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Sustainability and Energy Potential of Extrusion Processed Biomass Briquettes: A Systematic Literature Review

Dody Bimo Aji[1*], Ahmad Janan Febrianto[2], Reza Bayu Kurniawan[3], Gahar Albani Rasyid[4], Iqbal Maulana[5]

[1,2,4,5]Mechanical Engineering, Faculty of Engineering, Universitas Sarjanawiyata Tamansiswa, Yogyakarta
[3]Industrial Engineering, Faculty of Engineering, Universitas Sarjanawiyata Tamansiswa, Yogyakarta
*****Corresponding author**: bimo.ajidody@ustjogja.ac.id

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Abstract

The global energy crisis and the increasing volume of agro-industrial waste have accelerated the development of environmentally friendly and sustainable biomass-based alternative energy sources. Extrusion technology has emerged as a promising approach for converting biomass waste into high-quality energy briquettes with enhanced thermal performance and minimal environmental impact. This study aims to analyze the energy potential and sustainability contributions of extrusion-based biomass briquettes through a Systematic Literature Review (SLR) approach, providing a multidimensional thematic understanding of recent research trends. The review follows the PRISMA protocol and utilizes the Scopus database, systematically selecting 30 scientific articles published between 2019 and 2025 based on predefined inclusion and exclusion criteria. The analysis focuses on feedstock characteristics, processing technologies, energy outputs, and contributions to environmental, economic, and social sustainability. The findings reveal that agro-industrial residues such as rice husks, straw, and food waste, when processed through extrusion with natural binders, produce briquettes with high calorific values, low emissions, and efficient combustion performance. This approach also promotes waste reduction, cost efficiency, and the empowerment of community-based renewable energy enterprises. The study concludes that extrusion technology holds strategic potential in supporting the transition toward renewable energy and achieving sustainable development goals, applicable to both industrial and household energy scales.
Keywords: *biomass, extrusion briquettes, renewable energy, sustainability, systematic literature review*

Abstrak

Krisis energi global dan meningkatnya volume limbah agroindustri mendorong pengembangan energi alternatif berbasis biomassa yang ramah lingkungan dan berkelanjutan. Teknologi ekstrusi menjadi salah satu pendekatan potensial untuk mengubah limbah biomassa menjadi briket energi dengan kualitas termal tinggi dan dampak lingkungan yang minimal. Penelitian ini bertujuan untuk menganalisis potensi energi dan kontribusi keberlanjutan dari briket biomassa hasil proses ekstrusi melalui pendekatan *Systematic Literature Review* (SLR), untuk memperoleh pemahaman tematik dan multidimensi atas tren riset terkini. Kajian dilakukan dengan mengacu pada protokol PRISMA dan menggunakan database Scopus. Sebanyak 30 artikel ilmiah yang diterbitkan dalam periode 2019–2025 diseleksi secara sistematis berdasarkan kriteria inklusi dan eksklusi tertentu. Analisis difokuskan pada aspek bahan baku, teknologi proses, output energi, dan kontribusi terhadap keberlanjutan lingkungan, ekonomi, dan sosial. Temuan menunjukkan bahwa bahan baku dari limbah agroindustri seperti sekam, jerami, dan limbah pangan, yang diproses melalui ekstrusi dengan binder alami, mampu menghasilkan briket bernilai kalor tinggi, emisi rendah, dan efisiensi proses yang baik. Pendekatan ini juga mendukung pengurangan limbah, efisiensi biaya, serta pemberdayaan UMKM energi. Studi ini menyimpulkan bahwa teknologi ekstrusi memiliki potensi strategis dalam mendukung transisi energi terbarukan dan tujuan pembangunan berkelanjutan, baik dalam skala domestik maupun industri.
Kata Kunci: *biomassa; briket ekstrusi; energi terbarukan; keberlanjutan; systematic literature review*

1. Introduction

The global energy crisis is one of the most urgent challenges of the 21st century, threatening economic stability, widening social inequality, and accelerating environmental degradation. Heavy dependence on fossil fuels has created a vulnerable energy system in which oil price volatility, geopolitical tensions, and resource limitations repeatedly disrupt social and economic activities [1], [2]. At the same time, fossil energy use remains a major source of greenhouse gas emissions that intensify global warming and climate change [3], [4]. In this context, the transition toward a more sustainable and resilient energy system is a strategic necessity rather than an option[5].

