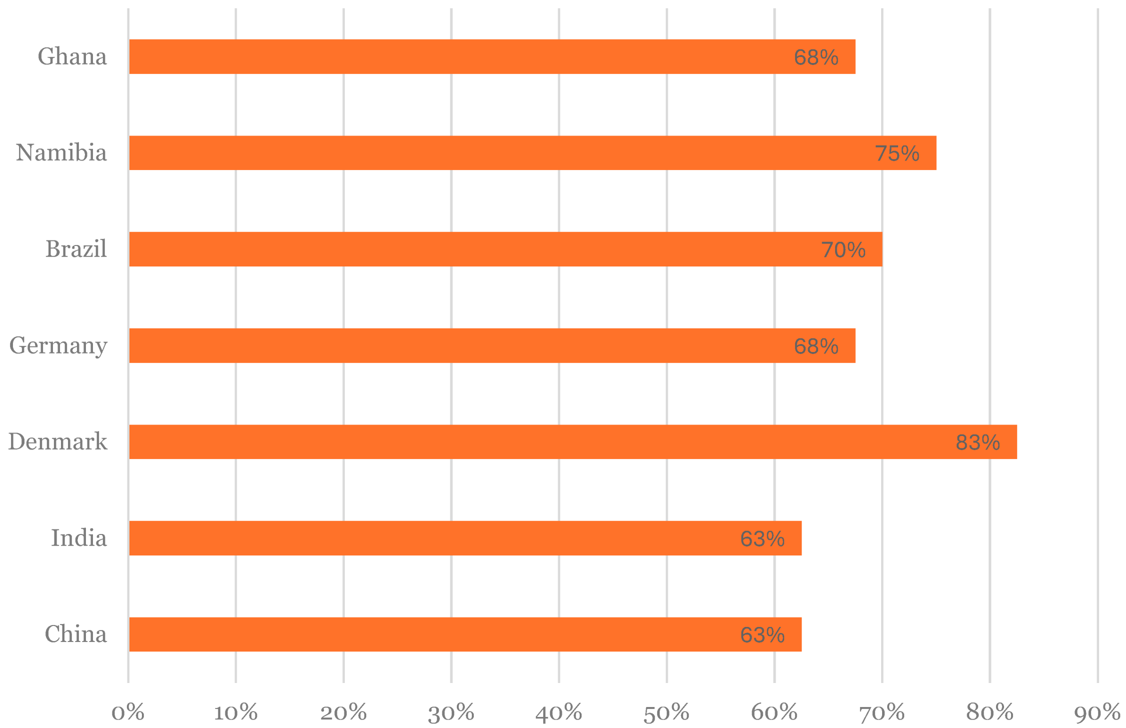

Figure 4 • Average performance of SDG achievements across the study regions.

Table 4 • Biomass energy contributions in selected countries.

Country	Planned biomass share (~%)	Current biomass share (~%)	Total energy from biomass (~TWh)	Primary feedstock
China	10	8	500	Agricultural residues, forestry waste
India	15	12	370	Crop residues, waste-to-energy
Denmark	35	20	43	Wood pellets, biowaste
Germany	25	9	110	Biogas, bioethanol
Brazil	27	27	160	Sugarcane ethanol
Namibia	12	5	10	Bush biomass, wood fuel
Ghana	40	40	30	Charcoal, firewood

~ is used to estimate figures.

Table 5 • Levels of SDG achievement across the selected regions.

Country	SDG 7 (%)	SDG 8 (%)	SDG 13 (%)	SDG 15 (%)	Average (%)
China	80	60	60	60	65
India	80	80	40	60	65
Denmark	100	80	80	80	85
Germany	80	80	80	60	75
Brazil	80	80	100	60	80
Namibia	60	60	80	80	70
Ghana	80	80	80	60	75

Table 6 • Comparative analysis of biomass conversion techniques.

