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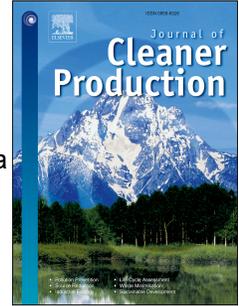
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An investigation of the environmental sustainability of palm biomass supply chains via dynamic simulation modeling: A case of Malaysia

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Abstract

With the ever-increasing need for clean and accessible energy sources, biomass has long been considered as a potential prospect. Malaysia is one of the leading suppliers and has the largest palm oil plantation in the world. Therefore, biomass from the palm oil industry appears to be a very promising alternative source of raw materials, including for renewable energy, in Malaysia. However, ensuring the environmental sustainability of the biomass supply chain (BSC) is one of the major challenges faced by the biomass industry. Therefore, this paper aims to assess the effect of changing the efficiency of transportation technology (TT) and production technology (PT) on the environmental sustainability of the palm oil BSC. We developed a dynamic simulation model to explore the greenhouse gas (GHG) emissions for 50 years (2000-2050) for three palm biomass suppliers (Johor, Perak and Pahang) in Malaysia. Results show that supplier in Perak produced the highest rate of GHG emissions in the whole system. Also, suppliers in Johor and Perak had the highest GHG emissions with 180-240 million tonnes (mt) CO₂ equivalent (CO₂e) and 375-400 mt CO₂e, respectively, from transportation of empty fruit bunches (EFB) product. In terms of production, the supplier in Perak had the highest (and constant value) of GHG emissions (up to 160 mt CO₂e). The analysis shows that the supplier in Pahang generated the lowest level of GHG emissions. Our findings suggest that improvement of the transportation and production efficiency of BSC should be the priority to work towards the sustainable development of the palm biomass industry.

Keywords: Biomass supply chain (BSC); Environmental aspect; Dynamic model; Palm oil; Sustainability; Malaysia

1. Introduction

Global warming (GW) has become one of the most crucial problems in the world. International communities are working towards reduction of greenhouse gas (GHG) emissions, which are believed to accelerate GW (Zahraee et al., 2018a). Hence, the development of renewable and sustainable energy sources plays a leading role to decrease GHG generation, especially in replacing fossil fuels (Zahraee et al., 2016). Biomass is one of the largest renewable and versatile energy sources used in combined heat and power (CHP) generation and transportation systems (Rentizelas et al., 2009). It is also the primary source of energy for nearly 50% of the world population (Zahraee et al., 2016). Biomass is developed from all plants and plant-derived substances, such as animal manure and sugar, as well as oil crops that are already being used for energy generation and nutrition (An et al., 2011).

In the past decade, the number of countries using biomass for the production of energy has increased rapidly, making biomass an attractive and promising option compared to other renewable energy sources. Biomass may be used for energy production at various scales, including large-scale power generation, CHP, or small-scale thermal heating projects at governmental, educational or other commercial facilities (Zahraee et al., 2016). Thus, the global use of biomass for energy has increased continuously in recent times (Loh, 2017). Recently, significant increases in the commercialization process of the biomass industry has been considered by governments, such as the United States, Brazil, Malaysia, and those of many European countries. The attempt has been made to increase the use of biomass as an alternative to fossil fuels.

Biomass is ample in nature, and generally spreads globally. Presently, million hectares of land in Malaysia are occupied by palm oil plantation generating huge quantities of biomass. In this

context, Fig. 1 shows the types of biomass resources in Malaysia. Palm oil industries appear to be a very promising alternative as a source of raw materials, including for renewable energy, in Malaysia. Development of the biomass industry in Malaysia is hampered because of issues such as limited traditional participation of small medium enterprises (SMEs) in low-value biomass utilization (Loh, 2017). The Malaysian government has implemented some action plans and energy policies for encouraging the use of biomass for power generation (e.g., Fifth Fuel Policy and 2030 target of Renewable Energy Policy and Action Plan) (How and Lam, 2017; Eusoff, 2018). Palm oil biomass resources was the largest export (19.9 million tonnes (mt)) from Malaysia in 2017 (Loh, 2017).

Fig. 1. Biomass resources in Malaysia (Agensi Inovasi Malaysia, 2011)

With the growth of palm oil production in Malaysia, the amount of residue generated has correspondingly increased. One hectare of palm oil plantation can produce about 50–70 tonnes of biomass residues (Umar et al., 2014). Therefore, the palm oil industry is currently producing about 50 mt of dry palm oil residues per year and will reach 100 mt per year by 2020 (Agensi Inovasi Malaysia, 2011). The Malaysian government has tried to promote renewable energy sources instead of conventional energy sources—such as coal, oil, and gas—to enhance energy security (Umar et al., 2014). The world's conversion from conventional energy sources to renewable energy is vital progress to support future generations (Shafeeyan et al., 2015). On the other hand, carbon balance for palm oil biomass utilization is a significant measurement for sustainability of palm biomass. When doing such carbon-cycle calculation, the release of carbon dioxide (CO₂) and other GHGs during the transport and production of palm oil biomass must be accounted for, showing that the distance in which the biomass has to be transported to power

generating plant may be an important factor (Umar et al., 2014). It is important to ensure that palm oil biomass delivered is sustainable. Roundtable on Sustainable Palm Oil (RSPO) in Malaysia, is established for sustainability of the palm oil plantation/industry. RSPO defines sustainable palm oil production as legal, environmentally appropriate, having socially beneficial management and operations, and economically viable (Nesadurai, 2013).

Malaysia needs to have an effective and sustainable source of energy to meet the increasing demand for energy as well as to reduce emissions of CO₂ and other GHGs while ensuring energy security. It should be noted that in a country like Malaysia, where palm oil biomass can be easily produced, the use of renewable energy is still very low. Hence, to handle this issue, designing a sustainable supply of good quality biomass raw material needs investigation and progress to streamline all stages of the biomass supply chain (BSC).

Some research that is in line with the Tenth Malaysia Plan has been conducted to enhance the development of the BSC industry in Malaysia. To maximize the profit and minimize the CO₂ emissions of BSC in West Malaysia, Lam et al. (2013) and Ng et al. (2013) had introduced a two-stage optimization model. Also, Tang et al. (2015) had developed a game theory technique to find the best strategy of palm biomass industries in Malaysia. Another study had investigated the effect of transportation cost on investment waste by applying a linearized cost function (How et al., 2016).

All the above investigations address important considerations of the biomass industry, but most of them do not consider the comprehensive sustainability concept in BSC models. Related to environmental sustainability, achieving low or zero GHG emissions, and achieving environmental protection, are becoming increasingly important for the biomass industry in Malaysia. Addressing sustainability issues in BSC models enables decision makers to reduce risk

and take advantage of the opportunities that sustainable BSC models present. Despite these benefits, there are very few investigations that have been carried out to handle this key issue of sustainability in the biomass industry. Therefore, it is important to assess and analyze the entire life cycle of the GHG emissions of biomass production and transportation from “cradle to gate” for main suppliers in Malaysia.

This paper aims to assess the effect of certain interventions on the environmental sustainability of the palm oil BSC. It is structured as follows. The next section presents a literature review. It is then followed by objective and scope of the study. Materials and methods adopted for the study are presented next. We then discuss the results. Finally, the paper concludes with a key summary of findings and recommendations for future study.

2. Literature review

2.1. Biomass supply chain

The BSC involves various activities, such as cultivation, harvesting, preprocessing, transportation, handling, and storage (Fig. 2). They include specific activities that require various resources (Mafakheri and Nasiri, 2014). Modeling tools are required to deal with the complexity in the design of such chains. The dynamics of the chain and decision variables—such as the amount harvested (which crop, where, when, what amount), the flow of the network (values transported), the safe storage level, and the essential resources (labors, harvesting equipment, vehicles, energy)—are significant to determine in line with total cost.

Fig. 2. Biomass supply chain network (Sokhansanj et al., 2009)

2.2. Simulation modeling of the biomass supply chain

Computer simulation is one of the most effective approaches due to its capability and flexibility in simulating and evaluating static and dynamic systems, considering the uncertainty in and variability between systems—such as production line (Hatami et al., 2014; Zahraee et al., 2018b), port and transportation industry (Shahpanah et al., 2014), supply chain management (Golroudbary and Zahraee, 2015), healthcare system (Zahraee et al., 2015), construction industry (Zahraee et al., 2014b), and building energy (Zahraee et al., 2014a)—none of which are easy to model.