Renewable energy sources such as solar, wind, hydro, geothermal, and biomass offer long-term pathways to strengthen energy security, diversify resources, and reduce environmental impacts [6]. Among these, biomass is particularly relevant for developing countries endowed with abundant agricultural and forestry residues [7], [8]. Biomass can be converted into various energy carriers; one widely implemented route is densification into briquettes, which have been recognized as clean, economical, and locally adaptable alternative fuels [9]. Biomass briquettes are solid fuels produced by compacting residues such as rice husks, sawdust, coconut shells, and other agro-industrial wastes[10], [11]. Compared with raw biomass, briquettes generally exhibit higher energy density, cleaner combustion, and improved handling properties for storage and transport [10]. Their utilization reduces dependence on fossil fuels while supporting waste management by transforming residues that would otherwise contribute to pollution [12], [13].

In recent years, extrusion technology has emerged as a promising method for producing high-quality biomass briquettes. Extrusion applies high pressure, often with elevated temperature, to form dense and relatively uniform briquettes [14], [15]. Widely used in food, pharmaceutical, and manufacturing industries for continuous and consistent production [16], extrusion is increasingly explored in the energy sector because it enables different biomass feedstocks to be converted into solid fuels with improved mechanical integrity and potentially better combustion characteristics, including higher calorific value and lower ash content[17]. Several studies have reported that extruded briquettes from coffee waste, vineyard pruning residues, and sawdust can reach calorific values close to 20 MJ/kg and achieve high combustion temperatures and long burning times when process parameters are well controlled [16], [18], [19]. Pretreatments such as torrefaction before extrusion have also been shown to increase calorific value and markedly reduce moisture content, further enhancing combustion efficiency and stability[20], [21].

Beyond technical performance, extrusion-based biomass briquettes may contribute to broader sustainability goals. The use of agricultural and industrial residues reduces waste volumes and methane emissions from uncontrolled decomposition [22], [23]. Briquette production can stimulate local economies through employment in feedstock collection, preprocessing, equipment operation, and distribution [20], [24]. By substituting coal and firewood in household and small-scale industrial applications, these briquettes can also help mitigate deforestation and reduce carbon emissions[9]. Such benefits are closely aligned with circular resource utilization and low-carbon development strategies.

Despite this potential, large-scale adoption of extrusion-based biomass briquettes remains limited. Research in this field is often fragmented and tends to prioritize technical indicators such as calorific value, combustion efficiency, and ash content while giving less attention to environmental, social, and economic dimensions [25]. Systematic reviews using Life Cycle Assessment (LCA) have highlighted that social and economic aspects are frequently underrepresented, complicating comprehensive sustainability evaluation [26], [27]. As a result, integrated, multi-criteria approaches are needed to link technical performance with real contributions to circular bioeconomy and energy-transition objectives [28], [29].

Additional barriers relate to the lack of harmonized quality standards and technical guidelines. Briquette properties are strongly influenced by moisture content, particle size, binder type, and extrusion conditions such as temperature and pressure [14], [15], [26]. Variability in these factors leads to inconsistent product quality across regions [29], [30]. Technically, extrusion systems may face challenges in process stability, surface quality, and handling of certain feedstocks [14,33]. Poor surface quality, for example, can reduce combustion efficiency or increase particulate emissions if not properly controlled[31]. Furthermore, capital investment and workforce training requirements can be significant constraints in resource-limited settings [6], [25].

Given these gaps, there is a need for a systematic effort to map and synthesize existing knowledge on extrusion-based biomass briquettes. This study employs a Systematic Literature Review (SLR) following the PRISMA protocol to analyze publications from databases such as Scopus, ScienceDirect, and SpringerLink. The review examines how sustainability dimensions (environmental, economic, and social) and energy performance parameters (e.g., calorific value, combustion efficiency, and emissions) have been investigated in the context of extrusion-based briquette production [20]. It further identifies key technical factors influencing briquette quality, practical implementation barriers, and opportunities for wider application in household and small-scale industrial energy systems. By integrating evidence across diverse studies, this article aims to strengthen the scientific basis for developing extrusion-processed biomass briquettes as a practical component of sustainable energy systems and the global green energy transition.

2. Material and Methods

2.1 Type of Research

This study adopts a Systematic Literature Review (SLR) to evaluate, synthesize, and map research developments on the energy performance and sustainability of biomass briquettes produced through extrusion technology. The SLR approach was selected because it applies structured, transparent, and replicable procedures, enabling a rigorous assessment of existing evidence and reducing subjective bias in literature selection and interpretation [1]. In general, the SLR process follows three core phases: planning, execution, and reporting [3].

In the planning phase, the study formulates focused research questions, develops a review protocol, and specifies clear inclusion and exclusion criteria to ensure relevance and consistency across selected publications [4]. The execution phase involves constructing search strategies and retrieving studies from reputable databases, followed by screening and eligibility assessment to identify publications that directly address extrusion-based briquettes and their technical, energy, and sustainability dimensions [5][6]. Subsequently, the reporting phase comprises systematic data extraction and synthesis, using thematic and/or descriptive-quantitative approaches to summarize findings and present results in a transparent narrative form [7].

