The Potential Utilization of Biomass as a Renewable Energy Source for the Electricity Sector: A Bibliometric and Content Review

Meiri Triani[1*], *Shochrul Rohmatul* Ajija[2], *Ahmad* Hudaifah[3], *Zidna* Fitriyana[2], and *Wahyu* Setyorini[2]

[1]PLN Research Institute, Jakarta, Indonesia
[2]Department of Economics, Faculty of Economics and Business, Airlangga University, Surabaya, Indonesia
[3]Universitas Internasional Semen Indonesia, Gresik, Indonesia

Abstract. Climate change is currently a global concern. The world needs to drastically reduce carbon emissions (decarbonization) to avoid the harmful effects of the climate crisis. Nowadays, in several countries, biomass co-firing technology in coal-fired power plants (CFPPs) has been widely used and is acknowledged as a popular short-term decarbonization technique. Co-firing refers to replacing coal with biomass materials such as sawdust and rice husk at a specific ratio. By conducting bibliometric and content analyses, this study analyzes global publication trends related to biomass research, specifically for using biomass to produce electricity. Bibliometrics investigated several studies on the relationship between biomass and electricity or energy topics from 2013 to 2023 and collected 2707 publications (articles and reviews) from the Scopus database. Content analysis provides a complementary review of the potential and challenges for biomass resources from the latest publication. This study reveals that biomass use is currently given greater significance due to the urgency of the energy transition. However, the main obstacles to biomass utilization sustainability are related to variations in biomass properties and supply chain characteristics. Future research will concentrate on studies regarding the implications of biomass characteristics and conversion technology.

1 Introduction

Energy transition to renewable sources is driven by the growing demand for energy and the decreasing supply of fossil fuel resources. Global warming issues with the associated social and health effects have accelerated the energy transition even further [1]. Therefore, replacing fossil fuels with renewable energy is a significant step in limiting the impact of global warming, as the intensification of fossil energy use is associated with economic, social, and environmental problems. Developing renewable energy resources in a region is a practical approach to achieving sustainable development goals [2]. However, the energy transition of

* Corresponding author: meiri2mail@gmail.com

the electricity sector has yet to happen fast enough. The level of renewable energy development varies widely among countries due to differing energy challenges, investment costs, energy policies, characteristics, and availability of energy resources. The study by Mottaghi et al. demonstrates that research on the relationship between biomass and the environment has significantly expanded globally over the last two decades. Using biomass provides an opportunity to replace coal, supporting energy security with considerations for environmental and economic aspects. The development of biomass co-firing with coal in existing power plants has received recognition, is seen as an economically sound choice for implementing decarbonization strategies and has been extensively adopted in various countries [1]. More than 50 power plants in the United States have implemented biomass co-firing. South Korea and Japan are also interested in implementing co-firing. Bioenergy is one of the European Union's (EU) predominant renewable energy sources [2].

Choosing the appropriate biomass type for co-firing is of the utmost importance because there is a large degree of variation in the quality of the biomass feedstock and significant differences in chemical and physical characteristics between biomass and coal. The differences in characteristics between biomass and coal often cause technical problems during co-firing implementation, such as increasing slagging and fouling risks. The characteristics of biomass materials can vary significantly based on their source, composition, and the techniques used in their processing. Biomass can be obtained from various sources, including municipal, industrial, and agricultural waste and forestry (including animal husbandry) [1]. Among various biomass sources, agricultural biomass is preferred in most developing countries because of its economic advantages and availability [3]. Meanwhile, woody biomass is also widely used for electricity generation due to its attractive characteristics, including being transportable, cultivable according to demand, storable, expanding in terms of chemical or physical characteristics, and producing a variety of bioproducts [3].