Technology	Efficiency (~%)	Carbon emissions (~kg CO_2/GJ)	Energy output (~MJ/kg)	Capital cost (~USD/kW)	LCOE or scalability (~USD/kWh)
Combustion	15–40	90–110	10–18	1500–3000	0.04–0.08
Fermentation	50–70	20–30	20–25	2000–5000	0.06–0.12
Pyrolysis	40–75	50–70	25–35	3000–6000	0.08–0.15
Gasification	70–85	30–50	30–45	4000–7000	0.07–0.14

~ is used to estimate figures while LCOE means levelized cost of energy.

use [48, 71, 72], while anaerobic digestion (fermentation) has gained prominence in China, India, and Brazil, contributing significantly to bioethanol and biogas production [73, 74]. Advanced biofuel technologies (pyrolysis), including second-generation biofuels from non-food feedstocks, are being pioneered in Germany, Denmark, and Brazil [75, 76]. Hybrid technologies combining multiple conversion processes are increasingly adopted in Namibia and Ghana to optimize resource utilization and energy output [37–42, 77].

Insights further reveal that the technological advancements across selected countries vary based on resource availability, policy support, and technological infrastructure (**Table 7**). This includes the following:

- China: Significant investment in anaerobic digestion and bioethanol production technologies [60–64].
- India: Focus on small-scale biogas systems for rural electrification [65, 66].
- Denmark: Leader in combined heat and power (CHP) biomass systems [25–27].
- Germany: Pioneering second-generation biofuel technology [28–32].
- Brazil: Extensive ethanol production infrastructure from sugarcane [17–24].
- Namibia: Emerging interest in hybrid biomass energy technologies [33–36].
- Ghana: Deployment of biomass gasification systems for electricity generation in rural areas [37–42].

Technological advancements in biomass energy conversion are critical to achieving energy security and global sustainability goals. Developed countries like Denmark and Germany have advanced significantly in integrated biomass systems, focusing on cleaner and more efficient biofuel technologies. Conversely, emerging economies such as China, India, and Brazil have prioritized bioethanol and biogas technologies due to their agricultural resource abundance. In Africa, Namibia and Ghana remain in the early stages of technological adoption, focusing on affordable and

Table 7 • Technological advancements in biomass energy conversion across selected countries.

Country	Technological focus	Key advancements	Application area
China	Anaerobic digestion	Biogas plants	Rural electrification
India	Biogas systems	Small-scale biogas technologies	Agriculture and domestic energy
Denmark	Combined heat and power	High-efficiency biomass plants	Industrial and urban heating
Germany	Second-generation biofuel	Advanced bioethanol production	Transport and industrial sector
Brazil	Ethanol production	Large-scale sugarcane ethanol	Transport sector
Namibia	Hybrid biomass technologies	Gasification and bioenergy mix	Rural electrification
Ghana	Biomass gasification	Off-grid biomass electricity	Remote communities

scalable technologies such as small-scale gasification and hybrid bioenergy systems. However, challenges remain, including limited financial resources, lack of technical expertise, and inconsistent policy frameworks.

Despite the efficiency in gasification technology, the global transition towards second-generation biofuels and hybrid biomass technologies represents a significant step forward in addressing energy poverty and climate change. Thus, policies supporting research, technology transfer, and international collaboration will be vital for sustained progress. To address this, this research further addresses the following question: how can biomass energy be leveraged in the context of countries' energy transition and sustainability goals? The results revealed in **Figure 5** illustrate how Germany and Denmark lead with advancements in second-generation biofuels and combined heat and power systems, respectively. China and India demonstrate significant progress in biogas technologies, while Brazil excels in ethanol production. Namibia and Ghana show emerging potential in hybrid biomass systems and biomass gasification, respectively.

The spatial distribution of technology efficiency in biomass energy conversion highlights significant regional disparities between developed and emerging economies and developing countries (**Figure 6**). Germany leads with the highest technological efficiency at 95%, followed closely by Denmark (90%) and Brazil (88%), reflecting their advanced technological infrastructure, strong research and development frameworks, and substantial policy support for other renewable energy. China (85%) also demonstrates high efficiency, showcasing significant progress driven by large-scale investments in clean energy technologies.

In contrast, developing countries exhibit lower efficiency levels. India (75%) shows moderate efficiency, indicating ongoing technological adoption but with existing barriers such as resource constraints and limited technological transfer. Ghana (65%) and Namibia (60%) record the lowest efficiencies, underscoring challenges like insufficient funding, limited access to advanced biomass technologies, and weaker institutional frameworks.