Simulation is one of the important approaches in BSC studies. It has been principally applied to model the logistics of the BSC and calculate the amount of delivered biomass to a bioenergy plant and the related logistics costs. Initially, simulation modeling was applied to schedule farm activities such as the choice of forage machinery on a dairy farm (Russell et al., 1983), the assessment of technologies or management practices in forage systems on dairy farms (Savoie et al., 1985), planning of labor and equipment for wheat harvesting (Elderen, 1987), and scheduling of hay-harvesting equipment (Axenbom, 1990). To achieve the optimal utilization from forest biomass, a computational stochastic model was adopted by Gallis (1996). Indeed, it has been pointed out that the straw handling model (SHAM) is one of the most useful simulation models created for designing a delivery system for biomass (Nilsson, 1999).

The SHAM model was then adapted by (Nilsson and Hansson, 2001) to integrate a new kind of crop known as reed canary grass (RCG). The investigation of applying RCG, as well as straw and oil, as feedstock in regional heating plants had demonstrated a decrease of around 15-20% in the total delivery cost when the mix of straw and RCG was applied in appropriate proportions instead of using only straw. Hansen et al. (2002) proposed another simulation model for

investigating a sugar harvest and mill delivery system in South Africa. Following that, Huisman (2003) also developed another simulation model to determine the minimum cost of the BSC by choosing the optimum harvesting and storage system for each energy crop. However, in that study, detailed information regarding the simulation model that helps to identify the optimum supply chain is not explained and only the framework of the simulation model is discussed.

A few more simulation investigations have been conducted on other agricultural productions, such as corn grain by Arinze et al. (2001) and Sokhansanj et al. (2003). They applied the simulation modeling to investigate the changes in the quality of potash fertilizer and alfalfa cubes during storage and transport. Sokhansanj et al. (2006) developed the Integrated Biomass Supply Analysis and Logistics (IBSAL) simulation model to demonstrate the various stages of biomass collection, storage, processing, and transport. It was applied to analyze the supply logistic system for a variety of crop residues, such as corn stover, cereal straw, and grasses like switch grass.

On the other hand, as cited in Sokhansanj and Fenton (2006), Sokhansanj et al. (2006), Sokhansanj et al. (2008), Sokhansanj and Hess (2009), Sokhansanj et al. (2009), Stephen (2008), and Stephen et al. (2010), the IBSAL can be applied to various kinds of biomass and logistic alternatives. The IBSAL calculates the loss of dry matter as biomass, and evaluates the effect of preprocessing modules like pelletizing and briquetting on the logistics and delivered feedstock quality. It also considers the machine breakdowns as an operational efficiency.

Ravula et al. (2008) used the discrete-event simulation model on the transportation system of cotton gin to schedule the trucks in the biomass logistic system. The Idaho National Laboratory (INL) and the U.S. Department of Energy (DOE) (Hess et al., 2009) also created a simulation model used to calculate the cost of the herbaceous lignocellulosic BSC for biofuel production. Their model included a plant the size of 800,000 ton/year, and a feedstock supply radius of 105

km for switch grass and 80 km for stover. Based on their results, the cost target of \$34.7/dt for DOE was not achieved in the conventional bale and pioneer uniform supply system because the average costs of delivery and logistics (\$/dt) for stover, switch grass, and corncob were \$55.4/dt, \$49.6/dt, and \$68.9/dt respectively. A sensitivity analysis was performed to show that improvement in biomass properties and equipment efficiency could result in a cost-effective bale stover supply chain system (Hess et al., 2009). It should be noted that all of these models, IBSAL and SHAM included, did not provide a schedule and plan that satisfied the daily demand. Moreover, the distance between the farms was assumed constant.

Simulation modeling was also applied to find the location of satellite storage sites in the BSC. Cundiff et al. (2009) applied the simulation modeling to find the transportation distance from the production plants to the satellite storage and the number of satellite storage locations in the supply chain. The results indicated that, based on the total operating time, the desirable hauling distance for bales is 3.2 km (2 mi) from a 16-ha field to the satellite storage.

Zhang et al. (2012) created a simulation model to study the woody residue supply chain. To achieve this goal, a simulation model of the biofuel supply chain was constructed using the Arena software and graphical user interface. This model included basic supply chain activities such as biomass harvesting/processing, on-site storage, and transportation. The delivery feedstock cost, GHG emissions, and energy consumptions were considered as the indicators to evaluate performance. In another recent study, Windisch et al. (2013) used a methodological framework of business process mapping to evaluate two forest BSCs in various operational environments in Finland and Germany to recognize business processes and stakeholders that make up the supply chains. In addition, discrete-event simulations were applied to estimate the work time cost for managerial organizational tasks for each of the supply chains (Windisch et al.,

2013). Another investigation presented the modeling of a typical biomass production chain using the computing platform known as SIMEVENTS (Pinho et al., 2016).

In the latest works, discrete-event simulation was used to investigate how new innovative chipper and vehicle types with increased chip carrying capacity would affect the cost and energy efficiency of the forest chip supply chain (Prinz et al., 2019). Munasinghe et al. (2019) conducted an evidenced-based analysis of sustainability of crude palm oil (CPO) supply chain in Para, Brazil. A dynamic simulation model was developed to assess the sugarcane supply chain under three strategies: chopping, baling, and integral harvesting. It was found that integral harvesting is the best strategy for supply of the residues in terms of cost (5.90 USD/dry t), energy inputs (56.89 MJ/dry t), and CO₂ emissions (4.18 kg CO₂/dry t) (Lozano-Moreno and Maréchal, 2019). Akhtari et al. (2019) used the AnyLogic software to develop a dynamic simulation model to compare demand fulfilment, cost, and emissions of a forest-based BSC for two inventory systems by considering multiple conversion facilities that use different types of biomass.

3. Objective and scope of study

From the reviewed literature, it can be found that simulation modeling is a useful method to evaluate the BSC by examining scenarios and circumstances. However, there is a lack of investigation related to environmental analysis, particularly the dynamic trend of CO₂ emissions and other GHG emissions in the BSC. A practical and problem-solving approach to biomass utilization is essential to ensure environmental protection along with low or zero GHG emissions. Due to the interconnectedness of multiple influences and uncertainty in the palm BSC, the problem of achieving environmental sustainability is dynamically complex. Therefore, to fill this important research gap, this study develops a dynamic simulation model of the palm

oil BSC to evaluate the trend of GHG emissions from transportation and production. We adopted the System Dynamics modeling technique to solve this complex problem because it can capture behavior that emerges from the feedback loops between its elements and the delays in its dynamics. We constructed a dynamic stock-and-flow simulation model that focuses on accumulations, which cause delays, in the system. Specifically, we assess the effect of changing the efficiency of transportation technology (TT) and production technology (PT) on the environmental sustainability of the palm BSC, with a focus on minimizing the GHG emissions. The assessment takes a long-term perspective (2000-2050) that is consistent with the One Malaysia Biomass Alternative Strategy and the Malaysian Ministry of Energy, Science, Technology, Environment and Climate change's proposed target of 20% of the country's electricity to be generated from renewable sources by 2030, an increase from 2% currently (Eusoff, 2018).

Our proposed dynamic simulation tool can assist decision makers to quantify the uncertainty of 'what-if' scenarios towards the development of a coherent suite of policies that facilitate the adoption of less-GHG-intensive strategies related to the production and transportation technologies of the BSC. Specifically, the contributions from this study are as follows:

- The dynamic simulation model estimates the GHG emissions from transportation and production in the BSC to design an effective sustainable strategy for the improvement of the biomass industry in Malaysia. The viability of the proposed model is tested via a case study of the BSC in Malaysia.
- The robustness of the model is demonstrated via sensitivity analysis by analyzing the effect of changes in the efficiency of TT and PT on the GHG emissions for three main suppliers of palm biomass in Malaysia for the time period of 2000-2050.

- From the results from the model, several barriers to the palm biomass industry development in Malaysia are discussed. Also, strategies to reduce these barriers are presented.

4. Materials and Methods

4.1. Case study

Fig. 3 shows the map of two regions of Malaysia called Peninsular Malaysia to the west and East Malaysia to the east. The main regions of palm oil plantation and empty fruit bunches (EFB) products are in the Peninsular that includes three main states of Malaysia: Johor, Pahang, and Perak. Hence, only these three states are considered for EFB collection points. In this study, we assume Johor, Pahang, and Perak as suppliers 1, 2, and 3, respectively. Fig. 4 shows the distribution of palm plantation in Malaysia. Table 1 provides the available amount of the EFB biomass feedstock for the three selected areas (Malaysian Palm Oil Board, 2016).

