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Optimizing Potential Supply Chain of Biomass Agricultural Waste for Co-firing of Coal Power Plant Using MCDA, GIS, and Linear Programming in the Java and Sumatra Islands, Indonesia

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Abstract

The development of renewable energy is a key priority for the Indonesian government and many other nations. Utilizing biomass as a co-firing fuel in coal-fired power plants (PLTUs) offers a viable pathway to meet renewable energy targets in the electricity sector. Co-firing technology involves substituting coal with biomass at specific ratios while maintaining the operational quality and efficiency of the power plants. Indonesia plans to implement a co-firing program in 114 PLTUs, with a combined capacity of 18.1 GW, requiring approximately 9 million tons of biomass annually. This study aims to develop a biomass supply chain model for co-firing, focusing on transportation cost optimization. Geographic Information Systems (GIS), Multi-Criteria Decision Analysis (MCDA), and Linear Programming are employed to map biomass potential from agricultural waste, identify optimal storage and factory locations, calculate the shortest distances to PLTUs, and design an efficient supply chain. Key biomass sources considered include agricultural waste from rice, corn, cassava, palm oil, coconut, sugarcane, and rubber. The study concentrates on co-firing in the Java and Sumatra regions, which house 14 and 12 PLTUs, respectively. Assuming a 5% biomass mix, the total annual bio-pellet demand is estimated at 3.34 million tons. By contrast, the annual production capacity of bio-pellets is calculated to be 143.58 million tons, indicating a surplus supply. Optimization results confirm that the available biomass supply can adequately meet the co-firing requirements for PLTUs in Java and Sumatra. The study also identifies optimal locations for storage facilities and bio-pellet factories near PLTU sites, enhancing supply chain efficiency. By integrating data on biomass potential, storage, factory, and PLTU locations, this research facilitates the design of an effective and efficient biomass supply chain, contributing to the broader goal of renewable energy development.

1. Introduction

The challenges of managing the global energy sector today and in the future are becoming increasingly complex, requiring concerted efforts and active participation from every nation. The world relies heavily on fossil fuels such as oil, natural gas, and coal to meet its energy needs. This dependence causes environmental problems and leads to economic instability due to price fluctuations and limited supply. Conventional energy resources like oil and natural gas are expected to become scarcer and less accessible over time. This situation poses significant challenges in ensuring a stable and affordable energy supply for the future [1].

The Indonesian government is also committed to the global effort to tackle climate change and mitigate the impacts of global warming. Indonesia aims to reduce greenhouse gas (GHG) emissions by 31.89% through national programs and up to 43.20% with international support by 2030, based on a business-as-usual scenario [2]. One of the main pillars to achieve these targets is increasing the utilization and development of renewable energy within the national energy mix. The power generation sector is critical for implementing renewable energy to reduce GHG emissions [3]. Currently, coal dominates as the primary fuel for electricity generation, necessitating efforts to transition toward cleaner and more sustainable energy sources. Various studies have explored options for using renewable energy in Indonesia's long-term power generation strategy. For instance, some researchers of BRIN [4] analyzed the cost-benefit of replacing coal-fired power plants (PLTU) with photovoltaic (PV) systems integrated with Battery Energy Storage Systems (BESS).

As an archipelagic country, Indonesia consists of thousands of islands and is divided into 38 provinces [5], with significant socio-economic disparities across regions. Each region has unique characteristics that influence renewable energy development based on local natural potential [6]. Natural conditions, resource availability, and energy demand are crucial in determining the types of renewable energy technologies prioritized for development in a given area [7]. One of the renewable energy sources that plays a significant role is biomass, which is derived from agricultural, plantation, and forestry waste. Using biomass helps reduce GHG emissions and offers a sustainable solution for managing agricultural and forestry waste [8]. However, the development of biomass as a renewable energy source faces challenges, particularly in terms of cost, which remains higher compared to coal. These challenges must be addressed through appropriate policies, investments in infrastructure to support the biomass supply chain, technological capacity building, and human resource development [9].

The government has launched a co-firing program to utilize biomass as a mixed fuel in coal-fired power plants (PLTU) [10]. This initiative is expected to significantly contribute to climate change mitigation while strengthening national energy security [11]. On a macro level, the challenges of the co-firing program have been discussed by some energy researchers of BRIN [4], focusing on political, economic, social, technological, environmental, and legal aspects. The biomass supply chain must be carefully prepared and developed to ensure a sustainable and economically viable supply. Another biomass technology researcher of BRIN explored the slagging and fouling aspects of biomass and coal combustion in the co-firing process [12]. However, there is still limited research specifically addressing the technical aspects of the biomass supply chain for co-firing in PLTU, which is essential to ensure the sustainability of its supply.

This situation presents two major challenges in biomass development [13]. First, there is a high investment required at the upstream level, as most biomass reserves are located in rural and forest areas far from industrial sites and power plants. Second, biomass is not a commodity that is easily collected and utilized. Ideally, there should also be consumers to absorb biomass in locations with available biomass resources. Therefore, biomass consumption can be facilitated by developing adequate transportation infrastructure, ensuring lower biomass delivery costs to consumers [14].

The development of biomass for use as a co-firing fuel alongside coal in PLTU in Indonesia faces several challenges and issues [15], including (1) limited biomass availability; (2) inadequate infrastructure and logistics; (3) high production costs; (4) required technology and installation adjustments; and (5) unsupportive regulations and policies. Nevertheless, the development of biomass utilization for co-firing in PLTU has the potential to reduce greenhouse gas emissions and contribute to diversifying Indonesia's energy sources toward sustainability [3]. These issues can be addressed with proper support from the government, industry, and other relevant stakeholders, enabling further progress in biomass utilization for co-firing in PLTU in the future [13].

In an effort to find solutions to the constraints and challenges in biomass development, several references are required. Sun et al. [16] used GIS (Geographic Information System) in their scenario determination phase, selecting potential crop candidates that were found to be highly suitable based on criteria

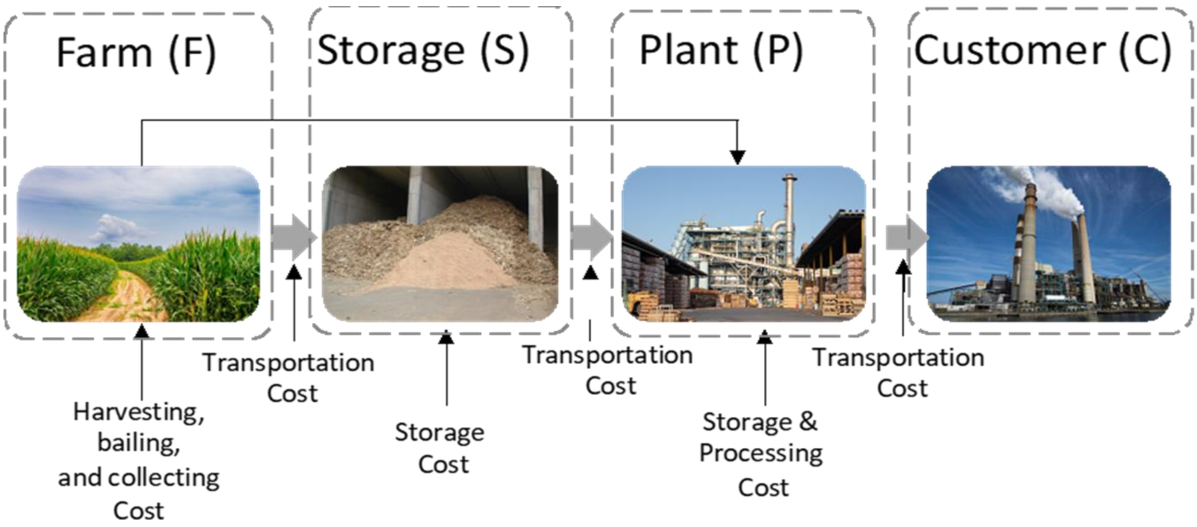


Figure 1. Supply chain of biomass agricultural waste [17].

such as biomass availability, distance from main roads, distance from substations, distance from water bodies, and potential flood risks. In addition to GIS, Terh and Cao [18] argued that MCDA (Multi-Criteria Decision Analysis) can support considerations of energy, engineering, economics, environmental factors, and ethical dimensions such as sustainability, equity, and the democratization of the energy sector.