This distribution suggests that while developed countries and emerging economies have optimized their technological capabilities for biomass energy conversion or efficiency, developing nations still face barriers requiring strategic interventions, technology transfer, and financial investments to bridge the efficiency gap. To address the inefficiency level of technological advancements,

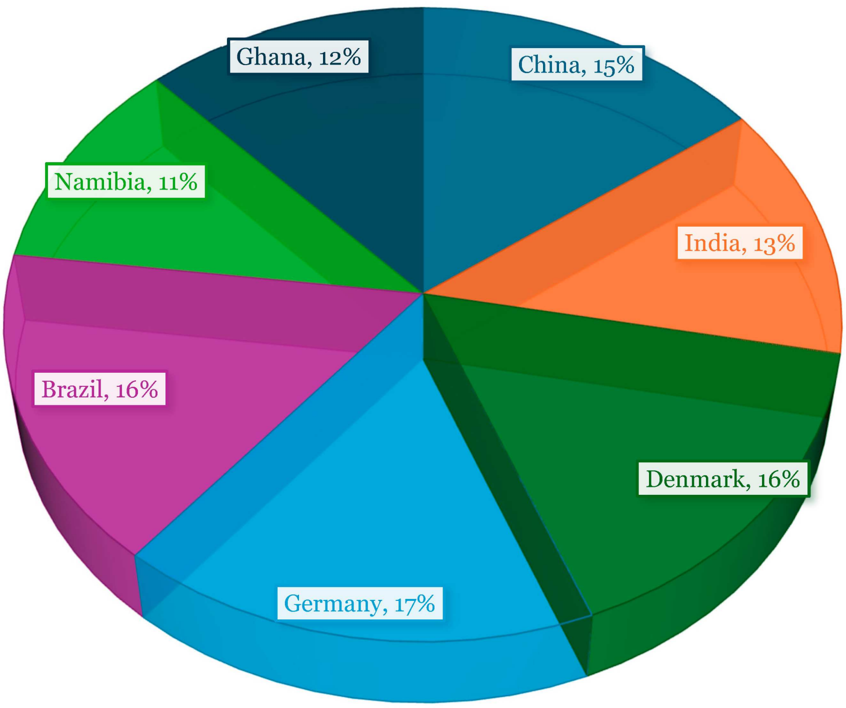

Figure 5 • Technological advancements in biomass energy efficiency and conversion by country.