Fig. 3. Map of Malaysia, including the main biomass supplier in Peninsular Malaysia

Fig. 4. Distribution of palm plantation in Malaysia

Table 1 Biomass feedstock availability for selected areas

4.2. Data collection

The required data were obtained from various sources, including three case studies in Malaysia (which consider Johor, Pahang, and Perak) by the authors along with existing related literature (Malaysian Palm Oil Board, 2016; Murillo-Alvarado et al., 2015; Ng and Ng, 2013; Zhang et al., 2013; Zheng et al., 2014). The BSC in Malaysia is investigated by considering the environmental aspect as it relates to the sustainable development goals. Using the System Dynamics method, introduced by Forrester (1997), the biomass flow and GHG emissions between 2000 and 2050 are analyzed. The analysis focuses on the complex inter-relationships between the various

suppliers, considers various transportation modes (truck, train, and pipeline), and various production stages. This quantification is a step toward improved selection of suppliers by examining the emissions of the raw materials supply.

4.3. Dynamic model of the biomass supply chain

A System Dynamics model represents a system under study as a set of stocks and flows. In the stock-and flow-model, state changes occur continuously over time. It is possible to define the relationships among the variables and analyze the dynamic characteristics between them in the model. Those relationships are used to establish mathematical equations to run simulations. We used AnyLogic (University 8.3.3) software to simulate the system because it is a leading simulation modelling software for supply chain management. This software has been used in many studies that model and simulate the stages of the supply chain, including some that analyse environmental sustainability (El Wali et al., 2018; Rahimpour Golroudbary et al., 2019a; Rahimpour Golroudbary et al., 2019b). This software is designed for modeling one or more quantities that change over time. In addition, it provides a graphical interface for modeling complex environments, the opportunity to test and explore scenarios, as well as the opportunity to observe system behavior over time at any level of detail. Also, it provides the opportunity for more precise forecast by capturing the details of known processes. In our study, AnyLogic is used to provide a flexible approach for decision makers to understand how complex relationships in the EFB BSC work under a wide range of ‘what-if’ scenarios with system uncertainties.

Based on Fig. 2 (the BSC network), by identifying the key variables and their interactions with each other throughout the life cycle stages of biomass, a primary structural model is designed and simulated. The structural simulation model refers to the details for analyzing relationships among every life cycle stage of biomass and variables that have the highest impact on the

behavior of the system. Long-term environmental supply chain structure planning has an influential effect on environmental performance decisions (Altmann and Bogaschewsky, 2014). To enable a detailed analysis of this planning task, the time duration of the simulation is fifty years (2000-2050) in the present study. The simulation model is constructed by the building blocks categorized as stocks, flows, connectors, and converters (Fig. 5, 6, 7, and 8). Stock variables (symbolized by rectangles) are the state of the system and they accumulate the difference between input and output variables that come in to and go out of the box in the system. Flow variables (symbolized by valves) are the rate of change in stock variables over time. They represent those activities that fill or drain the stocks. Converters (represented by circles) are intermediate variables used for miscellaneous calculations. Finally, the connectors (represented by simple arrows) are the links representing the dependencies between variables within the model structure. Fig. 5, 6, 7 and 8, as samples, show the dynamic simulation model of dry long fiber, bio-composite, cellulose, carboxymethyl cellulose (CMC), glucose, bio-ethanol, bio-ethylene, hemicellulose, xylitol, xylose, briquette, high pressure (HP) steam, medium pressure (MP) steam, low pressure (LP) steam, and electricity, respectively. Table 2 presents the nomenclature for variables and parameters. The next subsection and Appendix (Table S1) describe all variables by their mathematical equations.

Table 2 Description of variables and parameters of the biomass simulation model (Production stages: dry long fiber, bio-composite, cellulose, CMC, glucose, bio-ethanol, bio-ethylene, hemicellulose, xylitol, xylose, HP steam, MP steam, HP steam, and electricity).

Fig. 5. Simulation model for dry long fiber and bio-composite

Fig. 6. Simulation model for cellulose, CMC, glucose, bio-ethanol, and bio-ethylene

Fig. 7. Simulation model for hemicellulose, xylitol, and xylose

Fig. 8. Simulation model for briquette, HP steam, MP steam, HP steam, and electricity

4.4. Mathematical formulation

In System Dynamics modeling, state variables change continuously over time. Differential equations are used to represent such continuous changes in state variables. The simulation model of a complex system incorporates three types of variables: (i) a stock that is a reservoir of a given resource, (ii) a flow that adjusts the level of stock through input and output flows, and (iii) an intermediate variable (auxiliary) that is a function of stocks (and constants or exogenous inputs) (Sterman, 2000).

The dynamic behavior of the BSC is implemented by a set of differential or integral equations. Here we present the main formulas used in calculating material and GHG flows. All equations derived from the main formulas and the details of the model are given in Appendix, Table S1. Three main suppliers—supplier 1: EFB collection in Johor, supplier 2: EFB collection in Pahang, and supplier 3: EFB collection in Perak—are considered to supply the raw material. In the material flow, the behavior of Stock (t) in the time period of t_0 - t , where t_0 is the initial year considered and t is the final year (equation 1), is given by a time integral of the net inflows of input rate ($I_R(t)$) minus the net outflows of output rate ($O_R(t)$) (equation 2).

$$\text{Stock}(t) = \int_{t_0}^t (I_R(t) - O_R(t)) dt + \text{Stock}(t_0) \quad (1)$$

$$I_R(t) = f(\text{Stock}(t), V(t), P); O_R(t) = f(\text{Stock}(t), V(t), P) \quad (2)$$

where, $V(t)$ is an auxiliary variable in time t , and P represents constant input parameters. For example, in the biomass model, the stock of *dry long fiber* $\text{DLF}_S(t)$ has an input flow of *dry long fiber production* $\text{P}_{\text{DLF}_R}(t)$, which depends on the auxiliary variable *total supply of raw materials* $\text{TS}(t)$, which depends on the auxiliary variables *blended EFBs supplied by each supplier* $\text{EFB}_{\text{Si}}(t)$, which depends on the constants *production of fresh fruit bunch by each supplier* P_{Si_F}

and production of palm empty fruit bunch by each supplier P_{Si_P} . All input parameters are given in Appendix, Table S1.

The climate change problem is fundamentally due to the ‘stock’ of emissions that builds up in the atmosphere. The combustion of fossil fuels for energy contributes to emissions, of which CO_2 is the most common GHGs. In this study, two main sources of pollution are considered: transportation and production processes.

Various types of transportation—train, truck, and pipeline—are simulated by the model. It should be noted that there were no emissions from pipeline transportation. Based on data collected, each transportation mode in the system has its own GHG emissions level that varies with distance travelled and the CO_2 equivalent (CO_{2e}) coefficient in each process. The GHG emissions of each life cycle stage follows equation 3:

$$CO_{2_{x,m}}(t) = T_m(t) \times \sum_{n=1}^N \sigma_{n,m}(t) \quad (3)$$

where, $CO_{2_{x,m}}(t)$ is the GHG emissions of stage x at time t , $x= 1,2,\dots,N$ represents each life cycle stage of the BSC from mining to end product, and $m = 1, 2, 3$ is the type of transportation. In the model, we consider train and truck to calculate the amount of pollution from transportation. $T_m(t)$ corresponds to the emission coefficient from each type of transportation based on tonne of biomass transported. $n= 1,2,\dots,N$ corresponds to the different flows of material required or produced in the process in time t , and $\sigma_{n,m}(t)$ is the amount of material in the life cycle stage from each flow at time t .

Through the production process, the dynamic behavior of GHG emissions from three main sub-systems is simulated. These sub-systems produce pre-processed products such as dry long fiber, bio-compost, activated carbon, cellulose, hemicellulose, lignin, briquette, pellet, and torrefied pellet; intermediate products such as bio-composite, CMC, glucose, xylose, bio-resin, HP steam, xylitol, bio-hydrogen, bio-methanol, bio-ethanol, bio-syngas, bio-oil, and bio-char; and final products such as ammonia, formaldehyde, and bio-ethylene. The mathematical formulation is given in equation 4:

$$CO_{2,x,p}(t) = f_p(t) \times \sum_{n=1}^N \gamma_{n,p} * \sigma_{n,p}(t) \quad (4)$$

where, $CO_{2,x,p}(t)$ is the GHG emissions of stage x at time t , $x = 1, 2, \dots, N$ represents each life cycle stage of the BSC from mining to end product, and $p = 1, 2, 3$ is the sub-systems considered in the model: pre-processed, intermediate, and final. $f_p(t)$ corresponds to the emission coefficient for each flow based on one tonne of product produced. $n = 1, 2, \dots, N$ corresponds to the different flows of material required or produced in the process at time t , $\gamma_{n,p}$ is conversion factor of materials in the flow, and $\sigma_{n,p}(t)$ is the amount of material in the life cycle stage from each flow at time t .