This approach is particularly appropriate because extrusion-based biomass briquettes involve multidimensional variables, including extrusion process parameters and physicochemical briquette properties, energy indicators (e.g., calorific value and emissions), and broader sustainability aspects (environmental, economic, and social contributions) [8]. To strengthen methodological rigor and transparency, the review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol. PRISMA provides standardized guidance for documenting identification, screening, eligibility, and inclusion procedures, typically supported by a flow diagram and checklist, allowing readers to verify traceability and completeness of the review process [9][10].

Beyond improving reporting quality, PRISMA helps minimize selective reporting and strengthens the credibility of evidence synthesis [11]. It has been widely applied across diverse review types, from meta-analyses to qualitative syntheses, and supports evidence-based decision-making, including in renewable energy contexts [12][13]. Where relevant, PRISMA extensions (e.g., PRISMA-P, PRISMA-IPD, PRISMA-E) may guide protocol refinement for specific review needs [14]. Overall, applying SLR–PRISMA is expected to identify trends and gaps and generate practical recommendations to support the development and adoption of extrusion-based biomass briquettes as a sustainable clean-energy option in Indonesia and other developing regions [15].

2.2 Data Sources and Database

This study primarily uses Scopus as the main data source for literature retrieval. Scopus was selected because it is a widely recognized international abstract and citation database managed by Elsevier, providing broad coverage of peer-reviewed journals across relevant disciplines such as Energy, Environmental Science, and Engineering [1]. Its comprehensive indexing supports access to high-quality publications directly related to extrusion-based biomass briquettes and sustainable energy transitions.

Scopus also enables a systematic and iterative search through advanced features, including advanced query functions, document-type filters, subject-area classifications, and citation tracking. These tools facilitate accurate identification of relevant studies, mapping of research relationships, and exploration of keyword trends related to biomass briquettes, extrusion processes, and renewable energy [3][4]. Moreover, Scopus is commonly used in scientometric studies and research performance evaluations, reinforcing its credibility as a robust source for systematic reviews in clean-energy research [5].

To ensure topical relevance and capture recent technological and policy developments, the publication period was restricted to 2019–2025 [6]. All records retrieved from Scopus were screened and filtered using predefined inclusion and exclusion criteria, and the selection procedure was documented under the PRISMA framework to maintain transparency, traceability, and replicability [7]. The final corpus of included studies is expected to provide a reliable evidence base to support the objectives of this systematic review and contribute to future research directions [8].

2.3 Literature Search Strategy

The literature search was conducted systematically and transparently to answer the research questions on the sustainability and energy potential of extrusion-based biomass briquettes. The procedure followed the PRISMA protocol to ensure replicability [1]. Publications were limited to 2019–2025 to capture recent trends and innovations. The search was structured around four themes: biomass briquette raw materials, extrusion processes, energy and sustainability aspects, and key fuel technical parameters. Details are summarized in **Table 1**.

Table 1. Keywords and Boolean String

No	Main Topic	Main Keywords	Boolean String Used	Notes on Use
1	Biomass Briquette Raw Materials	biomass briquette, agricultural waste, sawdust, rice husk, coconut shell	("biomass briquette*" OR "bio-briquette*" OR "solid biofuel*" OR "biomass fuel")	Focused on raw material diversity and renewable sources used for briquette production.
2	Extrusion Process	extrusion process, compaction, densification, extruder, biomass pelletization	(extrus* OR extrud* OR "screw extrus*" OR compress* OR densificat* OR pellet* OR "mechanical densificat*")	Targets literature discussing extrusion-based densification and processing mechanisms
3	Renewable Energy	renewable energy, sustainability, clean energy, bioenergy, low carbon, carbon neutral	("renewable energy" OR sustainab* OR "clean energy" OR bioenergy OR "low carbon" OR "carbon neutral")	Identifies papers linking biomass briquettes with renewable energy policy and sustainability frameworks.
4	Quality and Technical Parameters	mechanical properties, physical properties, fuel quality, calorific value, durability	("mechanical propert*" OR "physical propert*" OR "fuel quality" OR "calorific value" OR performance OR durability)	Used to capture studies addressing physical, chemical, and energy performance parameters.
5	Exclusion Criteria	coal, charcoal	NOT (coal OR charcoal)	Excludes studies focusing on non-extrusion or non-solid biofuels to maintain scope relevance.
6	Boolean String Final	-	("biomass briquette*" OR "bio-briquette*" OR "solid biofuel*" OR "biomass fuel") AND (extrus* OR extrud* OR "screw extrus*" OR compress* OR densificat* OR pellet* OR "mechanical densificat*") AND ("renewable energy" OR sustainab* OR "clean energy" OR bioenergy OR "low carbon" OR "carbon neutral") AND ("mechanical propert*" OR "physical propert*" OR "fuel quality" OR "calorific value" OR performance OR durability) NOT coal AND PUBYEAR > 2018 AND PUBYEAR < 2026	The final Boolean search string applied in Scopus generated an initial dataset consisting of 1,104 documents.