Many researchers have developed bibliometric methods highlighting trends in specific topics. D. Yu & Meng conducted a bibliographic assessment of biomass energy research published from 2007 to 2016 with the VOSviewer. The study indicated that the United States contributed the largest number of studies in the field of biomass energy compared to other countries. Ferrari et al. performed bibliometric analysis on bioenergy research using the Scopus database limited to documents published from 2000 to 2019. The findings indicate that using bio-resources for energy is increasingly getting attention globally. Further study is necessary to determine how bioenergy can be integrated into other renewable energy sources. Sertolli et al. employ bibliometric studies regarding biomass research by accessing the Scopus database based on the documents published from 2000-2021. The findings show biomass utilization as an energy source is gaining increasing significance in contrast to other renewable natural resources, particularly for heat production. Moreover, some researchers choose only the content analysis method to gain a qualitative understanding of a topic. Through content analysis, Piwowar-Sulej et al. [4] found that technological issues are the main challenges related to the application of renewable energy projects. Only a few works, like Elgarahy et al. [5] have attempted to integrate bibliometric and technical evaluations, yet they mainly concentrate on biofuel conversion rather than electricity generation. Therefore, this study adopts a combined bibliometric and content-analysis approach to provide a more comprehensive understanding of the potential utilization of different biomass resources for electricity production from publications published between 2013 and 2023.

2 Methods

The study emphasized biomass resources and their utilization to generate electricity. The primary data source used is the Scopus database, considering that Scopus provides comprehensive coverage of publications across various fields. This study utilized quantitative and qualitative methods by conducting bibliometric and content analysis as described in sections 2.1 and 2.2. Many publications can be reviewed using bibliometric methods, which offer a comprehensive, literature-oriented perspective on the research subject. The research methodology used for this study is illustrated in Figure 1.

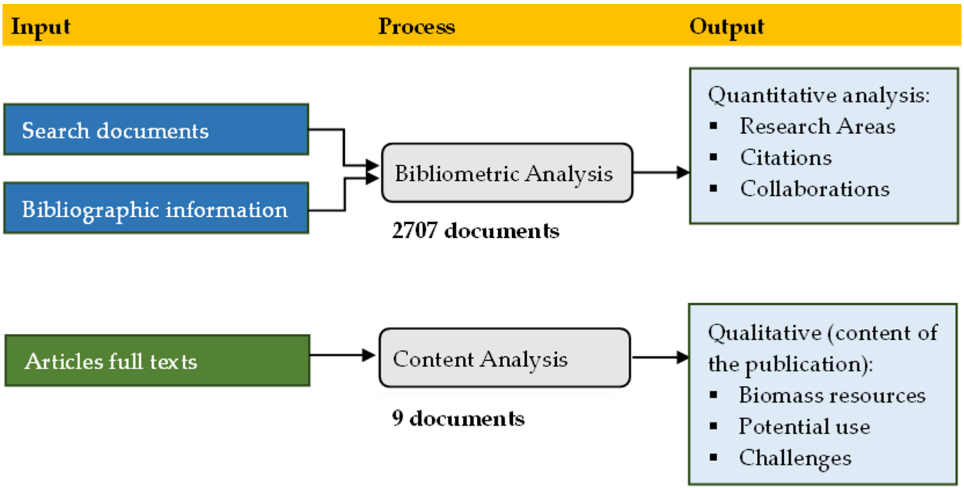

Fig.1. Research framework.

2.1 Bibliometric Analysis

Bibliometric analyses are valuable for assessing scientific productivity, quality, and impact of publications. Nowadays, bibliometrics is extensively used to evaluate trends and authorship contributions, particularly with highly cited articles [2]. For this study, the author utilized VOSviewer version 1.6.19 and Biblioshiny in R studio version 4.2.3 to perform the bibliometric analysis. R-studio provides an extensive range of visualization tools and bibliometric features. To simplify identifying research areas and trends, the specific keyword in Scopus's search within the article "biomass AND electricity OR energy" was applied. Initially, a total of 5,950 documents were found. This study implemented certain filters to ensure a more relevant selection of articles. Only reviews and articles published between 2013 and 2023 were included in the search. This adjustment resulted in a decrease in the number of documents from 5,950 to 2,905. During the screening phase, the author also included documents that met the following criteria: classified as final publication stage, journal source, and written in English languages. The search generated 2,707 documents from Scopus. The process of database selection is described in Figure 2.