4.5. Model Validation

The validity of a model indicates the suitability of the model in serving its purpose. To build confidence that the model is reliable, known values for variables such as the production rates of fresh fruit bunches (FFBs) by the various suppliers (Johor, Pahang, and Perak) were used. Differences between the results obtained from the model and experimental data of the above-mentioned variables on average amounted to 4.5, 2.5, and 1.1%, respectively. The results of validation and calculation of the error of the model are presented in Table 3.

Table 3 Calculation of the biomass model error

5. Results and Discussion

5.1. Emission trend for the three suppliers for 50 years

Interconnected environmental elements along with the interest to use biomass are two main issues that must be considered to utilize biomass for energy generation. The benefits of any biomass energy generation should be evaluated and analyzed together with some critical sustainability concerns and environmental indicators, such as carbon footprint. For example, if a high amount of resources and energy are used during the biomass production, the balance of the whole energy system will result in energy losses instead of benefits. In addition, low or zero CO₂ emissions from biomass production and transportation can be obtained with proper conditions in place. Hence, the lifecycle CO₂ emissions and energy equilibrium of such a system should be analyzed carefully.

In this section, we try to measure the GHG of the EFB BSC system for the three suppliers, including any additional energy and resources consumed to grow, produce, and transport the biomass feedstock by rail or road. Fig. 9 shows the GHG emissions trend from production and transportation for 50 years, as obtained from the dynamic simulation model for the EFB BSC. As can be seen in the graph (a and c), supplier 1 (Johor) and supplier 3 (Perak) have the highest rate of GHG emissions from transportation (180-240 mt CO₂e and 375-400 mt CO₂e, respectively) in the whole EFB BSC. GHG emissions from production is highest for supplier 2 (Pahang), with a constant value of 160 mt CO₂e (Fig. 9 (b)), which is only slightly higher than the GHG emissions for supplier 1 and supplier 3. According to Fig. 9 (d), supplier 3 produced the highest rate of

GHG emission in the whole system. By contrast, supplier 2 generates the lowest level of GHG emission from 2000 to 2050.

The scale of these forecast increase points to EFB BSC CO₂ emissions being highly dependent on the transportation emission and relatively inelastic to changes in fuel prices. Although current data and tools to support GHG accounting for EFB BSC transport are inadequate to address emerging public policy analysis needs, these results enable suppliers to identify the relative CO₂ emissions intensity of production and transportation activities to develop new low GHG intensity growth plans, considering both costs and benefits.

Additionally, managers should investigate the optimal processing routes, optimal transportation mode, and optimal production rate to decrease the CO₂ emission from transportation in the future. Depending on the distance and load of biomass and CO₂ emissions, typical modes of transportation, which include truck or train, could be selected by suppliers. Therefore, we analyzed the CO₂ emissions percentage for the three main suppliers in terms of the current situation of EFB BSC activities. Fig. 10 shows that the average percentages of total emissions of train transportation are 57%, 61%, and 54% for suppliers 1, 2, and 3, respectively. The main reason behind the higher total CO₂ emissions of rail transportation generated by each supplier as compared to road transportation is the extensive use of rail transportation in many stages of the BSC in Malaysia. These stages include aerobic digestion, DLF production, extraction plant, briquetting plant, pelletization mill, torrefied pelletization, alkaline activation (activated carbon) plant, bio-resin, acid hydrolysis, enzymatic hydrolysis, xylitol, anaerobic digestion, fermentation plant, and pyrolysis. Suppliers also use truck transportation in many stages, such as bio-composite, fermentation plant, anaerobic digestion, boiler combustion, and gasification. As can be seen in Fig. 10, Perak supplier has the highest percentage of CO₂

emission from train as compared to other suppliers. These emission analyses can be used to improve transportation planning and develop regulations on a case-by-case basis, based on the transportation modes' fixed cost components (e.g., loading and unloading, and capital cost of rail cars) and variable cost components (e.g., fuel and operating costs). Such an application of the analyses, however, is outside the scope of the present study and is recommended for future study.

Fig. 9. GHG emissions trend from production and transportation for three suppliers for 50 years

Fig. 10. Average percentage of CO₂ emissions from truck and train

5.2. Scenarios for the efficiency of transportation technology and production technology

The dynamic models are often used to study the behavior of a system under changing conditions. The studies of the scenarios representing the various possible situations or interventions are especially useful in this case. The environmental problem with the suppliers of biomass in Malaysia is related to the low efficiency of TT and PT, leading to performance that fails to comply with the Feed-in-Tariff system; new 2030 target from Ministry of Energy, Science, Technology, Environment and Climate; and the One Malaysia Biomass Alternative Strategy. Therefore, sensitivity tests can assist decision makers to learn how changes in assumptions, investments, or system management effectiveness might alter the estimate of CO₂ impacts.

To address this issue, the proposed model is used to evaluate the impact of alternative scenarios of TT and PT efficiency on the environmental performance of the suppliers in years 2000-2050. The knowledge of this impact is essential for making the decisions aimed at green supplier selection. Table 4 presents the percentage of GHG reduction through eight defined scenarios. Three strategies are suggested to reduce the GHG emissions by each supplier. The best strategy for all suppliers would be 20% improvement of the efficiency of both TT and PT,

followed by the strategy of 20% improvement of TT and 10% improvement of PT. Also, supplier 1 may reduce 13% of GHG emissions through 10% improvement of TT and 20% improvement of PT. The same strategy would be suggested to supplier 2 for 14% reduction of emission. Supplier 3 may achieve 15% emission reduction by applying 20% improvement of TT and no change in its PT.

Table 4 Scenarios for changing the efficiency of TT and PT

The year-by-year major flows of CO₂ reduction for supplier 1 is shown in Fig. 11. From 2000 to 2050, there is a constant pattern that shows that the quantities of CO₂ reduction have increased by almost threefold (27%) by the 20% increase of efficiency of transportation and production technology simultaneously. Moreover, it can be concluded from the plots that TT has a larger effect than PT on the CO₂ emission for supplier 1.

Fig. 11. CO₂ emission changes from 2000 to 2050 for supplier 1

Fig. 12 shows that the CO₂ emissions decreased in any year from 2000 to 2050 by increasing the efficiency of TT and PT for supplier 2. In contrast with supplier 1, an increase in PT efficiency has a more considerable impact than an increase in TT efficiency on the CO₂ reduction. For example, the CO₂ reduction increased by 5% through an increase of only 10% in the marketable PT for further industrial production or processing.

Fig. 12. CO₂ emission changes from 2000 to 2050 for supplier 2

Fig. 13 shows that, in any year, there is a stable growing trend of CO₂ emissions reduction with an increase in efficiency of TT and PT. Overall, CO₂ emissions decreased around 20% from

scenario 1 to scenario 8 by increasing the efficiency of TT and PT. With a doubling of the efficiency of TT and PT, the CO₂ reduction increased by 5%. In addition, CO₂ emissions have been decreased nearly 8% from 2000 to 2050 by increasing the efficiency of TT twofold (from 10% to 20%).

Fig. 13. CO₂ emission changes from 2000 to 2050 for supplier 3

Based on the above results, it is clear that a reduction of the CO₂ emissions from logistic and transportation activities in BSC is achievable through changes in TT and PT efficiencies. To this end, suppliers should strengthen their targets for CO₂ emission reductions by developing environmental action plans for the future. We suggest some production and transportation action plans to decrease the CO₂ emissions, as follow:

- Reducing vehicle transportation by consolidating biorefineries would allow the managers to organize shipments to customers and reduce the number of trucks needed.
- Reduction in truck and train transport by incorporating external warehouses inside the factory would decrease the number of vehicles runs between biorefineries and storage locations.
- Enhancing truck and train loading efficiency ratios by optimizing packing boxes would allow a decrease in the number of vehicle trips.
- Shipping distances can be decreased by redesigning logistic routes to make a direct route to the final stops.