Based on **Table 1**, the combination of thematically structured keywords produced a comprehensive Boolean string that was executed within the Scopus database. This strategy enabled an initial screening focused on literature addressing biomass briquettes, extrusion processes, energy sustainability, and fuel quality parameters, while excluding studies that concentrated on coal or other fossil fuels. This process served as the foundation for subsequent selection stages within the PRISMA framework.

2.4 Inclusion and Exclusion Criteria

Inclusion and exclusion criteria were defined to ensure that the reviewed literature directly supports analysis of the sustainability and energy potential of extrusion-based biomass briquettes. Included studies were limited to peer-reviewed journal articles indexed in Scopus, ensuring methodological rigor and data transparency [1]. Eligible publications had to report primary or secondary evidence relevant to technical and performance aspects (e.g., extrusion parameters, binder use, physicochemical properties), energy indicators (e.g., calorific value, combustion efficiency, emissions), and sustainability dimensions (environmental, economic, and social considerations) [3–4]. The publication period was restricted to 2019–2025 to capture recent advances in low-carbon biomass technologies [5]. Only English-language articles with full-text availability were included to support consistent interpretation and extraction of data [6].

Excluded were studies focusing solely on non-biomass fuels (e.g., coal/charcoal without biomass relevance), non–peer-reviewed sources (popular articles, posters), unpublished preprints, papers without accessible full text, and publications outside the defined time range [7]. These criteria strengthen transparency and replicability in alignment with the PRISMA framework [8–9]. A detailed summary is provided in **Table 2**.

Table 2. Inclusion and Exclusion Criteria

No	Aspect	Inclusion Criteria	Exclusion Criteria
1	**Type of Publication**	Peer-reviewed journal articles indexed in Scopus	Non peer reviewed articles, conference posters, unpublished preprints, or non-indexed documents.
2	**Language**	Full text articles written in English	Articles not available in full text or written in languages other than English.
3	**Publication Period**	Publications from 2019–2025, ensuring relevance to recent developments in low-carbon biomass technologies	Studies published outside the defined period
4	**Research Focus**	Studies discussing the sustainability and energy potential of biomass briquettes produced through extrusion technology.	Studies unrelated to biomass briquettes, extrusion technology, or sustainability context.
5	**Data Characteristics**	Publications containing primary or secondary data supporting technical, energy, environmental, or economic analysis.	Articles lacking empirical data or focusing only on theoretical or conceptual discussions without measurable parameters.
6	**Type of Data**	Presents primary or secondary data that support technical and sustainability analysis.	Essays without data, short commentaries, or studies with highly limited methodological information.

2.5 Article Selection and Validation Procedure

The article selection and validation were conducted systematically following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency, traceability, and methodological accountability throughout the screening process [1]. All records were retrieved exclusively from Scopus using a Final Boolean String covering biomass briquettes, extrusion processes, renewable energy, and fuel quality parameters. The search was restricted to publications from 2019–2025 to maintain the relevance of findings to recent low-carbon technology developments and current dynamics of biomass briquette production [3–4].

The initial search identified 1,104 documents. Filtering by publication type retained only journal articles, reducing the dataset to 807 records. A subsequent filter based on open-access availability narrowed the results to 338 articles. These records were then screened for relevance by examining titles, abstracts, and keywords, resulting in 249 eligible articles aligned with the research focus. Further terminological and conceptual screening identified 65 articles for in-depth assessment.

The final stage involved full-text screening to evaluate accessibility, methodological rigor, and the clarity of reporting on energy-related and technical parameters such as calorific value, combustion efficiency, and binder utilization. Articles were retained only if they met all eligibility criteria, were available in full-text format, and were thematically consistent with sustainability and the energy potential of extrusion-based biomass briquettes. Following this validation, 30 articles were included in the final synthesis, reflecting adequate academic quality in accordance with peer-reviewed journal standards and written in English or Indonesian [5–6]. The complete selection pathway is presented in the PRISMA 2020 Flow Diagram (**Figure 1**), documenting each stage from identification to inclusion and reinforcing the replicability of the SLR process [1][9].