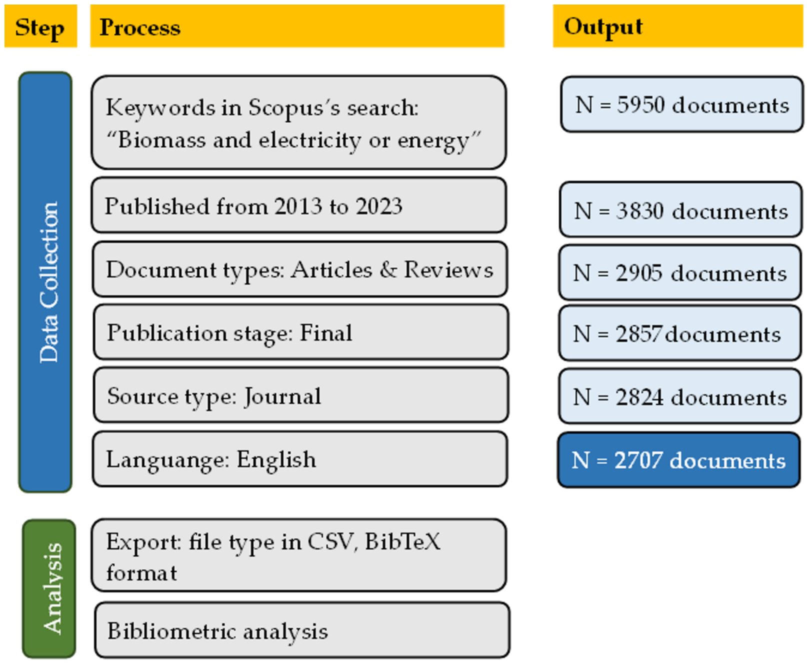

Fig.2. The process of data selection in this study.

2.2 Content Analysis

The literature review is typically conducted to analyze specific content from the selected relevant articles. The literature review process followed the approach suggested by Piwowar-Sulej et al. [4]: (1) identifying current publications, (2) selecting and assessing their findings, and (3) evaluating and synthesizing the evidence. This study conducted a content analysis for publications to assess the status of biomass's contribution from the publication in the Scopus database, with the subject area limited to "energy" and journal sources. This study also applied additional search criteria, including limiting the document type to articles and reviews, filtering for those in their final stage, and specifying the language as English. The studies observed various topics, by employing five combination keywords close to topics, including: "potential AND biomass AND resources AND renewable," (2) "biomass AND properties AND electricity OR power," (3) "biomass AND electricity OR co-firing AND characteristics," (4) "potential AND biomass AND electricity," and (5) "evaluation AND biomass AND electricity AND production OR generation."

3 Results

3.1 Research Areas

The authors performed a keyword co-occurrence analysis and thematic evolution map to identify patterns and developments in biomass research. The selected author's keywords are crucial in determining the scope of any research area. From a pool of 6365 keywords, the author created a network of keyword clusters by requiring at least 15 keyword co-occurrences, resulting in 7 clusters as shown in the overlay visualization map in Figure 3. Cluster 1: energy types (electricity, fuel cell, solar); Cluster 2: contribution of bioenergy associated with climate change, sustainability, and greenhouse gas emission reduction; Cluster 3: biomass classification of biomass; Cluster 4: biomass utilization; Cluster 5: biomass conversion technology (pyrolysis, gasification); Cluster 6: biomass impact on energy consumption and economic growth; Cluster 7: biomass resources.