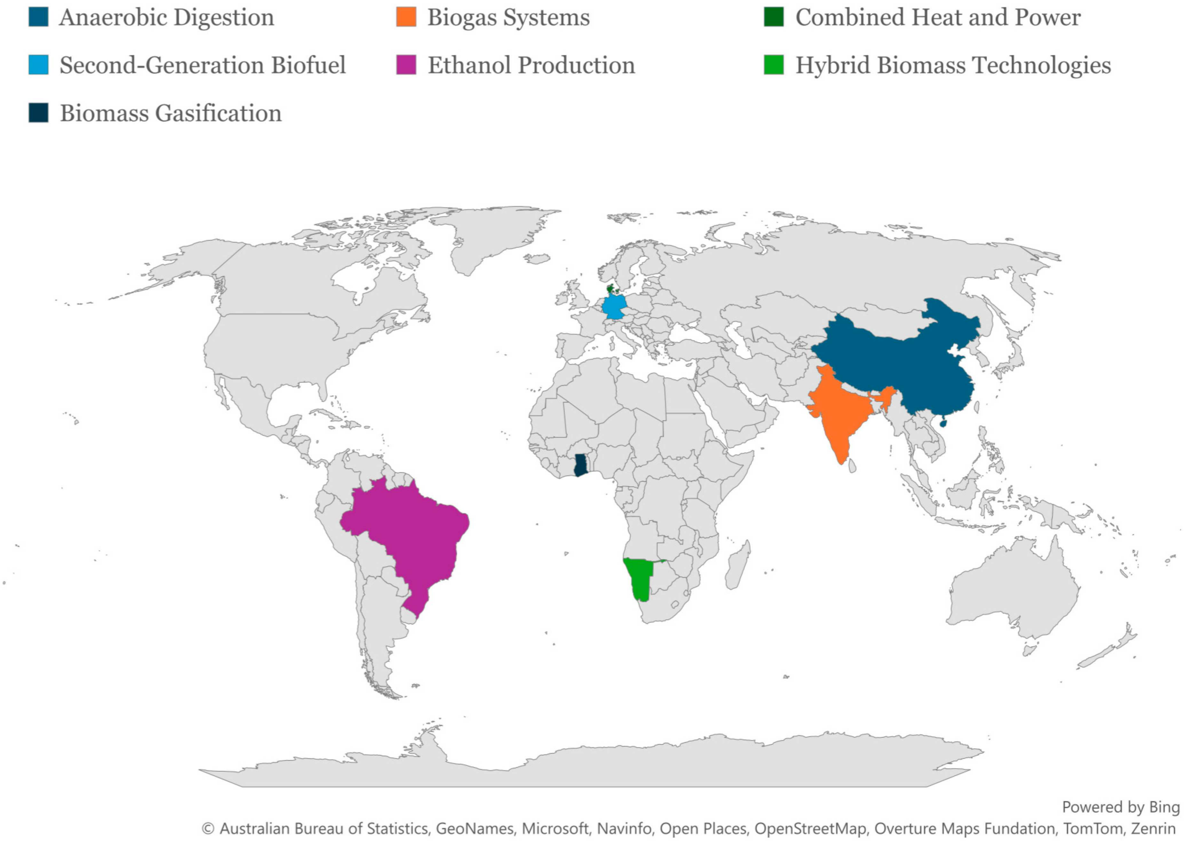

Figure 6 • Spatial distribution of biomass energy technology across selected regions.

catalytic advancements (e.g., ZnO, TiO2, Ni) and nanotechnology (e.g., nanocatalysts, nanomembranes) are enhancing conversion efficiency and reducing emissions [78–81]. These innovations are expected to improve biomass scalability and integration into global energy frameworks.

Despite the high efficiency of gasification, Pandey et al. [78] highlight that the integration of nanotechnology in biomass applications plays a transformative role in improving energy efficiency. Key innovations include the following:

- Nanocatalysts (Ni, Co, Fe, ZnO, TiO_2) enhance gasification, pyrolysis, and anaerobic digestion conversion efficiency.
- Nanomembranes improve biogas upgrading, while nanomaterials for carbon capture improve CO_2 sequestration.
- Nano-additives (CeO_2, Al_2O_3) enhance combustion efficiency while nanofiltration in biofuel purification increases fuel purity and reduces emissions.

There is no doubt that Germany and Denmark have made significant strides in nanotechnology applications for biomass conversion, particularly in catalytic pyrolysis and gasification, thus emerging as the most technologically efficient, although challenges still emerge. By learning from these case studies, other developing countries and emerging economies can leverage the biomass energy transition towards achieving sustainability goals.

4.3. Sustainability mandates

To harness the power of nature (biomass energy), this section unpacks comparative options for promoting global sustainability goals. It addresses the final research question: what are the policy implications of promoting biomass energy for sustainable development? It is common knowledge that policy frameworks play a crucial role in facilitating biomass energy adoption by providing regulatory clarity, financial incentives, and strategic direction for stakeholders. The results reveal that these frameworks vary across countries, reflecting differences in economic priorities, institutional capacities, and resource availability [17–42, 60–66].

Table 8 illustrates how developed nations such as Germany and Denmark have established robust policy frameworks emphasizing feed-in tariffs, subsidies, carbon pricing, and renewable portfolio standards (RPSs) to promote biomass energy. In Brazil, bioenergy policies focus on integrating agricultural residues into energy systems, supported by government-backed financial incentives. Emerging economies such as China have prioritized biomass energy adoption through national renewable energy targets, financial subsidies, and mandatory grid connections for bioenergy producers. India has implemented national bioenergy missions and subsidy programs, although bureaucratic delays and inconsistent policy enforcement limit their effectiveness. Developing countries in Africa, such as Namibia and Ghana, exhibit relatively weaker biomass energy policies, primarily focused on pilot projects, regional strategies, and donor-driven programs. Policy enforcement challenges, financial constraints, and inadequate monitoring frameworks continue to limit their scalability and effectiveness.