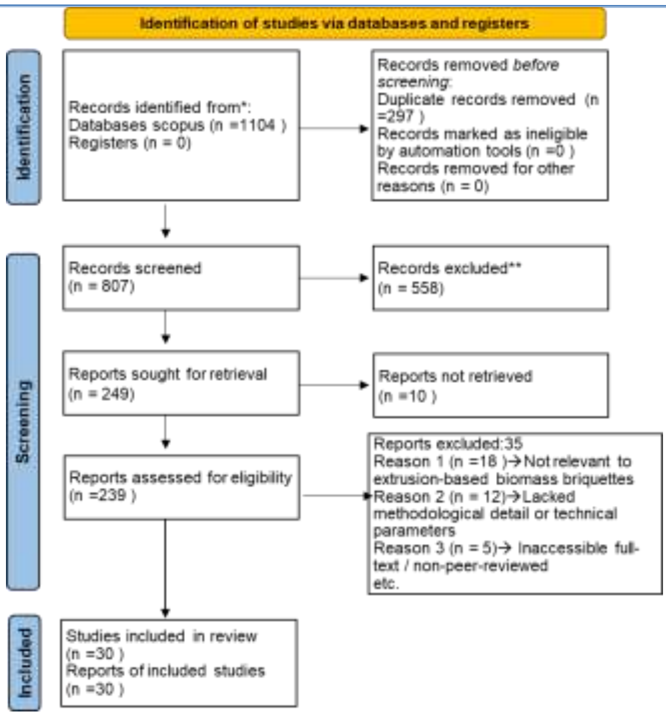

Figure 1. PRISMA Flow Diagram of the Article Selection Procedure

2.6 Data Analysis Technique

Data analysis was conducted on the 30 articles that met the final eligibility criteria under the PRISMA-based selection process. The synthesis followed a qualitative–systematic approach comprising three interrelated stages: (1) thematic open coding, (2) structured categorization, and (3) validation of the synthesized findings to ensure internal consistency and traceability across studies.

In the first stage, open coding was performed through careful full-text reading of each article. Key information was inductively extracted and coded, including biomass feedstock types, characteristics of extrusion and other densification technologies, and technical and energy-performance indicators such as calorific value, combustion efficiency, moisture and ash content, and reported emissions. In parallel, data related to sustainability covering environmental, economic, and social aspectswere recorded to capture how each study positioned extrusion-based biofuels within broader energy-transition and circular bioeconomy agendas.

The second stage involved organizing the codes into major analytical themes aligned with the research objectives. Typical themes included renewable energy potential, extrusion process conditions and optimization, waste-to-energy conversion pathways, and environmental and sustainability assessments. Coding sheets and thematic matrices were used to systematize the evidence and facilitate comparison across studies, in line with established guidance for systematic literature reviews that emphasizes transparent data handling and explicit synthesis procedures.

In the third stage, validation focused on examining the coherence of findings, methodological differences, and the contribution of each article to both theoretical understanding and practical application. Particular attention was paid to recurring patterns, relationships among key parameters (e.g., process conditions versus fuel quality and emissions), and remaining knowledge gaps, such as the limited integration of extrusion technology with locally available biomass resources and multi-dimensional sustainability evaluation. Overall, this analytical workflow enabled not only descriptive mapping but also critical synthesis to inform future research on bioenergy and sustainability.

3. Results and Discussion

3.1 Profile and Distribution of Reviewed Literatur

This study analyzed 30 peer-reviewed scientific articles that successfully passed a rigorous selection process based on the PRISMA protocol. All selected publications met the inclusion criteria, namely full-text accessibility, publication in English, and classification as peer-reviewed journal articles. The studies were published between 2019 and 2025, reflecting the most recent developments in low carbon extrusion based biomass technology.

The distribution of publications indicates a consistent upward trend in the number of studies over the years, with a noticeable increase in 2023 (14 articles) and 2024 (8 articles), as illustrated in Figure 2. This pattern demonstrates growing academic attention toward issues of renewable energy, solid biofuel efficiency, and environmental sustainability, particularly through the innovation of extrusion-based biomass processing technologies.

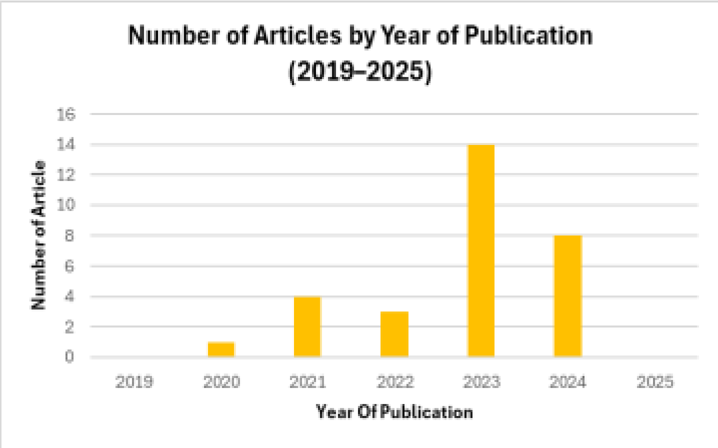

Figure 2. Distribution of Articles by Year of Publication (2019–2025)