Several experts use multidisciplinary analyses that include MILP, GIS, economic analysis, and sensitivity analysis. Wang et al. [19] employed LP (Linear Programming) to optimize the biomass supply chain in China from a strategic perspective in search of lower costs. Meanwhile, Shayan [20] used an LP mathematical model to maximize profits by defining the optimal weekly amount of woodcuts. Guo and Shen [21] used one of the models in Multi-regional Analysis (MRA), namely the Multiregional Input-Output (MR-IO) model, to investigate energy use for China's construction industry and inter-regional trade. The results showed that, according to sector-based demand calculations, the construction industry in China consumes coal equivalent to 29.6% of China's total national consumption, mostly through inter-regional energy trading. If these three methods (GIS, MCDA, LP, and MRA) are combined, they will certainly produce a new approach useful in comprehensive planning.

This research aims to develop an optimization model for the biomass supply chain from agricultural waste based on transportation costs for co-firing fuel in coal-fired power plants. This study uses GIS, MCDA, and LP to map the biomass potential from agricultural waste and make storage and factory locations projections, identifying the shortest distance. This approach integrates various criteria, such as biomass availability, transport access, and environmental impact, to determine the optimal location for co-firing implementation. Using GIS, MCDA, and Linear Programming, these studies can provide more detailed and accurate information on the potential use of biomass for co-firing in coal-fired power plants and support better decision-making in the planning and development of future biomass energy projects.

2. Materials and Methods

2.1. Establishment of the Agricultural Waste Biomass Supply Chain

The establishment of the agricultural waste biomass supply chain for co-firing fuel (coal and bio-pellets) in PLTU involves several key steps [22]. First, identify the types of agricultural waste available, such as straw, crop residues, or plantation waste, including an assessment of the location and the amount of waste generated. Second, develop a system for collecting the waste from farmers or processing sites, as it needs to be processed (e.g., drying and grinding) to meet fuel specifications. Third, design an efficient transportation system to deliver the biomass from collection sites to the power plant, involving selecting transportation methods (trucks, trains, etc.) and optimal routes [23].

Next, the fourth step is establishing quality standards for the biomass to be used as fuel, including analysis of energy content, moisture, and contaminants [24]. Fifth, develop an integration plan for mixing biomass with coal in the combustion process, including adjustments to equipment and operations to ensure efficiency and low emissions. Sixth, develop strategies to manage the waste produced from the combustion process, including ash and gas emissions, to ensure that this waste management complies with environmental regulations. Seventh, a cost analysis must be conducted to ensure that the supply chain is economically viable, including calculations for collection, processing, transportation costs, and the potential impact on energy savings. Eighth, partnerships should be formed with farmers, logistics service providers, and other stakeholders involved in the supply chain to ensure sustainability and smooth operations. Ninth, a system should be developed to monitor the performance of the supply chain periodically, including data collection on the efficiency and effectiveness of the established system [9]. The supply chain of biomass agricultural waste, as illustrated in Figure 1, outlines the processes from waste generation to its final utilization.

2.2. Characteristics, Potential, and Distribution of Biomass Locations

The process of identifying biomass characteristics involves several important steps that are typically carried out. First, biomass samples are collected from relevant sources, such as agricultural waste, food scraps, or energy crops. Second, the sample preparation is usually done through drying and grinding to ensure consistent size and moisture content. Third, physical characteristics, such as density, particle size, and composition, must be analyzed to understand how the biomass will behave during processing [25]. Fourth, a chemical analysis determines the chemical composition, including carbon, hydrogen, oxygen, nitrogen, and sulfur content. This also includes fiber, lignin, and cellulose analysis [26].

Next, the fifth step involves an energy analysis to measure the calorific value of the biomass to determine how much energy can be produced [27]. Sixth, biological analysis is important if the biomass is used for biological applications, such as fermentation, to evaluate the potential microorganisms in the sample. Quality testing ensures the biomass meets the required standards for specific applications, such as fuel or fertilizer. Eighth, statistical analysis can be done to assess biomass characteristics and identify its potential uses [28]. Based on various references [29] and [17], the characteristics of biomass in the conversion process into bio-pellets are formulated based on five parameters: proximate analysis, ultimate analysis, biopolymer content, bulk density, and bio-pellet standards [30].

Energy potential is calculated based on annual agricultural production data in the study areas [22] and [31]. Biomass from agricultural waste is converted into pellets for co-firing using formulas for Primary Agricultural Residue (PAR) and Secondary Agricultural Residue (SAR). Primary agricultural waste potential is calculated using methodologies referenced from The Biomass Assessment Handbook, Biomass Energy Europe, and The Asian Biomass Handbook. This ensures a consistent and reliable approach to determining the energy contributions of agricultural waste biomass. The formula for PAR is expressed as shown in Equation 1.

$$PAR = \sum (CAi\ x\ APi\ x\ PtRi\ x\ Avi) \qquad (1)$$

Where PAR represents the Primary Agricultural Residue (tons), CAi is the cultivated area for crop i (hectares), APi is the agricultural productivity of crop i (tons/hectare), $PtRi$ is the product-to-residue ratio of crop i (dimensionless), and Avi is the availability of crop i residue based on the current harvesting system (percentage or fraction). This formula integrates data on cultivated area, crop productivity, the ratio of primary product to its residue, and the residue's availability considering current harvesting practices. It quantitatively estimates biomass potential from primary agricultural residues, forming a basis for further energy potential calculations.

Several European countries have implemented regulations requiring all companies to report the volume and utilization methods of the waste they generate to the local statistical agency. However, if direct statistical data is unavailable, the assessment methodology uses the Equation 2:

$$Pti = Cri\ x\ PtSRi \qquad (2)$$

Where Pti represents the potential of secondary agricultural residue from crop i (tons/year), Cri is the production volume of crop i (tons/year), and $PtSRi$ is the product-to-secondary-residue ratio for crop i (dimensionless), this formula estimates the potential of secondary agricultural residues by relating the production volume of a specific crop to its residue generation ratio.

GIS [32] will assist in determining the location and mapping the position of biomass, warehouse (storage) construction that is closest to the biomass source to facilitate farmers in collecting agricultural waste and transporting it to the storage, as it will not be too far from the agricultural land, the main source of biomass material from agricultural waste, thus reducing transportation costs [33]. Several criteria used as references for determining the storage location are as follows: (1) the storage location must be a maximum of 80 km from the agricultural area (biomass source); (2) the daily agricultural waste potential must be at least 5 tons (in line with the minimum capacity of medium and large transport trucks) to avoid excessive transportation costs; (3) the location must be on a main road accessible by trucks with a minimum capacity of 5 tons (medium and large) for effectiveness and efficiency; (4) the location