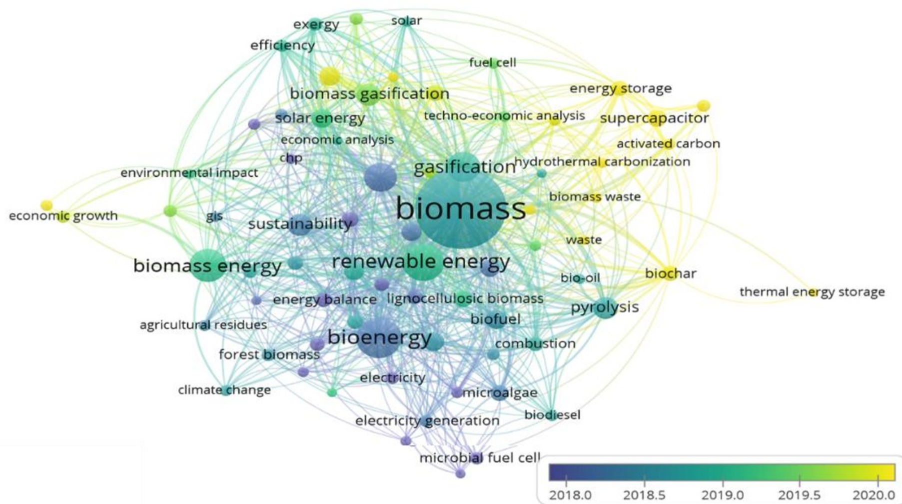

Fig.3. Co-occurrence network of the authors' keywords.

Thematic analysis is also used to identify research interests and their evolution over a specific period and provide insight into future research directions. Thematic analysis is beneficial for summarizing essential aspects of a vast data set [6]. The thematic analysis of the author's keywords shows an evolution of the topic in the last ten years from general categories such as "biomass" to several more specific terms primarily related to biomass contribution, as illustrated in Figure 4. Based on Figure 4, most of the research in the early periods (2013-2019) is concerned with various topics, including sources, characteristics (calorific value), and contribution of biomass (bioenergy, economic growth, supercapacitors). The second period (2020-2023) shows the emergence of other specific keywords, such as "Gasification" and "Fuel cell."

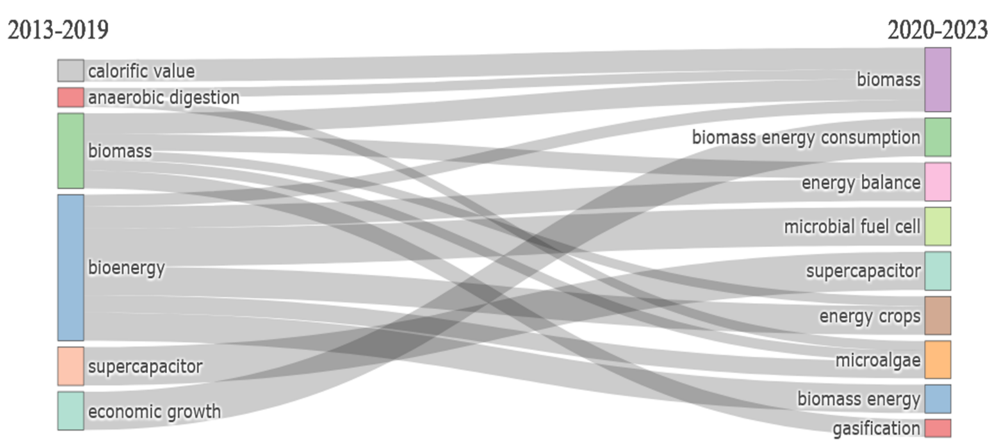

Fig.4. Thematic evolution of author's keywords from 2013 to 2023.

Thematic map analysis helps identify the significant topic distributions and trends based on the centrality and density level [6], as illustrated in Figure 5. The thematic map comprises four groupings: basic, motoric, emerging, and niche themes. The basic theme indicates the topics extensively discussed throughout the article's data collection. Topics related to bioenergy and renewable energy are the most discussed compared to biomass conservation technology topics (gasification and pyrolysis). The emerging theme contains the research topic that receives the most attention from researchers, such as biomass energy. Supercapacitors and energy balance are two examples of niche themes frequently discussed in a single article yet are still comparatively little studied. Meanwhile, topics related to microalgae, lignocellulosic biomass, and microbial fuel cells are included in motor themes.