From a geographical perspective, the analyzed literature originated from 17 different countries, reflecting a global distribution of interest in biomass briquette innovation. Poland contributed the highest proportion of publications (20%), followed by China and Malaysia (each 10%), as well as the United States, Thailand, and Italy (each 7%). This composition is illustrated in Figure 3, which highlights the dominance of contributions from countries with strong sustainable energy policies and active research initiatives in renewable bioenergy technologies.

Figure 3. Country Distribution of Authors' Institutional Affiliations

Furthermore, the analysis of journal publications reveals that the reviewed articles were distributed across 18 reputable scientific journals, reflecting the diversity of academic forums in which issues related to biomass and energy briquettes are actively discussed. The journal Energies holds the dominant position with the highest number of publications (six articles), followed by Renewable Energy and Energy Reports (each three articles), as well as Journal of Cleaner Production, Fuel, and Renewable & Sustainable Energy Reviews (each two articles). Meanwhile, twelve other journals contributed one article each, indicating a broad and interdisciplinary dissemination of research outputs. This distribution highlights that the themes of sustainability and energy potential of extrusion-based biomass briquettes have gained significant attention within leading academic outlets focusing on renewable energy and environmental engineering. **Table 4** presents a detailed breakdown of the number of articles according to the publishing journals.

Table 4. Number of Articles by Journal of Publication

No.	Journal Name	Number of Articles
1	Energies	6
2	Sustainability	4
3	Processes	2
4	Applied Sciences	2
5	Forests	2
6	Renewable Energy	2
7	Sustainable Production and Consumption	1
8	Environmental Science and Pollution Research	1
9	Process Safety and Environmental Protection	1
10	Resources, Conservation & Recycling	1
11	IJABE (International Journal of Agricultural and Biological Engineering)	1
12	Sustainable Chemistry and Pharmacy	1
13	Energy Conversion and Management	1
14	Resources	1
15	Revista Mexicana de Ingeniería Química	1
16	IJRED (International Journal of Renewable Energy Development)	1
17	Communications Materials	1
18	Fuel	1

The keyword frequency analysis of the 30 reviewed articles indicates that the most dominant term is "bioenergy" (22 occurrences), followed by "briquette" (17 occurrences), "sustainability" (10 occurrences), "green energy" (7 occurrences), and "calorific value" (6 occurrences). The prevalence of these keywords reflects that recent research in the past decade has primarily focused on the conversion of biomass waste into clean energy sources, the enhancement of fuel calorific value, and the contribution of bioenergy systems to sustainable energy development. The dominance of these terms reinforces the position of extrusion-based biomass briquette technology as a potential strategy in the transition toward low-carbon energy systems. The visualization of the keyword frequency distribution is presented in **Figure 4** below.

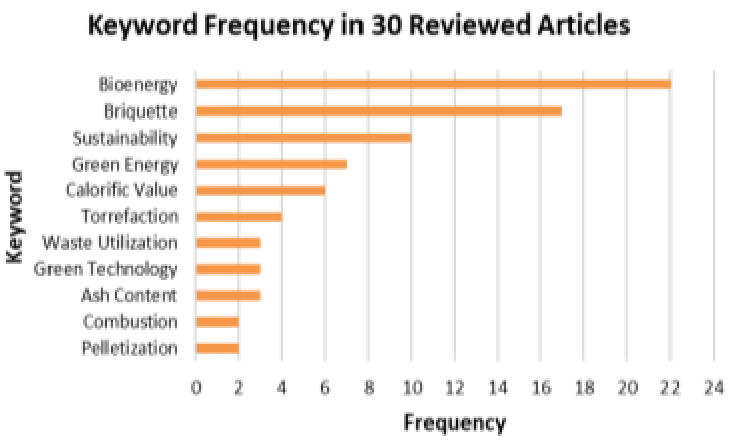

Figure 4. Keyword Frequency in 30 Reviewed Articles

In terms of methodological characteristics, the majority of the reviewed articles (66.7%) adopted an experimental approach, which involved direct testing of the physical properties, calorific value, combustion efficiency, and emission performance of extrusion-based biomass briquettes. A simulation approach was employed in 13.3% of the studies, primarily through numerical modeling or predictive algorithms to evaluate energy potential and system performance. Meanwhile, 20% of the articles combined both approaches by integrating laboratory experiments with simulation models or socio-economic sustainability assessments. This diversity in methodological designs indicates that research on extrusion-based biomass briquettes is not only technical in nature, but also multidimensional and cross-disciplinary. The complete distribution of methodological approaches is illustrated in **Figure 5** below.