6. Conclusion

Although simulation modeling has been identified by researchers as a potential tool to evaluate the BSC by examining scenarios and circumstances, there is a lack of investigation related to

environmental analysis, particularly the dynamic trend of GHG emissions in the BSC. To fill this research gap, this study developed a dynamic simulation model of palm oil BSC to evaluate the trend of GHG emissions from transportation and production. We selected three biomass suppliers from Malaysia as a case study. Recently, Malaysian Ministry of Energy, Science, Technology, Environment and Climate Change has set a target of 20% of the country's electricity to be generated from renewable sources by 2030, an increase from 2% currently, to minimize GHG emissions.

From the dynamic simulation study of the EFB BSC in Malaysia considering three suppliers over 50 years, it was observed that the CO₂ emission trend varied substantially among the suppliers depending on the efficiency of TT and PT. For example, the suppliers in Johor and Perak have the highest rate of GHG emissions (between 180 and 240 mt CO₂e in Johor; between 375 and 400 mt CO₂e in Perak) from transportation in the whole EFB supply chain system. Likewise, GHG emission from the production for the supplier in Perak has the highest and constant value of 160 mt CO₂e. Additionally, the supplier in Perak produced the highest rate of GHG emission in the whole system. By contrast, the supplier in Pahang generates the lowest rate of GHG emissions. Therefore, coordinated efforts need to be made by the BSC industry to improve the transportation and production efficiency of the BSC. Our findings suggest that improvement of the efficiency of transportation and production components of BSC should be the starting point to work towards the sustainable development of the palm biomass industry. Although the current results are based on a specific case study, the proposed model in this paper could be modified and applied to other similar case studies of the palm oil biomass industry as well as to other biomass industries (e.g., woody biomass) where transportation and production technology are important components.

The methodology and findings from our study may help the decision makers of the biomass industries to make strategic decisions to select the best supplier by taking into account environmental selection criteria (e.g., CO₂ emissions). Further, it assists decision makers to conduct ‘what-if’ scenario analyses of the effect of the supplier’s location and transportation mode on the sustainability performance of the BSC. The presented optimization approach could be useful for decision makers involved in EFB BSCs. In future, it is suggested to further develop the model to optimize transportation criteria such as transportation type, vehicle numbers, and road routes based on the socio-economic analysis for different biomass industries.

Appendix

Table S1. Equations and calculation processes for the biomass supply chain model

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Competing financial interests

The authors declare no competing financial interests.

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Table 1 Biomass feedstock availability for selected areas

Biomass feedstock	Fresh Fruit Bunch (FFB) yield (Tonne/hectare)	Plantation area (Hectare)	FFB production (Tonne)	EFB productions (Tonne)
EFB collection 1 (Johor)	18	745,630	13,272,214	3,052,609
EFB collection 2 (Pahang)	15	732,052	11,149,151	2,564,305
EFB collection 3 (Perak)	18	397,908	6,971,348	1,603,410
Total	51	1,875,590	31,392,713	7,220,324

Table 2 Description of variables and parameters of the biomass simulation model

(Production stages: dry long fiber, bio-composite, cellulose, CMC, glucose, bio-ethanol, bio-ethylene, hemicellulose, xylitol, xylose, HP steam, MP steam, HP steam and electricity)

Variable	Term
$EFB_{Si}(t)$	Blended empty fruit bunches collection by supplier where i represents the supplier index
$TS(t)$	Total supply of raw materials by all three suppliers (Johor, Pahang and Perak)
$P_{DLF_R}(t)$	Dry long fiber production rate
$DLF_S(t)$	Dry long fiber stock
$S_i(t)$	Sales of product where i represents the product index
$P_{BC_R}(t)$	Bio-composite production rate
$BC_S(t)$	Bio-composite stock
$CO_{2_DLF_P}(t)$	GHG emissions (carbon dioxide equivalent) from dry long fiber production
$CO_{2_BC_P}(t)$	GHG emissions (carbon dioxide equivalent) from bio-composite production
$CO_{2_DLF_TSi}$	GHG emissions (carbon dioxide equivalent) from train transportation between empty fruit bunches collection by supplier and dry long fiber production where i represents the supplier index
$CO_{2_BC_T}$	GHG emissions (carbon dioxide equivalent) from truck transportation between dry long fiber production and bio-composite production
P_{Si_F}	Production of fresh fruit bunch by supplier where i represents the supplier index
P_{Si_P}	Production of palm empty fruit bunch by supplier where i represents the supplier index

C_i	Conversion factor for production stage where i represents the production index
$S_{DLF}(t)$	Capacity of sales for dry long fiber product
$S_{BC}(t)$	Capacity of sales for bio-composite product
e_i	Emission coefficient of production stage where i represents the production index
D_i	Distance between production stages where i represents the supplier index
T_i	CO ₂ emission factor of transportation between production stages where i represents the production index
$P_{C_R}(t)$	Cellulose production rate
$C_S(t)$	Cellulose stock
$P_{AHi_R}(t)$	Acid Hydrolysis production rate from stock where i represents the stock index
$P_{EHi_R}(t)$	Enzymatic hydrolysis production rate from stock where i represents the stock index
$P_{FPI_R}(t)$	Fermentation plant production rate from stock where i represents the stock index
$P_{ADi_R}(t)$	Anaerobic digestion production rate from stock where i represents the stock index
$P_{Xi_R}(t)$	Xylitol production rate from stock where i represents the stock index
$P_{H_R}(t)$	Hemicellulose production rate
$BG_S(t)$	Bio-gas stock
$X_S(t)$	Xylitol stock
$HC_S(t)$	Hemicellulose stock
$XY_S(t)$	Xylose stock
$P_{BET_R}(t)$	Bio-ethylene production rate from bio-ethanol stock
$BE_S(t)$	Bio-ethanol stock
$BET_S(t)$	Bio-ethylene stock
$P_{CMC_R}(t)$	Carboxymethyl cellulose production rate
$CMC_S(t)$	Carboxymethyl cellulose stock
$P_{Br_R}(t)$	Briquette production rate
$P_{BiCi_R}(t)$	Boiler combustion production rate from stock where i represents the stock index
$Br_S(t)$	Briquette stock
$P_{Pe_R}(t)$	Pelletization production rate
$P_{Py1_R}(t)$	Slow Pyrolysis production rate
$P_{Py2_R}(t)$	Fast Pyrolysis production rate
$P_{Gai_R}(t)$	Gasification production rate from stock where i represents the stock index
$S_C(t)$	Capacity of sales for cellulose product
$S_G(t)$	Capacity of sales for glucose product
$S_{xy}(t)$	Capacity of sales for xylose product
$S_H(t)$	Capacity of sales for hemicellulose product
$S_X(t)$	Capacity of sales for xylitol product
$S_{BG}(t)$	Capacity of sales for bio-gas product
$S_{BE}(t)$	Capacity of sales for bio-ethanol product
$S_{BET}(t)$	Capacity of sales for bio-ethylene product
$S_{Br}(t)$	Capacity of sales for briquette product