In determining the effectiveness of existing policy frameworks, this research measures the efficiency of these regulatory approaches with eight parameters or key performance indicators and matrixes. These include (1) policy commitment and governance; (2) financial incentives and funding mechanisms; (3) institutional capacity and coordination; (4) technology integration and infrastructure development; (5) public awareness and stakeholder engagement; (6)

Table 8 • Policy frameworks supporting biomass energy adoption.

Country	Policy framework	Incentives and support mechanisms	Regulatory measures
China	National renewable energy targets	Financial subsidies	Mandatory grid connections
India	National bioenergy mission	Subsidy programs	Regulatory policies
Denmark	Renewable portfolio standards	Feed-in tariffs	Carbon pricing
Germany	Feed-in tariffs	Renewable energy subsidies	Regulatory compliance
Brazil	Bioenergy integration programs	Agricultural residue utilization	Financial incentives
Namibia	Pilot biomass projects	Donor-driven programs	Limited regulations
Ghana	Regional energy strategies	Subsidy programs	Policy monitoring

monitoring, reporting, and verification (MRV) systems; (7) sustainability and environmental safeguards; and (8) energy security and diversification.

The results revealed that China demonstrates a policy effectiveness of 85%, driven by large-scale investments, strategic policy direction, and the integration of biomass energy into national energy plans. India, with an effectiveness of 70%, relies on moderately effective frameworks characterized by regional initiatives and financial incentives. In Denmark, policy effectiveness stands at 95%, supported by strong governance, transparent regulatory mechanisms, and innovative financing structures, positioning the country as a global leader in biomass energy adoption. Similarly, Germany exhibits high policy effectiveness at 90%, driven by ambitious renewable energy targets and consistent governmental commitment to sustainable practices. Brazil, with an effectiveness of 80%, leverages biofuel mandates and incentives for biomass production to drive progress. Conversely, Namibia shows a lower effectiveness rate of 60%, hindered by policy enforcement challenges, limited financial resources, and weak institutional frameworks. Lastly, Ghana, with a 65% effectiveness score, reflects moderate success, focusing on localized bioenergy initiatives and financial support mechanisms. These varying levels of policy effectiveness highlight the importance of tailored frameworks that address each country's unique socio-economic and environmental contexts to optimize biomass energy adoption.

Figure 7 depicts the effectiveness of policy frameworks supporting biomass energy adoption across the selected countries, derived from their respective policy strengths, implementations, and outcomes. Despite the success stories of these developed countries, the implication is that both emerging economies and developing countries can emulate the best practices towards achieving global sustainability goals 7, 8, 13, and 15. Key recommendations including (1) incentives for biomass energy investment, (2) public–private partnerships, and (3) regulatory reforms are essential for harnessing the power of nature.