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Figure 5. Distribution of Research Methodological Approaches

3.2. Thematic Analysis: Energy Potential and Sustainability of Extrusion-Based Biomass Briquettes

The thematic analysis in this study aims to comprehensively explore two main dimensions in the development of extrusion-based biomass briquettes, namely energy potential and sustainability. The energy potential dimension emphasizes the technical aspects, including calorific value, combustion efficiency, and flue gas emissions such as CO_2 produced during the combustion process. Meanwhile, the sustainability dimension encompasses the evaluation of environmental impacts, economic feasibility, and social implications of utilizing this technology on a broader scale.

The separation of these themes is essential to provide a comprehensive and multidimensional understanding of the contribution of extrusion-based biomass briquette technology to the transition toward low-carbon energy. By presenting both aspects in parallel, this study establishes an empirical and theoretical foundation for assessing the feasibility, effectiveness, and socio-ecological relevance of the technology under investigation.

3.2.1. Energy Potential of Extrusion-Based Biomass Briquettes

The energy potential of extrusion-based biomass briquettes largely depends on the type of raw material used, the extrusion technique, and process modifications such as torrefaction or the use of natural binders. A synthesis of the selected articles indicates that the calorific value of biomass briquettes varies between 16.7 MJ/kg and 20.1 MJ/kg, depending on the composition of the raw materials and the processing technique applied.

For instance, the use of torrefaction and co-pelletization techniques applied to agricultural biomass yielded a high calorific value of 20.1 MJ/kg, with a combustion efficiency of 81.3% and CO_2 emissions of 75 g/MJ [1]. Conversely, briquettes produced from a combination of elderberry waste and sawdust through pelletization exhibited a lower calorific value of 16.7 MJ/kg, with a combustion efficiency of 76.4% and emissions of 82 g/MJ [2].

The extrusion technique plays a crucial role in determining overall energy performance. For example, microwave-assisted pyrolysis of food waste demonstrated a high combustion efficiency of 78.5%, although accompanied by relatively higher emissions (85 g/MJ) compared to other biomass sources [3]. Other innovations, such as the use of natural binders and controlled temperature and pressure during extrusion, have been shown to enhance thermal stability, calorific value, and emission reduction. A comparative summary of calorific value, emission, and combustion efficiency from various biomass feedstocks and extrusion techniques is presented in Table 5 below.

Table 5. Comparison of Calorific Value, Emission, and Efficiency of Various Extrusion-Based Biomass Briquettes

No	Biomass Feedstock	Extrusion Technique	Calorific Value (MJ/kg)	CO_2 Emission (g/MJ)	Combustion Efficiency (%)	Reference
1	Agricultural biomass	Torrefaction and co-pelletization	20.1	75	81.3	[1]
2	Elderberry waste and sawdust	Pelletization	16.7	82	76.4	[2]
3	Food waste	Microwave-assisted pyrolysis	19.5	85	78.5	[3]

No	Biomass Feedstock	Extrusion Technique	Calorific Value (MJ/kg)	CO_2 Emission (g/MJ)	Combustion Efficiency (%)	Reference
4	Rice husk and straw	Pyrolysis and compression molding	18.9	80	79.0	[4]
5	Palm oil empty fruit bunch (EFB) and POME	Microbial fermentation and extrusion	19.5	77	80.6	[5]

3.2.2 Sustainability Analysis of Briquette Production

The sustainability analysis of the 30 reviewed articles encompasses three primary dimensions environmental, economic, and social as emphasized in the framework of sustainable development [1]. The environmental dimension emerged as the most dominant, with all articles (100%) addressing issues such as energy efficiency, emission mitigation, and waste management. The economic dimension was discussed in 27 studies (90%), primarily focusing on cost efficiency, value-added potential, and business-scale feasibility. Meanwhile, the social dimension, which includes topics such as community empowerment, job creation, and technology acceptance, was identified in 18 articles (60%)

It is important to note that these numbers represent the frequency of sustainability dimensions discussed rather than distinct article counts. Several studies simultaneously addressed more than one sustainability dimension such as environmental economic or environmental social linkages reflecting the multidimensional and interrelated nature of sustainability research in extrusion-based biomass briquette production. The distribution of these focal dimensions is presented in Figure 6, which shows that environmental issues are the most consistently examined across the literature, whereas social aspects remain relatively underrepresented. This indicates that the current body of research tends to prioritize technical and environmental performance, with limited exploration of social sustainability and community-level impacts.