$S_{Pe}(t)$	Capacity of sales for pellet product
$S_{HPS}(t)$	Capacity of sales for HP steam product
$S_E(t)$	Capacity of sales for electricity
$S_{MPS}(t)$	Capacity of sales for MP steam
$S_{LPS}(t)$	Capacity of sales for LP steam
$CO_{2_{BR_P}}(t)$	GHG emissions (carbon dioxide equivalent) from bio-resin production
$CO_{2_{C_P}}(t)$	GHG emissions (carbon dioxide equivalent) from cellulose production
$CO_{2_{CMC_P}}(t)$	GHG emissions (carbon dioxide equivalent) from CMC production
$CO_{2_{HC_P}}(t)$	GHG emissions (carbon dioxide equivalent) from hemicellulose production
$CO_{2_{GS_P}}(t)$	GHG emissions (carbon dioxide equivalent) from glucose production
$CO_{2_{Xy_P}}(t)$	GHG emissions (carbon dioxide equivalent) from xylose production
$CO_{2_{Xi_P}}(t)$	GHG emissions (carbon dioxide equivalent) by xylitol production from stock where i represents stock index
$CO_{2_{ADi_P}}(t)$	GHG emissions (carbon dioxide equivalent) by bio-gas production where i represents anaerobic digestion index
$CO_{2_{FPI_P}}(t)$	GHG emissions (carbon dioxide equivalent) by bio-ethanol production where i represents plant index
$CO_{2_{BET_P}}(t)$	GHG emissions (carbon dioxide equivalent) by bio-ethylene production
$CO_{2_{Br_P}}(t)$	GHG emissions (carbon dioxide equivalent) by briquette production
$CO_{2_{HPS_P}}(t)$	GHG emissions (carbon dioxide equivalent) by boiler combustion 1, boiler combustion 2 and boiler combustion 3 toward HP steam production
$CO_{2_{LPS_P}}(t)$	GHG emissions (carbon dioxide equivalent) by LP steam production
$CO_{2_{MPS_P}}(t)$	GHG emissions (carbon dioxide equivalent) by MP steam production
$CO_{2_{E_P}}(t)$	GHG emissions (carbon dioxide equivalent) by electricity production
$CO_{2_{C_TSi}}$	GHG emissions (carbon dioxide equivalent) from train transportation between empty fruit bunches collection by supplier and cellulose production where i represents the supplier index
$CO_{2_{HC_TSi}}$	GHG emissions (carbon dioxide equivalent) from train transportation between empty fruit bunches collection by supplier and hemicellulose production where i represents the supplier index
$CO_{2_{G_T}}$	GHG emissions (carbon dioxide equivalent) from train transportation between glucose production and acid hydrolysis production
$CO_{2_{Xy_T}}$	GHG emissions (carbon dioxide equivalent) from train transportation between xylose production and enzymatic hydrolysis production
$CO_{2_{X_T}}$	GHG emissions (carbon dioxide equivalent) from train transportation between xylitol production and xylose production
$CO_{2_{ADi_T}}$	GHG emissions (carbon dioxide equivalent) from train transportation between bio-gas production and anaerobic digestion production where i represents anaerobic digestion index
$CO_{2_{FPI_T}}$	GHG emissions (carbon dioxide equivalent) from train transportation between bio-ethanol production and fermentation plant production where i represents plant index
$CO_{2_{HC_Ti}}$	GHG emissions (carbon dioxide equivalent) from train transportation between empty fruit bunches collection by supplier and briquette production where i represents the supplier index
$CO_{2_{BiCi_T}}$	GHG emissions (carbon dioxide equivalent) from truck transportation between pellet production and boiler combustion production where i represents the boiler combustion index

Table 3 Calculation of the biomass model error

Year	Historical data of FFBs production			Simulation model results		
	Johor (per1000 tonnes)*	Pahang (per1000 tonnes)*	Perak (per1000 tonnes)*	Johor (per1000 tonnes)	Pahang (per1000 tonnes)	Perak (per1000 tonnes)
2000	438	9,517	300	418	9,351	296
2001	12,676	12,445	299	12,110	12,050	296
2002	436	10,981	283	416	10,810	277
2003	9,693	8,053	300	9,257	7,834	296
2004	344	400	7,162	329	391	7,080
2005	11,185	10,249	300	10,680	10,030	297
2006	8,202	8,785	316	7,833	8,527	312
2007	9,693	369	283	9,257	361	280
2008	500	11,713	333	477	11,370	330
2009	505	430	317	482	417	311
2010	500	399	283	477	387	283
2011	531	10,249	300	507	9,928	299
2012	13,421	460	316	12,820	453	310
2013	616	622	340	588	609	339
2014	593	570	340	566	560	338
2015	14,913	573	359	14,240	564	354
2016	570	470	263	544	455	257
2017	656	564	354	626	551	352
2018	623	535	326	595	523	320
Ave.	4,531	4,599	672	4,328	4,483	665
			Error	4.5 %	2.5 %	1.1 %

*Note: In calculations, plantation area is considered as follows: Johor (supplier 1) 745,630 hectare, Pahang (supplier 2) 732,052 hectare, and Perak (supplier 3) 397,908 hectare (Malaysian Palm Oil Board, 2016).

Table 4 Different scenarios for changing the efficiency of (TT) and (PT)

	Scenarios	CO ₂ e Reduction (change%)		
		Supplier 1	Supplier 2	Supplier 3
1	TT (0% improvement)	3%	4%	2%
	PT (10% improvement)			
2	TT (0% improvement)	7%	8%	5%
	PT (20% improvement)			
3	TT (10% improvement)	7%	6%	8%
	PT (0% improvement)			
4	TT (10% improvement)	10%	10%	10%
	PT (10% improvement)			
5	TT (10% improvement)	13%	14%	12%
	PT (20% improvement)			
6	TT (20% improvement)	13%	11%	15%
	PT (0% improvement)			
7	TT (20% improvement)	17%	16%	18%
	PT (10% improvement)			
8	TT (20% improvement)	20%	20%	20%
	PT (20% improvement)			

Appendix

Table S1 Equations and calculation processes for biomass supply chain model

Variable	Term	Unit	Equation	Parameter/Coefficient
I. Supply and Processing				
$EFB_{Si}(t)$	Blended empty fruit bunches collection by first supplier in Johor	Tonnes	$P_{Si_F} + P_{Si_P}$	i represents the supplier Johor, Perak or Pahang index ($i = 1,2,3$) P_{Si_F} : Production of fresh fruit bunch by supplier i (Tonnes) P_{Si_P} : Production of palm empty fruit bunch by supplier i (Tonnes)
$TS(t)$	Total supply of raw materials by all three suppliers	Tonnes	$\sum_{i=1}^3 EFB_{Si}(t)$	i represents the supplier Johor, Perak or Pahang index ($i = 1,2,3$)
II. Production				
$P_{DLF_R}(t)$	Dry long fiber production rate	Tonnes year ⁻¹	$TS(t) * C_1$	C_1 : Conversion factor for dry long fiber production (Dimensionless)
$DLF_S(t)$	Dry long fiber stock	Tonnes	$\int_{t_0}^t (P_{DLF_R}(t) - S_1(t) - P_{BC_R}(t)) dt + DLF_S(t_0)$	
$S_1(t)$	Sales of dry long fiber product	Tonnes year ⁻¹	$\min(DLF_S(t), S_{DLF}(t))$	$S_{DLF}(t)$: Capacity of sales for dry long fiber product (Tonnes year ⁻¹)
$P_{BC_R}(t)$	Bio-composite production rate	Tonnes year ⁻¹	$DLF_S(t) * C_{10}$	C_{10} : Conversion factor for bio composite production (Dimensionless)
$BC_S(t)$	Bio composite stock	Tonnes	$\int_{t_0}^t (P_{BC_R}(t) - S_2(t)) dt + BC_S(t_0)$	

$S_2(t)$	Sales of bio composite product	Tonnes year ⁻¹	$\min(BC_S(t), S_{BC}(t))$	$S_{BC}(t)$: Capacity of sales for bio composite product (Tonnes year ⁻¹)
$P_{AD_R}(t)$	aerobic digestion production rate	Tonnes year ⁻¹	$TS(t) * C_2$	C_2 : Conversion factor for aerobic digestion production (Dimensionless)
$BCO_S(t)$	Bio compost stock	Tonnes	$\int_{t_0}^t (P_{AD_R}(t) - S_3(t)) dt + BCO_S(t_0)$	
$S_3(t)$	Sales of bio compost product	Tonnes year ⁻¹	$\min(BCO_S(t), S_{BCO}(t))$	$S_{BCO}(t)$: Capacity of sales for bio compost product (Tonnes year ⁻¹)
$P_{AA_R}(t)$	Alkaline activation production rate	Tonnes year ⁻¹	$TS(t) * C_3$	C_3 : Conversion factor for alkaline activation production (Dimensionless)
$AA_S(t)$	Activated carbon stock	Tonnes	$\int_{t_0}^t (P_{AA_R}(t) - S_4(t)) dt + AA_S(t_0)$	
$S_4(t)$	Sales of alkaline activation product	Tonnes year ⁻¹	$\min(AA_S(t), S_{AA}(t))$	$S_{AA}(t)$: Capacity of sales for activated carbon product (Tonnes year ⁻¹)
$P_{L_R}(t)$	Lignin production rate	Tonnes year ⁻¹	$TS(t) * C_6$	C_6 : Conversion factor for lignin production (Dimensionless)
$L_S(t)$	Lignin stock	Tonnes	$\int_{t_0}^t (P_{L_R}(t) - S_5(t) - P_{BR_R}(t)) dt + L_S(t_0)$	
$S_5(t)$	Sales of lignin product	Tonnes year ⁻¹	$\min(L_S(t), S_L(t))$	$S_L(t)$: Capacity of sales for lignin product (Tonnes year ⁻¹)
$P_{BR_R}(t)$	Bio resin	Tonnes year ⁻¹	$L_S(t) * C_{16}$	C_{16} : Conversion factor for bio resin production