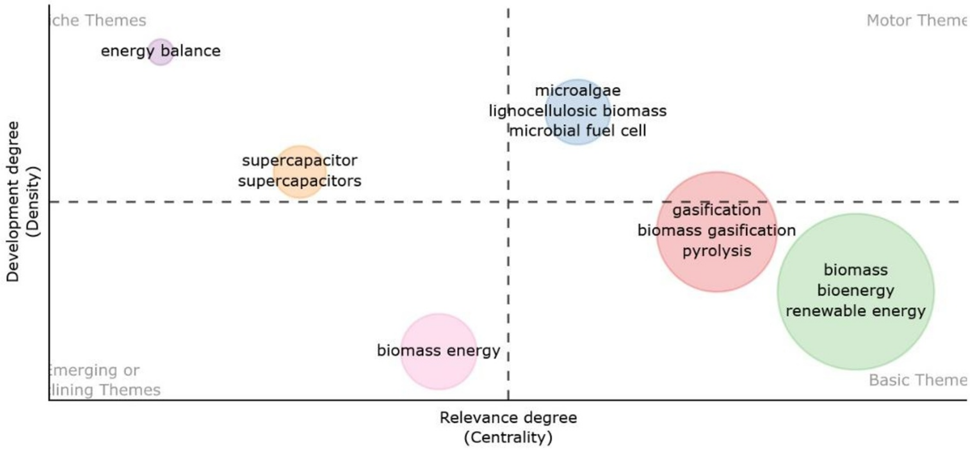

Fig.5. Thematic map.

3.2 Citation Analysis

Over the past decade, China has emerged as a significant contributor to biomass research, as shown in Figure 6. When compared to other nations, like the United States (10,605 citations), India (9,324 citations), the United Kingdom (5,750 citations), Italy (5,578 citations), Spain (5,226 citations), Germany (2,851 citations), Brazil (2,392 citations), and Poland (2,061 citations), China is consistently ranked highest with 21,552 citations. The journals that publish highly cited articles on biomass energy research are Green Chemistry (Q1), Energy & Environmental Science (Q1), Renewable & Sustainable Energy Reviews (Q1), Journal of Materials Chemistry A (Q1), Journal of Cleaner Production (Q1), Material Research Letters (Q1), Nature Catalyst (Q1), and Journal of Power Sources (Q1). All journals in the most cited journal category for biomass topics are reputable Q1 journals.

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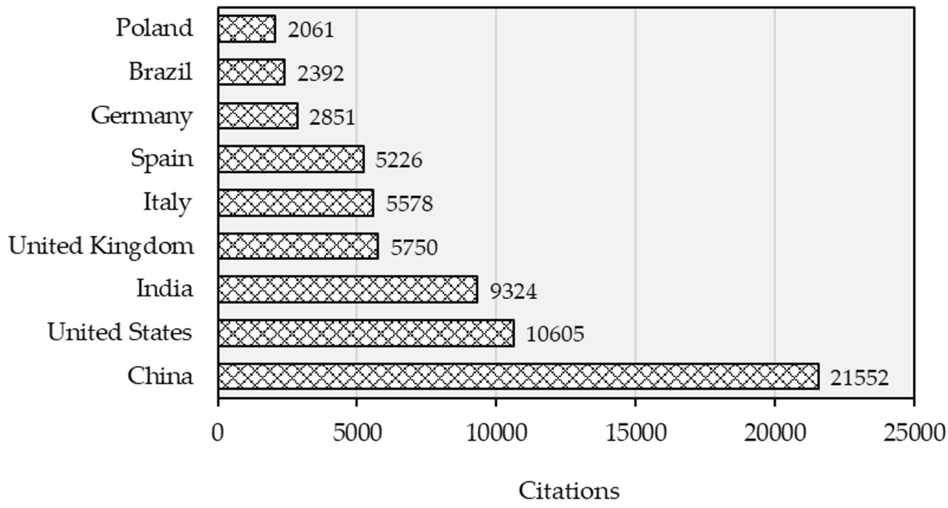

Fig.6. Number of citations by country.