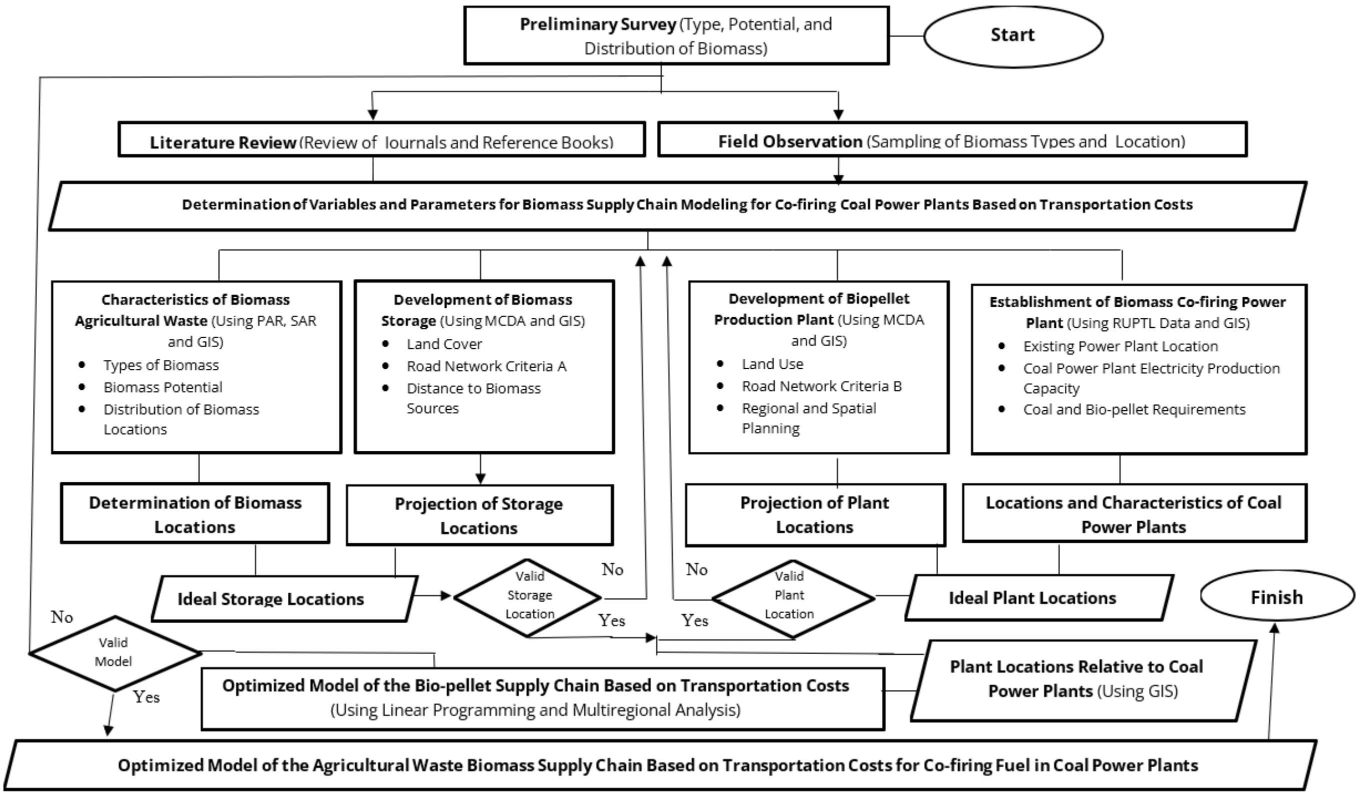


Figure 2. Flow of biomass research implementation.

must not be in residential or densely populated urban areas; and (5) the location must comply with land use regulations as set by the government (RUTR/RTRW). The flow of biomass research implementation, as depicted in Figure 2, illustrates the stages from research initiation to practical application.

2.3. Determining Biomass Storage Location

Data and maps of land cover and land use are crucial in determining storage locations [34]. Land cover maps serve as a reference to avoid selecting storage sites that do not align with spatial planning and land designation. Road network data and maps are also essential factors in determining storage facility locations for biomass. Biomass is a specific commodity that must be transported using specialized vehicles and requires roads of a certain class. The distance from the biomass source to population centers is important in selecting storage site locations for agricultural waste biomass.

This storage location projection will be used to estimate transportation costs, delivery times, and transport capacity and to determine the location of bio-pellet plant construction. The overlay results will form a map of projected storage locations, which, when combined with data and analysis, will yield the ideal location for building storage facilities. The ideal location is safe, close to main roads (at least a district road class), low-cost, near biomass waste sources, located on land suitable for the intended purpose, and accepted by the local community.

The process of determining the ideal location for biomass storage (warehouse for collection, initial processing, and storage) and for the construction of bio-pellet plants uses MCDA and GIS [35]. MCDA determines the criteria needed to set up storage facilities for the initial processing and storage of agricultural waste biomass. GIS determines the ideal location and creates a distribution map for the storage sites to be developed.

2.4. Determining the Bio-pellet Plant Location

Data and land use maps are crucial in determining the location for constructing a bio-pellet plant for agricultural biomass waste conversion [29]. This data is a key factor in selecting the most ideal location for the bio-pellet plant to avoid conflicts with existing land use. Land use maps are referenced to ensure the plant location aligns with spatial planning and land designation. Furthermore, road network data and maps are essential in determining the location for building the bio-pellet plant. Biomass is a specific commodity that requires specialized transportation and must be transported via roads of a certain class. The selection of road class affects travel distance and determines transportation costs. Of course, the road class required for storage differs from that for the bio-pellet plant location.

Next, data and maps of regional planning (spatial planning) are also important factors in determining the bio-pellet plant location. This spatial planning data is a foundation for choosing the most ideal plant location to avoid conflicts with existing land use. Spatial planning maps act as references to avoid selecting a plant location that does not align with future land use planning and zoning. The plant location projection will be used to establish transportation cost projections from the storage to the plant, followed by the PLTU, delivery times for biomass material, transportation capacity, and transportation costs to the nearest existing PLTU. The overlay results will form a map of projected plant locations, which, combined with data and analysis, will yield the ideal location for constructing the biopellet plant for agricultural biomass waste conversion, ready for use in coal-fired power plants.

The ideal location is safe, close to main roads (at least a district road class), cost-effective, near storage locations and PLTUs, environmentally safe, located on land suitable for its purpose, and accepted by the surrounding community. Determining the ideal location for the biopellet plant uses MCDA and GIS [36]. MCDA is used to define the various criteria required for constructing the plant. GIS is used to determine the ideal location and create a distribution map of the plant locations to be developed, ensuring they are effective and efficient, maintaining bio-pellet quality, ensuring a reliable supply to the PLTU, and offering competitive prices compared to coal.

2.5. Determining Coal-Fired Power Plants (PLTU) for Co-firing with Biomass

The data and maps of existing PLTU locations come from PLN [37], which, in collaboration with the government, has designated 52 coal-fired power plants for co-firing. Across Indonesia, 234 PLTU use coal as fuel, with a total capacity of 45.35 Gigawatts (GW). However, only 52 of these PLTUs have been designated as co-firing plants. Among them, 14 PLTUs are located on Java (including Madura and Bali), and 12 PLTUs are on the island of Sumatra (including Riau Archipelago and Bangka Belitung). Next, the electricity production capacity data for each PLTU is derived from the PLN's RUPTL (Electricity Supply Business Plan) and the Ministry of Energy and Mineral Resources, indicating the maximum electricity capacity that can be generated when all units of the plant are fully operational [38]. The coal-fired PLTU electricity production capacity in Indonesia as of April 2024 is 51.56 GW. This is derived from 254 coal-fired PLTU units operating in Indonesia. The electricity production capacity of PLTUs in the Jamali region (Java, Madura, and Bali) is 16,525 MW. In contrast, the Sumatra region currently operates 33 coal-fired PLTUs, with a total capacity of 3,566.5 MW. In the planning stage, according to the RUPTL 2021-2030 [39], there is a 4,000 MW capacity with 14 PLTU units planned in Sumatra.

The locations of coal-fired PLTUs to be converted into co-firing PLTUs are identified using satellite imagery and data from PT PLN (Persero) [40]. The characteristics of the coal-fired PLTUs come from PT PLN and the Ministry of Energy and Mineral Resources. Coal-based PLTUs have varying locations and characteristics. The location of PLTUs also considers transportation accessibility, such as roads, ports, and other infrastructure, to facilitate coal delivery and electricity distribution. The efficiency of coal-fired PLTUs varies depending on the technology used. More modern PLTUs have higher efficiency compared to older ones. Coal-fired PLTUs produce greenhouse gas emissions and other pollutants, such as sulfur dioxide (SO_2) and nitrogen oxides (NO_2).

Using GIS, identifying existing coal-fired PLTU points designated as co-firing PLTUs is based on data from PLN and the Ministry of Energy and Mineral Resources (ESDM) [41]. The identification and mapping of PLTU locations involve several structured steps. Topographic maps and satellite imagery provide an initial view of the location and accessibility. Evaluation is carried out regarding access to transportation infrastructure, such as roads, ports, and electrical grids. The identification must also consider proximity to coal sources, water, and other supporting infrastructure. Additionally, reviewing the environmental impact and applicable regulations in the area is crucial.

2.6. Development of a Biomass Supply Chain Model for Co-firing Based on Transportation Costs

The calculation of the distance between the biomass storage location, bio-pellet plant, and co-firing PLTU locations is aimed at finding the shortest (distance) route, which will consequently result in the lowest transportation costs (minimum) using MCDA and GIS [18]. Applications like Google Maps can be used to calculate distances based on transportation routes (roads). First, input the locations of biomass storage and the PLTU to obtain the best route and note the distance displayed by the application. Second, calculate the distance between several points, namely (1) the distance from storage to PLTU by measuring the distance between the biomass storage location and PLTU; (2) the distance from the plant to the PLTU by measuring the distance between the biopellet plant and PLTU; and (3) the distance from storage to the plant, by calculating the distance between the storage and the biopellet plant. Third, compare the obtained distances with the logistics requirements and transportation efficiency, assuming that shorter distances are generally more efficient and economical for raw material and product deliveries.