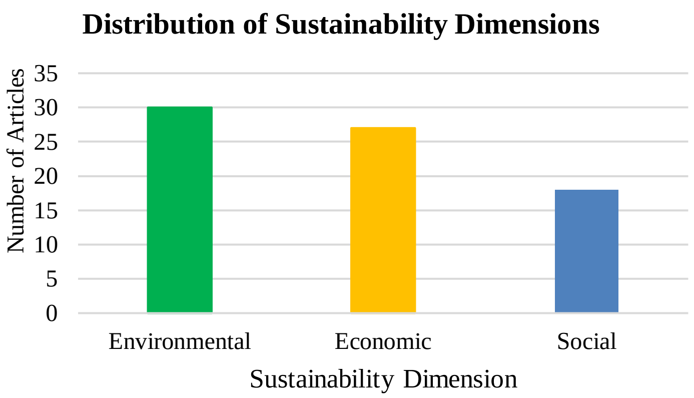

Figure 6. Distribution of Sustainability Dimensions in 30 Reviewed Articles

3.2.3 Multidimensional Thematic Synthesis

The multidimensional thematic synthesis integrates the interrelations among input aspects, technological processes, energy outputs, and sustainability outcomes in the production of extrusion based biomass briquettes. The primary feedstock factors include the type of agro-industrial waste, moisture content, and energy density (Ozili & Ozen, 2023)[1], which are subsequently processed through extrusion technologies incorporating natural binders, torrefaction, and microwave pyrolysis to enhance thermal efficiency and product quality (Kreps, 2020)[2]. These processes yield energy outputs characterized by high calorific values, low emissions, and optimal combustion efficiency (Husaini et al., 2019). Such outputs contribute to sustainability across three dimensions: environmental, social, and economic. The economic dimension, in particular, extends toward practical applications at the domestic scale, small and medium-sized renewable energy enterprises, and broader industrial contexts sing(S. Singh, 2021). Figure 7 presents a conceptual framework that illustrates the systemic and multidimensional interconnections among these variables, reflecting the strategic role of extrusion-based biomass technology in advancing sustainable energy development.

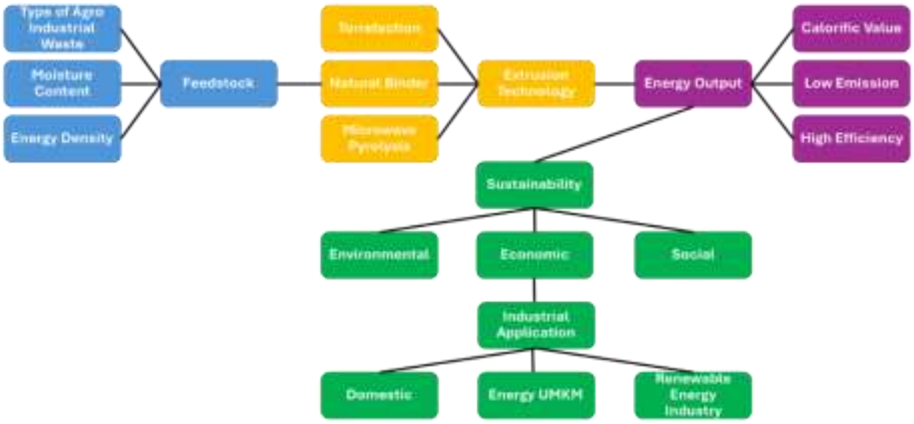

Figure 7. Conceptual Map of Multidimensional Thematic Synthesis

4. Conclusion

This systematic review provides a comprehensive mapping of the energy potential and sustainability aspects of extrusion-processed biomass briquettes. Based on a multidimensional thematic synthesis of 30 selected scientific articles, the findings indicate that the energy efficiency of briquettes is strongly influenced by feedstock type, moisture content, energy density, and the use of natural binders. The integration of extrusion with pre-treatment technologies such as torrefaction and microwave pyrolysis has been shown to enhance calorific value, reduce emissions, and produce stable and efficient energy outputs.

From a sustainability perspective, the results demonstrate that extrusion-based biomass briquettes contribute positively across three major dimensions: environmental, economic, and social. Environmentally, they promote waste reduction and carbon mitigation in agro industrial processes. Economically, they enhance production cost efficiency and commercialization potential. Socially, they empower community based renewable energy enterprises and improve domestic energy access. The application of these briquettes is considered viable for both renewable industrial operations and household scale energy needs. In conclusion, extrusion-based biomass briquettes hold strong potential as an environmentally friendly and economically feasible alternative energy solution. Nevertheless, further research is recommended to evaluate large scale industrial performance and the integration of sustainable energy policies across diverse geographical and socio economic contexts.

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