3.3 Collaboration Analysis

This study determined a country's minimum number of documents to be 10. Globally, articles on biomass research are contributed from 58 countries. The larger the dimensions of the circle and the thicker the connection, the greater the collaboration between countries (as shown in Figure 7). The analysis of the collaboration resulted in the identification of six clusters. China is recognized as one of the most productive and collaborative countries since 2019 in the research areas under investigation, followed by the United States and India. China has developed network collaborations with countries such as Australia, Canada, Iran, Iraq, Egypt, Hong Kong, and Nigeria. The unites states collaborated with Italy, Germany, and the Netherlands. India collaborated with South Africa, Taiwan, and Malaysia.

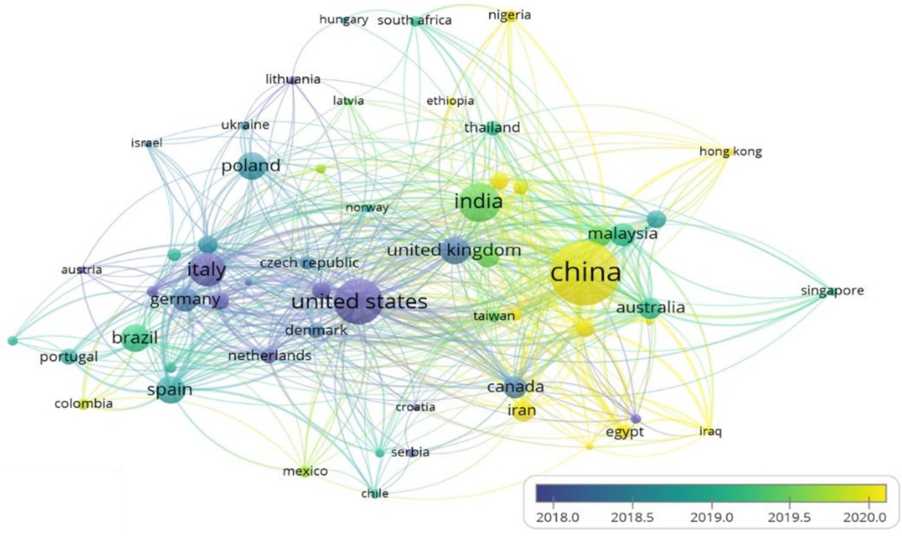

Fig.7. Collaboration patterns among countries.

3.4 Content Analysis

The specific subject to investigate through content analysis is divided into the following categories: biomass resources, potential and challenges of biomass. Several studies evaluated the application prospects of various biomass sources as bioenergy. Safarik et al. [7] calculated the Czech Republic's possible supply of dendromass, or residual forest biomass, for electricity production. Residual forest biomass includes by-products of conventional forestry, industrial processes, demolition, construction, and packaging processes. According to the study, the Czech Republic will have 13.473 million tons of dendromass accessible annually for energy use until 2036. 56.7% of the total quantity will originate from by-products from conventional forestry. Currently, 60% of the energy produced in the European Union (EU) comes from bioenergy derived from wood wastes, dominating the market for green energy.