Next, transportation costs for transporting agricultural biomass waste from the plant to the PLTU will be calculated based on distance (movement/path length) and the transportation mode used through linear programming (LP). The transportation cost calculation for agricultural biomass waste from the plant to the PLTU involves several steps. Standard cost references applicable in the region, according to local government regulations, are used to simplify the calculation and determination of transportation costs. In general, the modeling in Java and Sumatra refers to the prevailing freight transportation rates in Indonesia.

Developing a biomass supply chain model from agricultural waste is based on biomass supply, PLTU demand, distance (movement), and minimum transportation costs, involving several steps. The data collection and processing in the supply chain modeling may consist of several main components: (1) gathering data on agricultural waste sources, the supply volume from each source, and biomass characteristics; (2) determining the biomass requirements for PLTU, including the required volume and delivery times; (3) mapping routes between biomass source locations and PLTUs, including the distance required for each route; (4) calculating transportation costs based on distance and vehicle characteristics.

A linear program determines the decision variables (the amount of biomass transported from each source to the PLTU) and creates an objective function to minimize total transportation costs. The linear program uses the simplex method to find the optimal solution. The next model development involves adding more comprehensive and in-depth variables and parameters. Sensitivity analysis is also conducted to see how changes in supply, demand, or transportation costs affect the model. This sensitivity analysis helps understand the resilience of the supply chain.

2.7. Development of a Multiregional Bio-pellet Trade Potential Analysis

Spatial (multi-regional) analysis is used to project the potential for biomass trade between regions based on the biomass supply chain by comparing the supply/demand across different regions [42]. If one region has a surplus while another has a deficit, the potential for biomass trade between regions or even countries can be realized. Identifying biomass sources in each region, including types of agricultural waste, supply volume, and geographical location, is essential. Information on the biomass demand from PLTUs or other industries in each region should be gathered, including the required volume and delivery times. Maps of transportation routes, road conditions, and existing logistics infrastructure in each region are also necessary.

GIS software is used to map the regions to be analyzed. A map is created for each region showing the locations of biomass sources, PLTUs, and transportation infrastructure. The total biomass supply from each region and the total biomass demand from PLTUs or other industries in each region are calculated. A table is created comparing the supply and demand in each region. This can be done using a simple formula: a positive balance indicates a surplus, while a negative balance indicates a deficit.

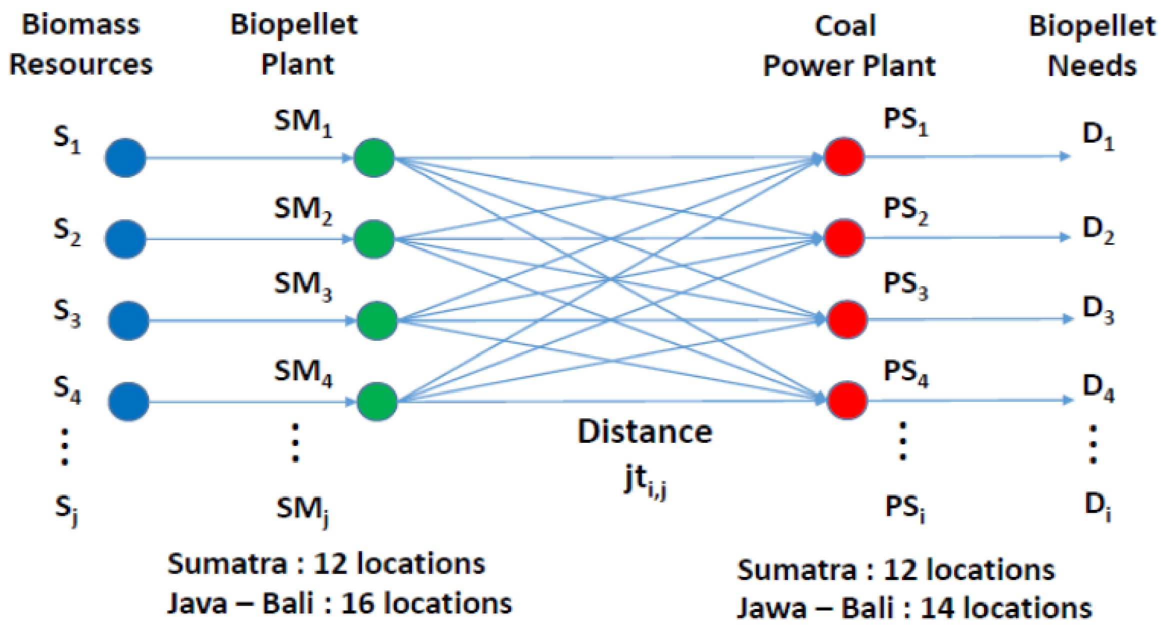
The distance between supply sources and demand points and the associated transportation costs are calculated. Network analysis determines the optimal route for biomass transportation between regions. A mathematical model is developed that considers supply, demand, transportation costs, and other factors (e.g., market prices and regulations). Several scenarios are tested to understand how changes in supply, demand, or transportation costs might impact the trade potential. An interactive map shows the potential for biomass trade between regions, highlighting supply sources, demand points, and proposed transportation routes. Graphs are created to compare supply/demand in each region and trade projections.

The model is tested for various parameters (such as biomass price fluctuations or changes in infrastructure) to understand their impact on trade projections. Based on the analysis, recommendations are provided for developing the biomass supply chain between regions. This may include infrastructure improvements, incentive policies, or inter-regional cooperation.

3. Results and Discussion

3.1. Optimized Biomass Supply Chain Model for Co-firing in Coal-Fired Power Plants

The supply of agricultural waste biomass in Region Java (including Madura Island and Bali) and Region Sumatra (including the Riau Archipelago and Bangka Belitung Islands) is distributed across various areas with diverse material resources (rice, corn, cassava, palm oil, coconut, sugarcane, and rubber). Figure 3 illustrates the supply chain of biomass from agricultural waste. As discussed in the previous subsections, the biomass potential has been calculated and mapped, and the ideal storage locations have been determined for sorting and initial processing of biomass into semi-finished materials. Subsequently,



Where:

- **S : Supply**
- **D : Demand**
- **SM : Sumatra Manufacture/Biopellet Plant in the Sumatra Region**
- **PS : Coal Power Plant in Sumatra**

Figure 3. Illustration of biomass of agricultural waste supply chain.

the prepared biomass is transported to factories to be processed into pellets with characteristics similar to coal.

These pellets will then be delivered to PLTU as a mixed fuel (co-firing) under several scenarios, gradually starting from 5%, 10%, and so on. It is hoped that in the future, to support the NZE (Net Zero Emission) program, the pellet composition in co-firing at coal-fired power plants will increase further (additional research is needed to achieve compositions of 15%, 20%, 30%, and so on).

Several issues in the development of biomass for co-firing in PLTU include material availability (still reliant on natural biomass and competing with non-energy uses), supply stability (biomass locations are far from PLTUs with inadequate transportation infrastructure), and higher costs (compared to coal prices). These issues arise due to a biomass supply chain that has not been managed as a well-planned, directed, integrated, and sustainable system. Therefore, these supply chain issues must be addressed, and a biomass supply chain management system must be established. Conducting a supply chain analysis using a linear programming optimization formula is necessary. This supply chain optimization is key to ensuring efficiency, sustainability, and biomass availability as a co-firing fuel for coal-fired power plants, whose demand is increasing.

In examining the biomass supply chain, the primary factor requiring in-depth analysis is transportation costs, which are a significant determinant of biomass prices. The transportation system used in this calculation is land-based and utilizes trucks. The use of trucks assumes that there are no obstacles during transit. Based on data from Deliveree [43] and Logisticsbid [44], transportation costs are calculated at IDR 1,500 per ton per kilometer. This cost is assumed to apply uniformly across all regions in Java and Sumatra. Although inter-island transportation uses ships, such as from Java to Sumatra or Java to Bali and vice versa, the per-ton-per-kilometer cost remains the same (with negligible differences).