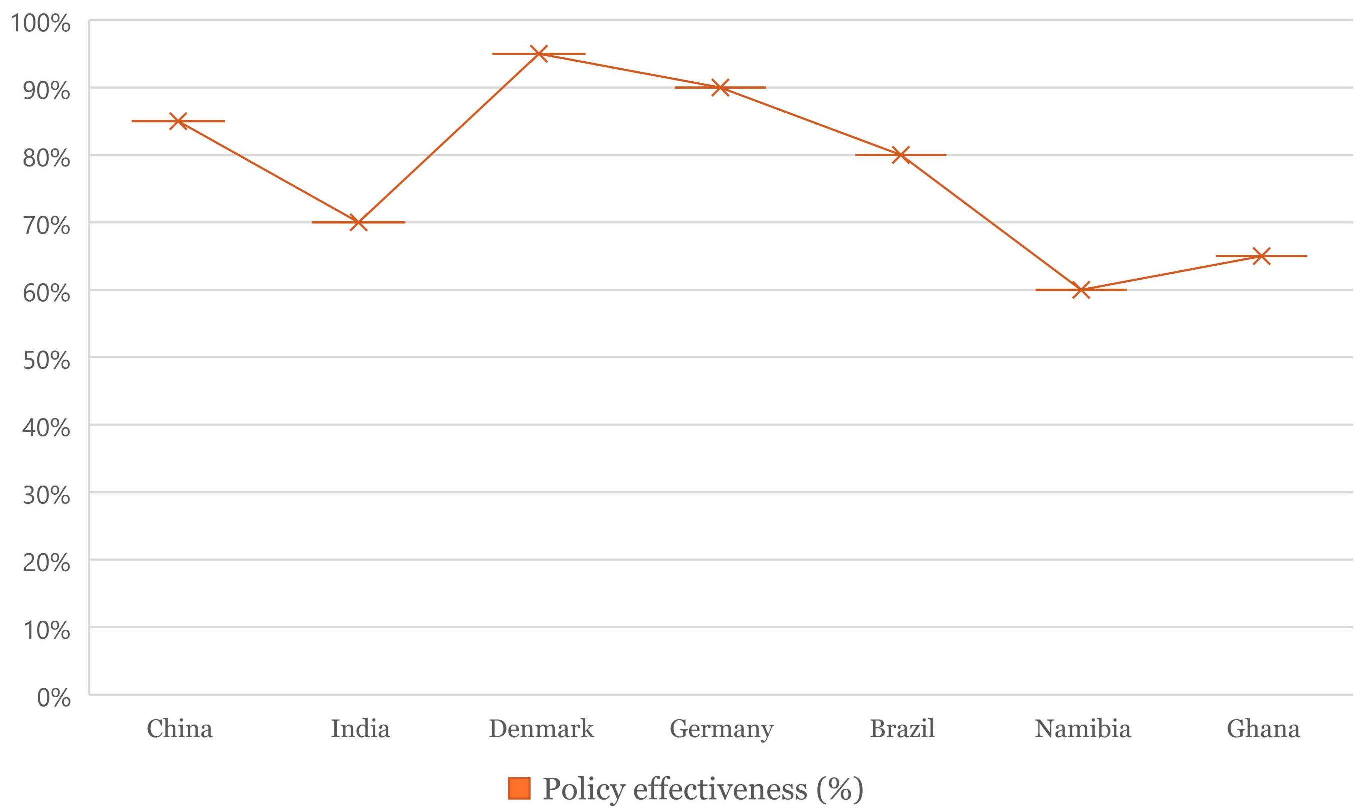

Figure 7 • Effectiveness of policy frameworks supporting biomass energy adoption.

5. Conclusions

This study analyzed the role of biomass energy in achieving global sustainability goals, with a focus on evaluating the contribution of technological advancements and assessing the effectiveness of policy frameworks across China, India, Denmark, Germany, Brazil, Namibia, and Ghana. The findings underscore significant regional disparities in biomass energy adoption, with technological efficiency, policy effectiveness, and financial sustainability emerging as key determinants of success. Countries such as Denmark, Germany, and Brazil demonstrated strong policy alignment with SDGs, leveraging advanced biomass conversion technologies, targeted financial incentives, and institutional frameworks that drive sustainable energy adoption. In contrast, Namibia and Ghana displayed moderate progress, hindered by financial constraints, technological inefficiencies, and policy fragmentation. These insights reinforce the need for a multi-dimensional approach that integrates technology, governance, and financial viability to unlock the full potential of biomass energy for sustainable development.

Technological advancements have played a crucial role in determining biomass energy efficiency and scalability. Countries with advanced gasification and anaerobic digestion systems, such as Germany and Denmark, reported higher energy conversion efficiencies ($\geq$85%) and lower lifecycle emissions ($\leq$20 gCO_2/MJ), contributing significantly to SDGs 7 (affordable and clean energy), 8 (decent work and economic growth), and 13 (climate action). Conversely, Namibia and Ghana exhibited lower efficiency rates (<50%), reflecting a pressing need for technological upgrades, infrastructure expansion, and enhanced knowledge transfer. Given these disparities, policymakers should prioritize research and development in localized biomass technologies, ensuring alignment with country-specific resource availability and industrial capacity.

The economic implications of biomass energy adoption vary across the selected countries, primarily driven by feedstock availability, production costs, and investment incentives. Countries such as Brazil and India have successfully deployed feed-in tariffs (USD 0.08/kWh and USD 0.07/kWh, respectively), alongside tax exemptions and capital subsidies, to promote private-sector investment in biomass energy projects. Conversely, Namibia and Ghana lack well-defined incentive structures, leading to high capital expenditure (CAPEX) burdens, restricted investor confidence, and limited scalability. To address these gaps, governments should implement performance-based financial mechanisms, such as 30% capital investment subsidies and preferential loan schemes (interest rates <5%), to stimulate market participation and encourage technological innovation.