Abelha et al. [8] quantified the potential combustion improvements through the upgrading processes (washing and steam explosion) from selected biomass residuals used, including raw sugar cane bagasse and empty fruit bunch. The primary subjects of this study were the propensity of NO_x, aerosol, slagging, and fouling formation. The combustion process highly influences NO_x formation. Due to the high concentrations of corrosive NaCl and KCl, aerosols generated from bagasse-based materials pose operational risks when they accumulate on hot heat exchanger surfaces. Consequently, further washing or the use of specific mineral additives is necessary to mitigate the negative impact. The washing process reduced the K content of slag deposits but could not eliminate the slagging phenomenon, as slagging in sugarcane is mainly attributed to Fe in Fe–Ca–alumino-silicates. As a result, even if potassium is entirely removed, slagging is not eliminated through a washing step. Hubetska et al. [9] found the prospects of agricultural residual (sunflower seed husk) as bioenergy because of their abundant feedstock, affordable price, and minimal environmental effect. Fei et al. [10] investigated the possibility of algal utilization in co-firing applications. This study demonstrates that while co-firing coal with algae reduces emissions of gaseous pollutants such as NO_x and SO_2, it simultaneously increases $PM_{2.5}$ emissions, which are further accelerated at higher combustion temperatures and larger biomass fractions.

Nadaleti et al. [11] evaluated the usage of agro-industrial residual resulting from producing rice and peaches in southern Brazil as bioenergy. Because biohydrogen has high energy and is widely recognized as a carbon-free fuel that does not contribute to greenhouse gas emissions, this study discovered the possibility of generating electricity using biohydrogen derived from agro-industrial waste. Livestock residues (animal waste) and urban human waste also can be used as bioenergy. Livestock residues are estimated to have the highest energy potential, followed by urban human waste. This study demonstrates that Tanzania may produce electrical energy from these residues, lowering its reliance on fossil fuels and offering environmental advantages associated with waste management.

The hybrid concentrated solar biomass (HCSB) technology is a viable alternative for sustainable electricity sources [12]. This technique can utilize the abundant solar and biomass resources (from agricultural and forestry residues) in New South Wales. HCSB plants are becoming more crucial in assisting with the energy transition due to their ability to produce dispatchable renewable electricity. Nevertheless, the availability of biomass and the necessary large-scale transportation of biomass to an industrial facility are likely to influence sustainable bioenergy utilization in the future when employing biomass as a raw material. The challenges associated with the sustainability producing electricity from biomass are also due to various biomass characteristics, pre-treatment requirements, combustion stability, and energy efficiency. Consequently, it is recommended to explore research on the variability of biomass properties, planning the biomass supply chain, and the potential of biomass conversion technologies.

4 Discussion

The significant differences between the characteristics of biomass and coal, together with the variability of biomass feedstock properties, often create challenges in its utilization as a sustainable alternative energy source, particularly in co-firing applications. These challenges include unstable combustion and potential technical disturbances such as boiler shutdowns or increased maintenance requirements. Evaluating the physical and chemical characteristics of biomass through ultimate and proximate analyses is therefore essential to predict combustion behavior and performance during co-firing [8]. In Indonesia, supply-related constraints have also been identified, such as limited access to biomass sources and storage difficulties, which affect the continuity of the biomass supply chain [3]. These challenges highlight the need for developing optimized supply-chain strategies and selecting appropriate conversion technologies to stabilize the feedstock supply [13]. A resource-focused and demand-driven approach is necessary to evaluate availability and utilization, reducing the risk of mismatch between supply and demand, which may result in price volatility and irregular operation of biomass power plants.

Biomass, unlike gaseous or liquid fuels, cannot be easily handled, stored, or transported due to its low bulk density and high moisture content [5]. Consequently, converting solid biomass into liquid or gaseous fuels with higher energy density and easier handling becomes an important step for large-scale utilization. Several thermochemical conversion routes—combustion, gasification, pyrolysis, hydrothermal processes, and torrefaction—have been developed to address these limitations [13]. Among these, torrefaction has gained attention as a mild thermochemical pretreatment that improves the fuel quality of biomass by reducing its oxygen and hydrogen contents while enriching carbon concentration, thereby increasing energy density and hydrophobicity [14]. Torrefaction typically operates in an oxygen-deficient atmosphere at 200–300 °C for 10–60 minutes, leading to partial decomposition of hemicellulose and an increase in grindability and storage stability [5]. The key process variables include residence time, temperature, reactor type, and feedstock moisture content, all of which significantly influence product quality and calorific value [14]. Furthermore, integrating torrefaction with other thermochemical processes such as pyrolysis and gasification has been shown to improve conversion efficiency and reduce overall process energy requirements [15]. Torrefied biomass exhibits coal-like characteristics, which facilitate blending and co-processing with coal, thereby reducing greenhouse-gas emissions while maintaining combustion performance [15]. This synergy makes torrefaction a promising technology for sustainable biomass utilization, especially for regions aiming to expand renewable electricity generation from local biomass resources.