Therefore, the primary optimization issue depends on the distance parameter between biopellet factories and coal-fired power plants spread across these regions. Based on GIS mapping, Figures 4, 5, 6, and 7 illustrate the distribution and supply chain of biomass agricultural waste, biomass storage, biopellet plants, and coal-fired power plants in Java and Sumatra, while Figure 8 summarizes the locations of biopellet plants and coal power plants in the region.

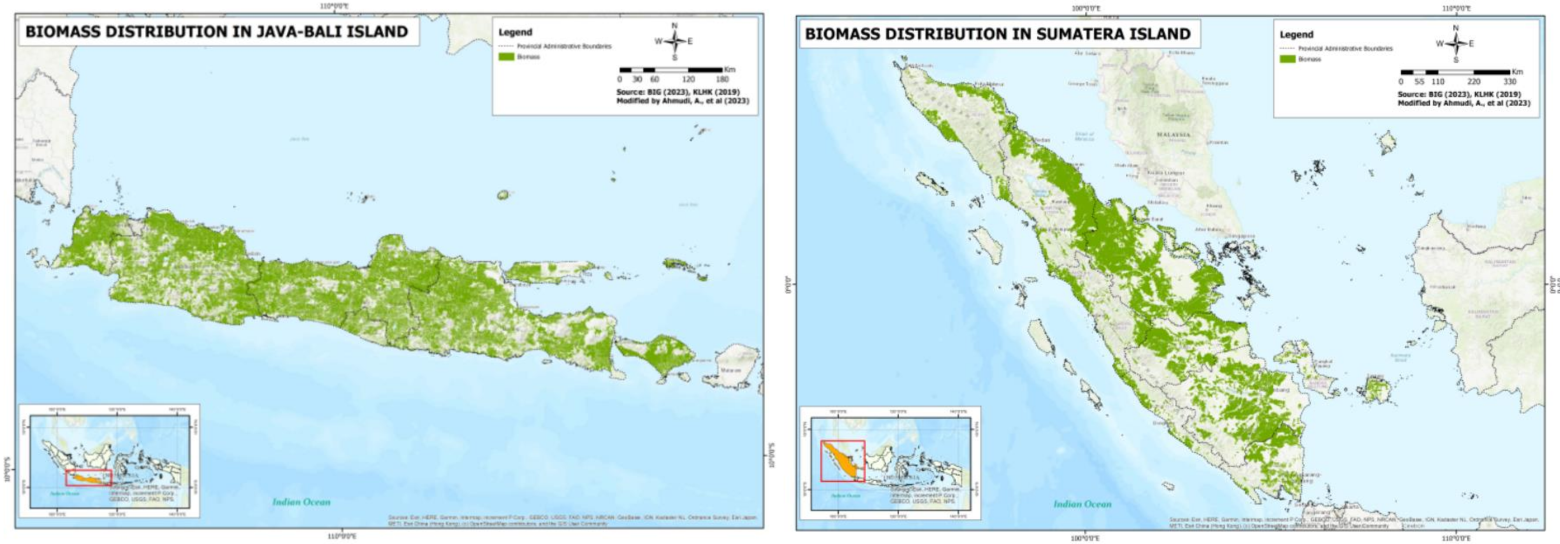


Figure 4. The distribution location of biomass agricultural waste in the region of Java and Sumatra.

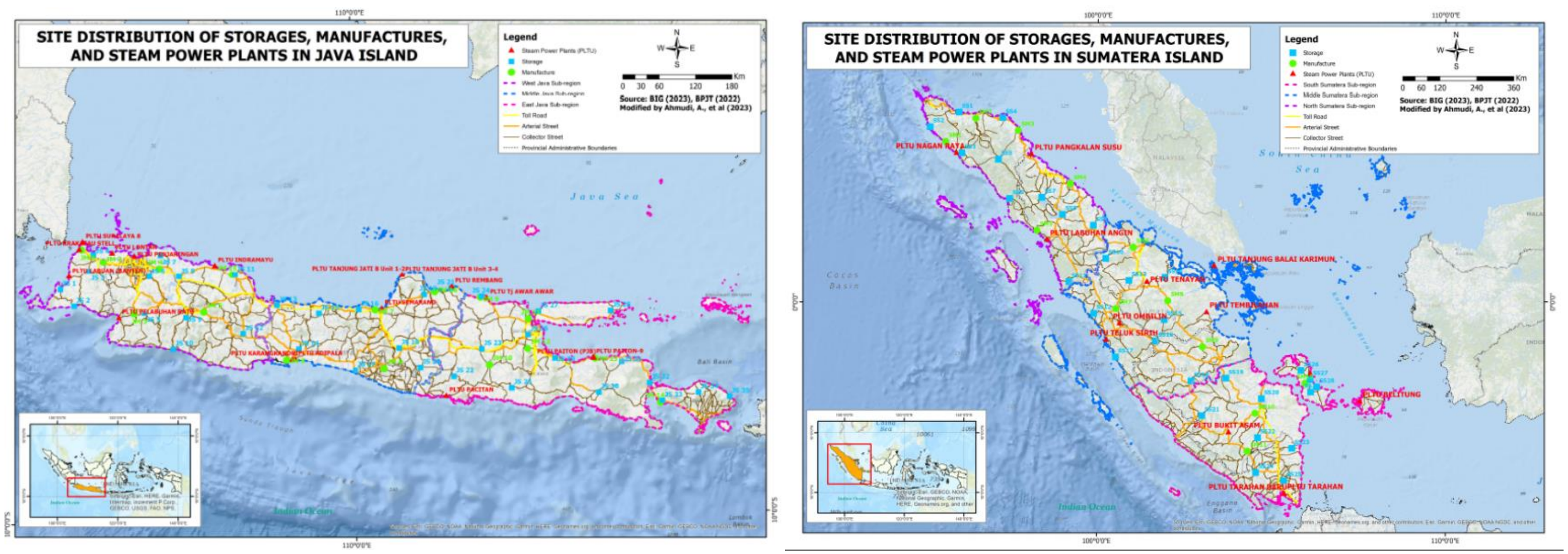


Figure 5. The distribution of biomass storage, biopellet plant dan PLTUs co-firing in the region of Java and Sumatra.

Figure 6. The supply chain map of biomass agricultural waste for electricity in the region of Java (Sub-region of Western Java, Central Java and Eastern Java)

Figure 7. The supply chain map of biomass agricultural waste for electricity in the region of Sumatra (Sub-region of Nothern Sumatra, Central Sumatra and Southern Sumatra)

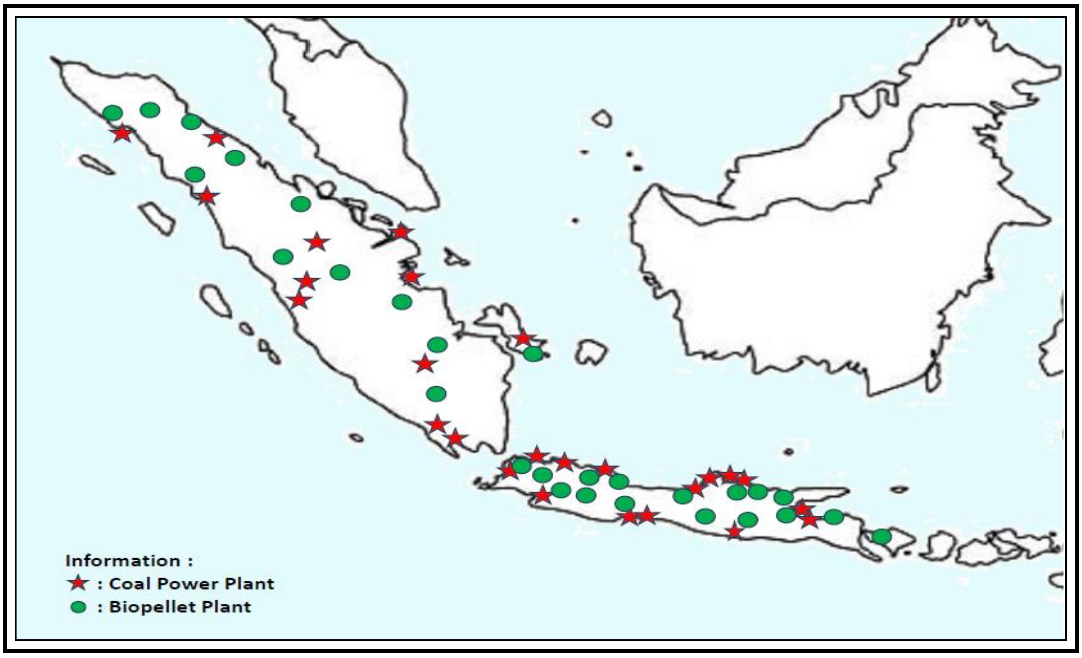


Figure 8. The location of biopellet plant and coal power plant in the region of Java and Sumatra.