	production rate			(Dimensionless)
$BR_S(t)$	Bio resin stock	Tonnes	$\int_{t_0}^t (P_{BR_R}(t) - S_6(t)) dt + BR_S(t_0)$	
$S_6(t)$	Sales of bio resin product	Tonnes year ⁻¹	$\min(BR_S(t), S_{BR}(t))$	$S_{BR}(t)$: Capacity of sales for bio resin product (Tonnes year ⁻¹)
$P_{C_R}(t)$	Cellulose production rate	Tonnes year ⁻¹	$TS(t) * C_4$	C_4 : Conversion factor for cellulose production (Dimensionless)
$C_S(t)$	Cellulose stock	Tonnes	$\int_{t_0}^t (P_{C_R}(t) - S_7(t) - P_{AH_R}(t) - P_{EH_R}(t)) dt + C_S(t_0)$	
$S_7(t)$	Sales of cellulose product	Tonnes year ⁻¹	$\min(C_S(t), S_C(t))$	$S_C(t)$: Capacity of sales for cellulose product (Tonnes year ⁻¹)
$P_{AH1_R}(t)$	Acid hydrolysis production rate from cellulose stock	Tonnes year ⁻¹	$C_S(t) * C_{12}$	C_{12} : Conversion factor for acid hydrolysis production from cellulose stock (Dimensionless)
$P_{EH1_R}(t)$	Enzymatic hydrolysis production rate from cellulose stock	Tonnes year ⁻¹	$C_S(t) * C_{13}$	C_{13} : Conversion factor for enzymatic hydrolysis production from cellulose stock (Dimensionless)
$S_9(t)$	Sales of glucose product	Tonnes year ⁻¹	$\min(G_S(t), S_G(t))$	$S_G(t)$: Capacity of sales for glucose product (Tonnes year ⁻¹)
$S_{11}(t)$	Sales of xylose product	Tonnes year ⁻¹	$\min(XY_S(t), S_{xy}(t))$	$S_{xy}(t)$: Capacity of sales for xylose product (Tonnes year ⁻¹)
$P_{FP1_R}(t)$	Fermentation	Tonnes year ⁻¹	$G_S(t) * C_{31}$	C_{31} : Conversion factor for fermentation plant production

	plant production rate from glucose stock			from glucose stock (Dimensionless)
$P_{AD1_R}(t)$	Anaerobic digestion production rate from glucose stock	Tonnes year ⁻¹	$G_S(t) * C_{25}$	C_{25} : Conversion factor for anaerobic digestion production from glucose stock (Dimensionless)
$P_{X2_R}(t)$	Xylitol production rate from glucose stock	Tonnes year ⁻¹	$G_S(t) * C_{42}$	C_{42} : Conversion factor for xylitol production from glucose stock (Dimensionless)
$P_{AH2_R}(t)$	Acid hydrolysis production rate from hemicellulose stock	Tonnes year ⁻¹	$HC_S(t) * C_{14}$	C_{14} : Conversion factor for acid hydrolysis production from hemicellulose stock (Dimensionless)
$G_S(t)$	Glucose stock	Tonnes	$\int_{t_0}^t \left(P_{AH1_R}(t) + P_{AH2_R}(t) - S_9(t) - P_{FP1_R}(t) - P_{AD1_R}(t) - P_{X2_R}(t) \right) dt + G_S(t_0)$	
$P_{H_R}(t)$	Hemicellulose production rate	Tonnes year ⁻¹	$TS(t) * C_5$	C_5 : Conversion factor for hemicellulose production (Dimensionless)
$S_{10}(t)$	Sales of hemicellulose product	Tonnes year ⁻¹	$min(H_S(t), S_H(t))$	$S_H(t)$: Capacity of sales for hemicellulose product (Tonnes year ⁻¹)
$P_{EH2_R}(t)$	Enzymatic	Tonnes year ⁻¹	$HC_S(t) * C_{15}$	C_{15} : Conversion factor for enzymatic hydrolysis

	hydrolysis production rate from hemicellulose stock			production from hemicellulose stock (Dimensionless)
$P_{X1_R}(t)$	Xylitol production rate from xylose stock	Tonnes year ⁻¹	$Xy_S(t) * C_{27}$	C_{27} : Conversion factor for xylitol production from xylose stock (Dimensionless)
$P_{AD2_R}(t)$	Anaerobic digestion production rate from Xylose stock	Tonnes year ⁻¹	$Xy_S(t) * C_{26}$	C_{26} : Conversion factor for anaerobic digestion production from xylose stock (Dimensionless)
$S_{12}(t)$	Sales of xylitol product	Tonnes year ⁻¹	$min(X_S(t), S_X(t))$	$S_X(t)$: Capacity of sales for xylitol product (Tonnes year ⁻¹)
$S_{13}(t)$	Sales of bio gas product	Tonnes year ⁻¹	$min(BG_S(t), S_{BG}(t))$	$S_{BG}(t)$: Capacity of sales for bio gas product (Tonnes year ⁻¹)
$BG_S(t)$	Bio gas stock	Tonnes	$\int_{t_0}^t (P_{AD1_R}(t) + P_{AD2_R}(t) - S_{13}(t)) dt + BG_S(t_0)$	
$X_S(t)$	Xylitol stock	Tonnes	$\int_{t_0}^t (P_{X1_R}(t) + P_{X2_R}(t) - S_{12}(t)) dt + X_S(t_0)$	

$HC_S(t)$	Hemicellulose stock	Tonnes	$\int_{t_0}^t (P_{H,R}(t) - P_{AH2,R}(t) - P_{EH2,R}(t) - S_{10}(t)) dt + HC_S(t_0)$	
$P_{FP2,R}(t)$	Fermentation plant production rate from xylose stock	Tonnes year ⁻¹	$Xy_S(t) * C_{32}$	C_{32} : Conversion factor for fermentation plant production from xylose stock (Dimensionless)
$Xy_S(t)$	Xylose stock	Tonnes	$\int_{t_0}^t (P_{EH1,R}(t) + P_{EH2,R}(t) - P_{FP2,R}(t) - S_{11}(t)) dt + Xy_S(t_0)$	
$P_{BET,R}(t)$	Bio ethylene production rate from bio ethanol stock	Tonnes year ⁻¹	$BE_S(t) * C_{41}$	C_{41} : Conversion factor for bio ethylene production from bio ethanol stock (Dimensionless)
$S_{14}(t)$	Sales of bio ethanol product	Tonnes year ⁻¹	$\min(BE_S(t), S_{BE}(t))$	$S_{BE}(t)$: Capacity of sales for bio ethanol product (Tonnes year ⁻¹)
$S_{15}(t)$	Sales of bio ethylene product	Tonnes year ⁻¹	$\min(BET_S(t), S_{BET}(t))$	$S_{BET}(t)$: Capacity of sales for bio ethylene product (Tonnes year ⁻¹)
$BE_S(t)$	Bio ethanol stock	Tonnes	$\int_{t_0}^t (P_{FP1,R}(t) + P_{FP2,R}(t) - P_{BET,R}(t) - S_{14}(t)) dt + BE_S(t_0)$	

$BET_S(t)$	Bio ethylene stock	Tonnes	$\int_{t_0}^t (P_{BET_R}(t) - S_{15}(t)) dt + BET_S(t_0)$	
$P_{CMC_R}(t)$	CMC production rate	Tonnes year ⁻¹	$C_S(t) * C_{11}$	C_{11} : Conversion factor for carboxymethyl cellulose production (Dimensionless)
$S_8(t)$	Sales of CMC product	Tonnes year ⁻¹	$min(CMC_S(t), S_{CMC}(t))$	$S_{BET}(t)$: Capacity of sales for carboxymethyl cellulose product (Tonnes year ⁻¹)
$CMC_S(t)$	CMC stock	Tonnes	$\int_{t_0}^t (P_{CMC_R}(t) - S_8(t)) dt + CMC_S(t_0)$	
$P_{Br_R}(t)$	Briquette production rate	Tonnes year ⁻¹	$Br_S(t) * C_7$	C_7 : Conversion factor for Briquette production (Dimensionless)
$S_{16}(t)$	Sales of briquette product	Tonnes year ⁻¹	$min(Br_S(t), S_{Br}(t))$	$S_{Br}(t)$: Capacity of sales for briquette product (Tonnes year ⁻¹)
$P_{BiC1_R}(t)$	Boiler combustion production rate from Briquette stock	Tonnes year ⁻¹	$BiC1_S(t) * C_{17}$	C_{17} : Conversion factor for boiler combustion production from briquette stock (Dimensionless)
$Br_S(t)$	Briquette stock	Tonnes	$\int_{t_0}^t (P_{Br_R}(t) - P_{BiC1_R}(t) - S_{16}(t)) dt + Br_S(t_0)$	
$P_{Pe_R}(t)$	Pelletization production rate	Tonnes year ⁻¹	$Pe_S(t) * C_8$	C_8 : Conversion factor for pelletization production (Dimensionless)
$S_{28}(t)$	Sales of pellet product	Tonnes year ⁻¹	$min(Pe_S(t), S_{Pe}(t))$	$S_{Pe}(t)$: Capacity of sales for pellet product (Tonnes year ⁻¹)
$P_{Py1_R}(t)$	Slow pyrolysis	Tonnes year ⁻¹	$Pe_S(t) * C_{21}$	C_{21} : Conversion factor for slow pyrolysis production