This study highlights a strong correlation between policy effectiveness and biomass energy deployment. Countries with comprehensive national biomass strategies, such as Denmark and Brazil, have benefited from well-structured policy instruments, including renewable portfolio standards, carbon pricing mechanisms, and decentralized energy planning. By contrast, Namibia and Ghana exhibit policy inconsistencies, characterized by weak regulatory enforcement, fragmented institutional frameworks, and limited stakeholder engagement.

To bridge this gap, governments should adopt a three-tiered policy framework: (1) Regulatory alignment with SDGs, thus establishing national biomass energy roadmaps explicitly linked to SDGs 7, 8, 13, and 15, integrating clear sustainability targets (e.g., 40% renewable share by 2030). (2) Incentivizing private sector investment, thus introducing country-specific financial incentives, such as production-based tax credits (USD 0.05/kWh for gasification in Namibia and Ghana), to mitigate investment risks and foster technology adoption. (3) Strengthening institutional governance through developing centralized biomass energy agencies to oversee policy implementation, enforce compliance, and coordinate multi-sectoral partnerships.

A crucial aspect of biomass energy adoption involves the technological and financial feasibility of different conversion techniques. While advanced gasification and pyrolysis have demonstrated higher efficiencies in Europe, simpler direct combustion and anaerobic digestion may be more feasible for countries with lower technological capacity, such as Namibia and Ghana. Policymakers must, therefore, tailor technology selection to their economic and infrastructural realities.

This study provides compelling evidence that biomass energy can serve as a pivotal driver of global sustainability, particularly when supported by robust technological advancements, policy coherence, and financial sustainability. Countries such as Denmark, Germany, and Brazil exemplify successful biomass energy integration through strategic policy frameworks, advanced conversion technologies, and financial incentives that encourage private-sector engagement. On the other hand, Namibia and Ghana demonstrate that without targeted technology adaptation and policy support, biomass energy adoption remains constrained, limiting its contribution to sustainability objectives.

This research underscores the need for localized biomass solutions, emphasizing that a one-size-fits-all approach is ineffective. Instead, governments must implement context-specific policies, tailored financial mechanisms, and adaptive technologies that align with national development priorities. Additionally, regional cooperation and cross-border knowledge transfer should be strengthened to accelerate biomass energy innovation in low-income countries.

While this study provides a comprehensive assessment of biomass energy adoption across diverse geopolitical contexts, several critical areas warrant further investigation: (1) The empirical validation of biomass energy financing models through future research should explore the long-term viability of green bonds, carbon credits, and international climate financing in supporting large-scale biomass projects in developing nations. (2) Decentralized biomass energy systems entail assessing the impact of community-led biomass initiatives on rural electrification, job creation, and socio-economic resilience, providing valuable insights into grassroots energy sustainability. (3) Comparative lifecycle assessments through further studies should evaluate the environmental and economic trade-offs of different biomass conversion techniques to guide policy decisions on optimal technology deployment. Lastly, digital integration in biomass energy monitoring entails the role of AI-driven predictive analytics and blockchain-based carbon tracking, which should be investigated to enhance transparency and efficiency in biomass energy value chains.

In conclusion, biomass energy presents a viable pathway toward achieving energy security, carbon neutrality, and socio-economic development, but its success is contingent on an integrated approach that balances technological advancements, policy interventions, and financial mechanisms. Countries lagging in biomass energy adoption must prioritize capacity building, regulatory coherence, and international collaboration to harness the full potential of this renewable energy source. By implementing scientifically grounded, economically viable, and policy-driven strategies, biomass energy can emerge as a cornerstone of global sustainability efforts.

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Author contributions

Conceptualization, P.M. and E.Y.; methodology, P.M.; software, P.M.; validation, P.M. and E.Y.; formal analysis, P.M.; investigation, P.M.; resources, P.M.; data curation, P.M. and E.Y.; writing—original draft preparation, P.M.; writing—review and editing, P.M. and E.Y.; visualization, P.M. and E.Y.; supervision, E.Y.; project administration, P.M.; funding acquisition, P.M. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflicts of interest.

Data availability statement

Data supporting these findings are available within the article, at https://doi.org/10.20935/AcadEnergy7556, or upon request.

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