3.2. Model Equation of Biomass Supply Chain

The supply chain optimization model using Linear Programming (LP) is used to determine the amount of biopellets (in thousand tons) to be delivered from factories to PLTU. The objective is to minimize transportation costs (in million Rupiah), expressed in this research as TC (Transportation Cost). The calculation results will provide the optimal allocation of biopellet supply with the most efficient transportation costs. The formulated equation is as shown in Equation 3:

$$Minimize\ TC = \sum_{i=1}^{N}\sum_{j=1}^{M}(Qt_{i,j} * ct_{i,j} * jt_{i,j}) \quad (3)$$

Where $Qt_{i,j}$ represents the quantity of bio pellets transported from factory location i to PLTU location j in thousand tons, $ct_{i,j}$ is the transportation cost in thousand Rupiah per ton per kilometer, $jt_{i,j}$ denotes the distance from factory location i to PLTU location j in kilometers, N is the number of bio pellet factories, and M is the number of PLTUs co-firing.

The constraint function ensures the model can be solved according to the intended objectives. Generally, the pellet demand for PLTUs must be greater than or equal to the supply from factories. Briefly, the constraint function equation can be expressed as shown in Equation 4, where Qs_i is the total quantity of biopellets shipped from factory i i in thousand tons, Qd_j is the total quantity of biopellets delivered to PLTU j in thousand tons, S_i represents the total production capacity of biopellets from factory i in thousand tons, and D_j denotes the total biopellet demand from PLTU j in thousand tons.

$$\begin{gathered} Qs_i = \sum_{j=1}^{M} Qt_{i,j} \\ Qd_j = \sum_{i=1}^{N} Qt_{i,j} \\ Qs_i \leq S_i \\ Qd_j \leq D_j \\ Qt_{i,j} \geq 0 \end{gathered} \quad (4)$$

3.3. Co-firing of Coal-Fired Power Plants (PLTU)

The utilization of biomass as a mixed fuel in the form of co-firing for PLTU is one option to support the achievement of renewable energy (RE) targets in the electricity sector. Biomass co-firing in coal-fired PLTUs is a technology that substitutes coal with biomass fuel at a certain ratio while maintaining the fuel quality and operational feasibility of the PLTU.

The planned co-firing potential will be implemented in 114 PLTU units across Indonesia, with a total capacity of 18.1 GW spread throughout the country, requiring approximately 9 million tons of biomass annually. This potential opens opportunities for communities to

Table 1. Biopellet requirements for co-firing coal-fired PLTUs in the Java region.

Symbol	Description	Coal Demand Without Co-firing (thousand tons/year)	Co-firing Program (5%)	
			Coal Demand (thousand tons/year)	Biopellet Demand (thousand tons/year)
PJ1	Labuan (Banten)	2,720.0	2,584.0	136.0
PJ2	Lontar	4,320.0	4,104.0	216.0
PJ3	Suralaya 8	2,960.0	2,812.0	148.0
PJ4	Suralaya Unit 1-4	5,760.0	5,472.0	288.0
PJ5	Indramayu	4,560.0	4,332.0	228.0
PJ6	Pelabuhan Ratu	4,800.0	4,560.0	240.0
PJ7	Adipala	3,040.0	2,888.0	152.0
PJ8	Rembang	2,880.0	2,736.0	144.0
PJ9	Tanjung Jati B Unit 1-2	6,080.0	5,776.0	304.0
PJ10	Tanjung Jati B Unit 3-4	6,080.0	5,776.0	304.0
PJ11	Pacitan	2,880.0	2,736.0	144.0
PJ12	Paiton-9	3,040.0	2,888.0	152.0
PJ13	Tanjung Awar Awar	3,200.0	3,040.0	160.0
PJ14	Paiton (PJB)	2,880.0	2,736.0	144.0
Total Demand of the Java Region		**55,200.0**	**49,704.0**	**2.760.0**

Where: PJ = Coal Power Plant in the Java Region; PJB = Pembangkitan Jawa Bali

Table 2. Biopellet requirements for co-firing coal-fired PLTUs in the Sumatra region.

Symbol	Description	Coal Demand Without Co-Firing (thousand tons/year)	Co-Firing Program (5%)	
			Coal Demand (thousand tons/year)	Biopellet Demand (thousand tons/year)
PS1	Nagan Raya	1,280.0	1,216.0	64.0
PS2	Labuhan Angin	1,312.0	1,246.4	65.6
PS3	Pangkalan Susu	2,240.0	2,128.0	112.0
PS4	Tenayan	1,280.0	1,216.0	64.0
PS5	Ombilin	848.0	805.6	42.4
PS6	Teluk Sirih	1,280.0	1,216.0	64.0
PS7	Tembilahan	128.0	121.6	6.4
PS8	Tanjung Balai Karimun	64.0	60.8	3.2
PS9	Bangka Baru	432.0	410.4	21.6
PS10	Belitung	240.0	228.0	12.0
PS11	Tarahan	1,248.0	1,185.6	62.4
PS12	Tarahan Baru	1,248.0	1,185.6	62.4
Total Demand of the Sumatra Region		**11,600.0**	**11,020.0**	**580,0**

Where: PS = Coal Power Plant in the Sumatra Region

participate in providing raw materials. Using biomass can encourage the efficient management of agricultural and industrial waste that has not been effectively utilized.

In this study, only the co-firing of coal-fired PLTUs in the Java Region and Sumatra Region is discussed. In the Java Region, there are 14 PLTUs, and in the Sumatra Region, there are 12 PLTUs with the potential for co-firing. Assuming a biomass blend in the form of biopellets at 5%, the potential biopellet demand in these regions is shown in the Table 1 and Table 2. The total annual biopellet requirement is 3,340 thousand tons.

3.4. The Supply of Biopellets from Biomass Agricultural Waste

Based on the previous calculations, Table 1, Table 2, and Table 3 show the potential biomass that can be processed into pellets. The annual production capacity of biopellets reaches 143,576 thousand tons, which can be considered more than sufficient compared to the existing demand. This table summarizes the coal and bio-pellet demand for co-firing in coal-fired power plants in the Sumatra Region under a 5% biomass co-firing scenario.

3.5. Optimization Results

The optimization results show that the supply of biopellets is abundant enough to meet the entire demand for co-firing in coal-fired PLTUs. The total transportation cost for delivering bio pellets amounts to 278,870.4 million Rupiah per year per factory. The cost comes from calculations using trucks, assuming that the transportation cost by truck is Rp 1,500 per ton per km, which is assumed to be the same for all regions in Java

Table 3. Availability of biopellet supply for co-firing coal power plants.

Region of Java		**Region of Sumatra**	
Symbol	**Biopellet Availability (thousand ton/year)**	**Symbol**	**Biopellet Availability (thousand ton/year)**
JM 1	4,211.0	SM 1	3,400.0
JM 2	4,211.0	SM 2	3,400.0
JM 3	4,211.0	SM 3	3,400.0
JM 4	4,211.0	SM 4	3,400.0
JM 5	4,211.0	SM 5	3,400.0
JM 6	7,296.0	SM 6	2,919.0
JM 7	7,296.0	SM 7	2,919.0
JM 8	7,296.0	SM 8	2,919.0
JM 9	6,220.0	SM 9	2,919.0
JM 10	6,220.0	SM 10	7,710.0
JM 11	6,220.0	SM 11	7,710.0
JM 12	6,220.0	SM 12	7,710.0
JM 13	6,220.0	-	-
JM 14	6,220.0	-	-
JM 15	4,211.0	-	-
JM 16	7,296.0	-	-
Production of the Jawa Region	91,770.0	Production of the Sumatra Region	51,806.0
Total Production of the Java and Sumatra Region			**143,576**

Where: JM = Java Manufacture/Biopellet Plant in the Java Region; SM = Sumatra Manufacture/Biopellet Plant in the Sumatra Region

Island and Sumatra Island. Although inter-island transportation uses ships, namely from Java Island to Sumatra Island and from Java Island to Bali Island, and vice versa, the cost per ton per km is still considered the same. Therefore, the main optimization issue depends solely on the distance parameter between the bio-pellet factory and the PLTU scattered across the region.