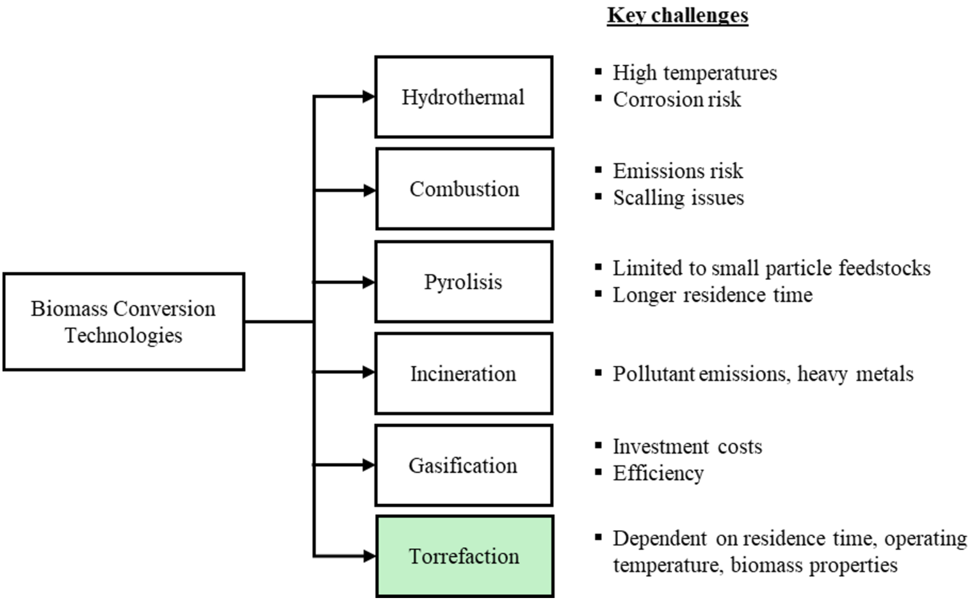

Fig.8. Overview of biomass conversion technologies with key challenges.

5 Conclusions

The significance of biomass in co-firing projects is increasingly emphasized in scientific literature, reflecting the urgency of the energy transition. Among the several categories of biomass, agricultural and forestry residues are the most extensively utilized due to their availability and inherent properties. Nonetheless, discrepancies in the quality of biomass feedstock and an unstable supply of raw materials affect the advancement of biomass utilization. Consequently, for the sustainability of biomass utilization in the upcoming years, numerous researchers have emphasized the necessity of comprehending the potential and challenges associated with biomass properties, conversion methods, and supply and demand characteristics. Given the significant potential of biomass leftovers, optimizing conversion technology is essential for enhancing the advantages of biomass as an alternative energy source. Torrefaction has gained attention as a viable biomass conversion method because it can notably modify the chemical composition of biomass, imparting coal-like qualities. Key variables, such as residence time, temperature, moisture content, calorific value, reactor type, and biomass type, significantly influence the resulting properties of the torrefied biomass. Effectively managing these factors is essential for optimizing the process and improving the biomass quality for use in energy generation or other applications. Future research should prioritize investigations of biomass characteristics and the selection of appropriate conversion technologies. In addition, complementary studies on techno-economic evaluations, lifecycle environmental assessments, and policy frameworks are essential to ensure both the technical feasibility and the long-term sustainability of biomass utilization in the energy sector.

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