The distribution of biopellets from factories to coal-fired PLTUs is shown in the Table 4 and Table 5. From the optimization calculations, several factories were found to be unfeasible for supplying biopellets are SM2, SM4, SM6, SM9, SM10, SM11, JM4, JM5, JM7, JM8, JM11, JM12, and JM14. Meanwhile, some biopellet factories can supply bio pellets to multiple power plants at lower transportation costs, namely are SM7, SM8, SM12, JM1, JM13, and JM16. These bio-pellet factories are capable of producing bio-pellets that can meet the entire material requirement for co-firing at PLTU, in accordance with PLN regulations, which specify a minimum of 5% of the total coal requirement at the PLTU.

3.6. Sensitivity Analysis

The amount of bio-pellets available for co-firing in PLTU is abundant, so the prospects for inter-regional bio-pellet trade have not yet been fully realized. Sensitivity analysis can be conducted by assuming that bio-pellets produced in factories are not only for co-firing in coal-fired power plants but also for various other purposes, including the cement industry, fuel for industries previously using coal or wood pellets, and others. Bio-pellets are also used as an export commodity required for energy sources in various countries.

In more detail, bio-pellets as a renewable energy source is not limited to co-firing in coal-fired power plants. Bio-pellets, typically made from organic materials such as agricultural waste, wood, or other biomass residues, have beneficial applications in various sectors. Some of the uses of bio-pellets, besides co-firing in coal-fired power plants, include (1) as a source of energy for heating in households; (2) as an energy source for industries and factories; (3) for off-grid electricity generation; (4) as fuel for vehicles (biofuel); (5) as animal feed and compost fertilizer; (6) for waste processing and pollution reduction; (7) for agricultural applications as pesticides or fungicides; (8) for the development of plant care products; and other functions.

The quantity of biopellets available for co-firing in coal-fired PLTUs is abundant, indicating limited prospects for inter-regional biopellet trade. Sensitivity analysis can be performed by assuming that biopellets produced by factories are not solely for co-firing but also export as a commodity. The assumption made is that only 10% of the factory's total production capacity is available for co-firing. This study assumes that the biopelet factory could only release 10% of its production capacity for PLN co-firing. This policy is taken in response to PLN's price for biopellet that is still lower market price. Subsequently, re-optimization was performed, and the distribution of biopellets transported from factories to coal-fired PLTUs was analyzed.

Table 4. Distance between biopellet factory and coal power plant.

	PS1	PS2	PS3	PS4	PS5	PS6	PS7	PS8	PS9	PS10	PS11	PS12	PJ1	PJ2	PJ3	PJ4	PJ5	PJ6	PJ7	PJ8	PJ9	PJ10	PJ11	PJ12	PJ13	PJ14
SM1	86	618	588	1135	1063	1125	1426	1303	2008	2781	2144	2144	2194	2200	2149	2149	2382	2364	2607	2813	2771	2771	2910	3144	2951	3154
SM2	220	748	327	1051	1134	1197	1343	1056	2007	2716	2079	2079	2129	2135	2084	2084	2317	2299	2542	2748	2706	2706	2845	3079	2886	3089
SM3	377	559	139	863	946	1008	1154	868	1822	2527	1890	1890	1940	1946	1895	1895	2128	2110	2353	2559	2517	2517	2656	2890	2697	2900
SM4	600	302	202	563	688	750	854	765	1522	2227	1590	1590	1640	1646	1595	1595	1828	1810	2053	2259	2217	2217	2356	2590	2397	2600
SM5	472	61	388	607	506	568	899	1019	1451	2224	1587	1587	1637	1643	1592	1592	1825	1807	2050	2256	2214	2214	2353	2587	2394	2597
SM6	913	405	592	166	409	497	457	1155	1125	1830	1193	1193	1243	1249	1198	1198	1431	1413	1656	1862	1820	1820	1959	2193	2000	2203
SM7	943	436	813	205	69	157	489	1375	999	1771	1134	1134	1184	1190	1139	1139	1372	1354	1597	1803	1761	1761	1900	2134	1941	2144
SM8	1182	674	861	111	329	419	189	1314	857	1562	925	925	975	981	930	930	1163	1145	1388	1594	1552	1552	1691	1925	1732	1935
SM9	1419	912	1099	348	379	469	218	1090	634	1338	702	702	752	758	707	707	940	922	1165	1371	1329	1329	1468	1702	1509	1712
SM10	1737	1230	1509	758	765	855	628	776	319	958	321	321	371	377	326	326	559	541	784	990	948	948	1087	1321	1128	1331
SM11	1794	1286	1677	927	821	911	796	944	487	901	264	264	314	320	269	269	502	484	727	933	891	891	1030	1264	1071	1274
SM12	1943	1436	1743	993	971	1060	863	592	42	1259	622	622	672	678	627	627	860	842	1085	1291	1249	1249	1388	1622	1429	1632
JM1	2172	1640	1670	1123	1195	1133	832	955	250	751	114	114	64	70	19	19	252	234	477	683	641	641	780	1014	821	1014
JM2	2207	1675	1705	1158	1230	1168	867	990	285	199	149	149	99	36	64	64	209	192	435	640	599	598	738	971	779	971
JM3	2362	1830	1860	1313	1385	1323	1022	1145	440	354	304	304	254	166	219	219	229	39	455	660	619	618	758	991	799	991
JM4	2304	1772	1802	1255	1327	1265	964	1087	382	296	246	246	196	108	161	160	114	156	339	545	503	503	642	876	683	876
JM5	2436	1904	1934	1387	1459	1397	1096	1219	514	428	378	378	328	240	293	292	164	179	230	494	452	452	591	825	632	825
JM15	2456	1924	1954	1407	1479	1417	1116	1239	534	448	398	398	348	260	312	312	40	308	223	429	387	386	526	760	567	760
JM6	2640	2108	2138	1591	1663	1601	1300	1423	718	632	582	582	532	443	496	496	264	491	22	417	375	374	321	653	461	653
JM7	2686	2154	2184	1637	1709	1647	1346	1469	764	678	628	628	578	490	543	542	311	538	257	160	118	117	257	491	298	491
JM8	2820	2288	2318	1771	1843	1781	1480	1603	898	125	762	762	712	623	676	676	444	671	173	280	223	222	147	456	263	456
JM16	2809	2277	2307	1760	1832	1770	1469	1592	887	114	751	751	701	613	666	666	434	661	380	34	80	80	253	441	102	441
JM9	2975	2443	2473	1926	1998	1936	1635	1758	1053	280	917	917	867	779	832	832	600	827	441	54	167	167	237	279	16	279
JM10	2965	2433	2463	1916	1988	1926	1625	1748	1043	270	907	907	857	769	822	822	590	817	432	203	369	368	118	252	140	252
JM11	3038	2506	2536	1989	2061	1999	1698	1821	1116	343	980	980	930	842	895	895	663	890	504	159	442	441	229	180	96	180
JM12	3027	2495	2525	1978	2050	1988	1687	1810	1105	332	969	969	919	831	884	884	652	879	493	210	431	430	219	136	148	136
JM13	3177	2645	2675	2128	2200	2138	1837	1960	1255	482	1119	1119	1069	981	1034	1034	802	1029	643	333	581	580	369	5	271	5
JM14	3350	2818	2848	2301	2373	2311	2010	2133	1428	655	1292	1292	1242	1154	1207	1207	975	1202	816	506	754	753	541	178	444	178

Where: SM = Sumatra Manufacture/Biopellet Plant in the Sumatra Region; JM = Java Manufacture/Biopellet Plant in the Java Region; PS = Coal Power Plant in the Sumatra Region; PJ = Coal Power Plant in the Java Region.

Table 5. Biopellet Delivery from Factory to Coal Power Plant (thousand tons/year)

	PS1	PS2	PS3	PS4	PS5	PS6	PS7	PS8	PS9	PS10	PS11	PS12	PJ1	PJ2	PJ3	PJ4	PJ5	PJ6	PJ7	PJ8	PJ9	PJ10	PJ11	PJ12	PJ13	PJ14
SM1	64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM3	0	0	112	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM5	0	65.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM7	0	0	0	0	42.4	64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM8	0	0	0	64	0	0	6.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM12	0	0	0	0	0	0	0	3.2	21.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JM1	0	0	0	0	0	0	0	0	0	0	62.4	62.4	136	0	148	288	0	0	0	0	0	0	0	0	0	0
JM2	0	0	0	0	0	0	0	0	0	0	0	0	0	216	0	0	0	0	0	0	0	0	0	0	0	0
JM3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	240	0	0	0	0	0	0	0	0
JM4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JM5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JM6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	152	0	0	0	0	0	0	0
JM7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JM8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JM9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	160	0
JM10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	144	0	0	0
JM11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JM12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JM13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	152	0	144
JM14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JM15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	228	0	0	0	0	0	0	0	0	0
JM16	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	144	304	304	0	0	0	0

Where: SM = Sumatra Manufacture/Biopellet Plant in the Sumatra Region; JM = Java Manufacture/Biopellet Plant in the Java Region; PS = Coal Power Plant in the Sumatra Region; PJ = Coal Power Plant in the Java Region.

Table 6. Optimization results with the assumption of 10% biopellet availability.

	PS1	PS2	PS3	PS4	PS5	PS6	PS7	PS8	PS9	PS10	PS11	PS12	PJ1	PJ2	PJ3	PJ4	PJ5	PJ6	PJ7	PJ8	PJ9	PJ10	PJ11	PJ12	PJ13	PJ14
SM1	64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM3	0	0	112	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM5	0	65.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM7	0	0	0	0	42.4	64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM8	0	0	0	64	0	0	6.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM12	0	0	0	0	0	0	0	3.2	21.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JM1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	148	273.1	0	0	0	0	0	0	0	0	0	0
JM2	0	0	0	0	0	0	0	0	0	0	62.4	62.4	136	145.3	0	14.9	0	0	0	0	0	0	0	0	0	0
JM3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	240	0	0	0	0	0	0	0	0
JM4	0	0	0	0	0	0	0	0	0	0	0	0	0	70.7	0	0	0	0	0	0	0	0	0	0	0	0
JM5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JM6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	152	0	0	0	0	0	0	0
JM7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JM8	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JM9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22.4	0	0	0	0	160	0
JM10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	144	0	0	0
JM11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JM12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JM13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	152	0	144
JM14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JM15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	228	0	0	0	0	0	0	0	0	0
JM16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	121.6	304	304	0	0	0	0

Where: SM = Sumatra Manufacture/Biopellet Plant in the Sumatra Region; JM = Java Manufacture/Biopellet Plant in the Java Region; PS = Coal Power Plant in the Sumatra Region; PJ = Coal Power Plant in the Java Region.

The optimization results are shown in Table 6. The total transportation cost for one year amounts to 302,070.8 million Rupiah per year per factory. Compared to the previous results, costs increased 8.3% due to the scarcity of biomass sources. PJ8 (Java 8 Power Plant) receives its bio-pellet supply from two locations: JM9 (Java 9 Bio-pellet Factory/Plant) and JM16 (Java 16 Bio-pellet Factory/Plant).

4. Conclusions and Recommendations

4.1. Research Conclusion

This study calculates and maps the energy potential of agricultural waste biomass and develops a model (specifically from the supply chain aspect) for biopellet production as a co-firing fuel for PLTU in the Java Region (including Madura and Bali Islands) and Sumatra Region (including Riau Islands and Bangka Belitung Islands, representing the electricity conditions in Indonesia. Using agricultural waste biomass could pave the way for strengthening protected area management systems, contributing more to biodiversity conservation, sustainable development, energy resilience, and improving the welfare of farmers in Indonesia. This is particularly relevant for the Java Region (covering Banten, DKI Jakarta, West Java, Central Java, DI Yogyakarta, East Java, and Bali Provinces) and the Sumatra Region (covering Aceh, North Sumatra, West Sumatra, Jambi, Riau, Riau Islands, South Sumatra, Lampung, Bengkulu, and Bangka Belitung Provinces) in the future. The findings may also reference similar developments across Indonesia and other countries, with necessary adjustments based on local and contemporary conditions.

Based on previous calculations, the annual production capacity of biopellets reaches 143,576 thousand tons, which, compared to existing demand, can be considered more than sufficient. The optimization results show that bio-pellet resources are abundant enough to meet the overall demand for co-firing in coal-fired PLTUs. The total transportation cost for delivering biopellets is 278,870.4 million Rupiah per year. This spatially based study (MRA) using MCDA, GIS, and MILP has proven to generate a comprehensive analysis, including the development of complete data, maps, and information, which can serve as a reference for optimizing the development of biomass potential from agricultural waste for co-firing fuel in coal-fired power plants, particularly in the Java Region and Sumatra Region. Additionally, it provides recommendations for locating storage facilities and bio-pellet factories that can be constructed nearest and most accessible to PLTUs, along with their supply chains.

Research on the development of agricultural waste biomass based on spatial/multi-regional approaches using a combination of MCDA, GIS, LP, and MRA has proven to result in a comprehensive study that includes the development of complete and continuous data, maps, and information. This research is suitable to serve as a reference for optimizing the development of biomass potential from agricultural waste for co-firing fuel in PLTU. This aligns with the expectation that the biomass supply chain model, formed from an integrated process flow in agricultural waste biomass development—such as calculating potential biomass and mapping its distribution, determining the best locations for biomass storage and bio-pellet factories, creating an optimization model for the supply chain based on transportation costs, and conducting multi-regional biomass development analysis with inter-regional trade—will facilitate the effort to meet the bio-pellet supply needs for coal-fired power plants with more competitive prices and controlled distribution times, thereby promoting the long-term development of the biomass industry.

This research also demonstrates that relevant policies based on sustainable innovation must be developed to make biomass energy utilization more effective and efficient. From the outset of this study, the researcher formulated the hypothesis that "if" an optimized biomass supply chain model can be used to create minimum transportation cost scenarios to achieve maximum economic feasibility as a reference for developing agricultural waste biomass industries, then the bioenergy industry will become more viable and develop rapidly. The results proved that using GIS, MCDA, and LP provides a solution for creating a biomass supply chain (BSC) model that enables efficiency and effectiveness in balancing the biomass supply/demand for electricity and other uses.

4.2. Recommendation for Research Development

It is important to be considered as a subject of study for the future development of biomass energy that the use of four methods, namely MRA, LP, GIS, and MCDA, has been discussed and can be demonstrated from the results of this study and further developed. This is regardless of whether similar approaches exist; however, as explained throughout the article, the combination of these methods has proven to provide a different approach and seems closer to real-world conditions.

Further research is needed to identify various types of agricultural waste with high potential for conversion into biomass, such as rice straw, corn cobs, rice husks, peanut shells, and others. Determining these wastes' physical and chemical characteristics (e.g., moisture content, ash content, carbon content, and calorific value) will be crucial for evaluating their effectiveness as fuel in co-firing. Developing methods to enhance biomass's calorific value and fuel quality, using processing technologies such as torrefaction or pelleting, can improve biomass fuel's energy density and consistency.

Further studies are also required on the environmental impacts of using agricultural biomass, including the potential changes in land use patterns (e.g., converting agricultural land to biomass production) and the sustainability of biomass use in the long term. Developing policies and technologies supporting the sustainable use of agricultural biomass, such as incentives for farmers who manage agricultural waste for biomass use or applying circular economy principles in biomass management, is essential.

Therefore, efforts to address some of the challenges that have emerged should be considered in future research related to the development of this model. As an improvement going forward, this study recommends that compliance with social, economic, and environmental criteria and adaptation to policies and regulations be emphasized. Consideration of climate change as a factor exacerbating uncertainties in the complexity of the Biomass Supply Chain (BSC) should also be included. Additionally, it is suggested that regulatory targets be achieved through environmental restrictions, addressing increasingly challenging emissions control issues.

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