$P_{Py2_R}(t)$	production rate Fast pyrolysis production rate	Tonnes year ⁻¹	$(Pe_S(t) * C_{20}) + (TPe_S(t) * C_{24})$	(Dimensionless) C ₂₀ : Conversion factor for fast pyrolysis production from pellet (Dimensionless) C ₂₄ : Conversion factor for fast pyrolysis production from torrefied Pellet (Dimensionless)
$P_{BiC2_R}(t)$	Boiler combustion production rate from Pellet stock	Tonnes year ⁻¹	$BiC2_S(t) * C_{18}$	C ₁₈ : Conversion factor for boiler combustion production from pellet stock (Dimensionless)
$P_{Ga1_R}(t)$	Gasification production rate from Pellet stock	Tonnes year ⁻¹	$Pe_S(t) * C_{19}$	C ₁₉ : Conversion factor for gasification production (Dimensionless)
$Pe_S(t)$	Pellet stock	Tonnes	$\int_{t_0}^t (P_{Pe_R}(t) - P_{Ga1_R}(t) - P_{BiC2_R}(t) - P_{Py1_R}(t) - P_{Py2_R}(t) - S_{28}(t)) dt + Pe_S(t_0)$	
$S_{31}(t)$	Sales of bio-char product	Tonnes year ⁻¹	$\min(BCh_S(t), S_{BCh}(t))$	$S_{BCh}(t)$: Capacity of sales for bio-char product (Tonnes year ⁻¹)
$BCh_S(t)$	Bio-char stock	Tonnes	$\int_{t_0}^t (P_{Py1_R}(t) - S_{31}(t)) dt + BCh_S(t_0)$	
$S_{30}(t)$	Sales of bio-oil product	Tonnes year ⁻¹	$\min(BO_S(t), S_{BO}(t))$	$S_{BO}(t)$: Capacity of sales for bio-oil product (Tonnes year ⁻¹)
$P_{BOU1_R}(t)$	Bio-oil upgrading toward bio	Tonnes year ⁻¹	$BO_S(t) * C_{29}$	C ₂₉ : Conversion factor for bio-oil upgrading toward bio gasoline production (Dimensionless)

$P_{BOU2_R}(t)$	gasoline production rate Bio-oil upgrading toward bio diesel production rate	Tonnes year ⁻¹	$BO_S(t) * C_{30}$	C_{30} : Conversion factor for bio-oil upgrading toward bio gasoline production (Dimensionless)
$P_{BiC3_R}(t)$	Boiler combustion production rate from Torrefied pellet stock	Tonnes year ⁻¹	$BO_S(t) * C_{22}$	C_{22} : Conversion factor for boiler combustion production from torrefied Pellet stock (Dimensionless)
$P_{SR_R}(t)$	Steam reforming toward bio hydrogen production rate	Tonnes year ⁻¹	$BO_S(t) * C_{28}$	C_{28} : Conversion factor for steam reforming toward bio hydrogen production (Dimensionless)
$BO_S(t)$	Bio-oil stock	Tonnes	$\int_{t_0}^t (P_{Py2_R}(t) - P_{BOU1_R}(t) - P_{BOU2_R}(t) - P_{SR_R}(t) - S_{30}(t)) dt + BO_S(t_0)$	
$S_{29}(t)$	Sales of torrefied Pellet product	Tonnes year ⁻¹	$min(TP_S(t), S_{TP}(t))$	$S_{TP}(t)$: Capacity of sales for torrefied pellet product (Tonnes year ⁻¹)
$P_{TP_R}(t)$	Torrefied pellet production rate	Tonnes year ⁻¹	$TS_S(t) * C_9$	C_9 : Conversion factor for torrefied pellet production (Dimensionless)
$P_{Ga_R}(t)$	Gasification production rate from Torrefied pellet stock	Tonnes year ⁻¹	$TP_S(t) * C_{23}$	C_{23} : Conversion factor for gasification production from torrefied pellet stock (Dimensionless)
$S_{23}(t)$	Sales of bio-syngas product	Tonnes year ⁻¹	$min(BS_S(t), S_{BS}(t))$	$S_{BS}(t)$: Capacity of sales for bio-syngas product (Tonnes year ⁻¹)

$P_{M_R}(t)$	Methanol production rate	Tonnes year ⁻¹	$BS_S(t) * C_{36}$	C_{36} : Conversion factor for methanol production (Dimensionless)
$P_{FTL2_R}(t)$	FTL toward bio gasoline production rate	Tonnes year ⁻¹	$BS_S(t) * C_{39}$	C_{39} : Conversion factor for FTL toward bio gasoline production (Dimensionless)
$P_{FTL1_R}(t)$	FTL toward Bio diesel production rate	Tonnes year ⁻¹	$BS_S(t) * C_{38}$	C_{38} : Conversion factor for FTL toward bio diesel production (Dimensionless)
$S_{27}(t)$	Sales of bio-gasoline product	Tonnes year ⁻¹	$min(BG_S(t), S_{BGS}(t))$	$S_{BGS}(t)$: Capacity of sales for bio-gasoline product (Tonnes year ⁻¹)
$S_{26}(t)$	Sales of bio-diesel product	Tonnes year ⁻¹	$min(BD_S(t), S_{BD}(t))$	$S_{BD}(t)$: Capacity of sales for bio-diesel product (Tonnes year ⁻¹)
$BG_S(t)$	Bio-gasoline stock	Tonnes	$\int_{t_0}^t (P_{FTL2_R}(t) + P_{BOU1_R}(t) - S_{27}(t)) dt + BG_S(t_0)$	
$BD_S(t)$	Bio-diesel stock	Tonnes	$\int_{t_0}^t (P_{FTL1_R}(t) + P_{BOU2_R}(t) - S_{26}(t)) dt + BD_S(t_0)$	
$P_{SP_R}(t)$	Separation plant production rate	Tonnes year ⁻¹	$BS_S(t) * C_{37}$	C_{37} : Conversion factor for separation plant production (Dimensionless)
$S_{25}(t)$	Sales of bio-Hydrogen product	Tonnes year ⁻¹	$min(BH_S(t), S_{BH}(t))$	$S_{BH}(t)$: Capacity of sales for bio-hydrogen product (Tonnes year ⁻¹)
$S_{24}(t)$	Sales of bio-methanol product	Tonnes year ⁻¹	$min(BM_S(t), S_{BM}(t))$	$S_{BM}(t)$: Capacity of sales for bio-methanol product (Tonnes year ⁻¹)
$P_{A_R}(t)$	Ammonia	Tonnes year ⁻¹	$BH_S(t) * C_{43}$	C_{43} : Conversion factor for ammonia production

	production rate			(Dimensionless)
$P_{F_R}(t)$	Formaldehyde production rate	Tonnes year ⁻¹	$BM_S(t) * C_{40}$	C_{40} : Conversion factor for formaldehyde production (Dimensionless)
$BH_S(t)$	Bio-hydrogen stock	Tonnes	$\int_{t_0}^t (P_{SP_R}(t) + P_{SR_R}(t) - P_{A_R}(t) - S_{25}(t)) dt + BH_S(t_0)$	
$BM_S(t)$	Bio-methanol stock	Tonnes	$\int_{t_0}^t (P_{M_R}(t) - P_{F_R}(t) - S_{24}(t)) dt + BM_S(t_0)$	
$S_{22}(t)$	Sales of ammonia product	Tonnes year ⁻¹	$min(A_S(t), S_A(t))$	$S_A(t)$: Capacity of sales for ammonia product (Tonnes year ⁻¹)
$S_{21}(t)$	Sales of Formaldehyde product	Tonnes year ⁻¹	$min(F_S(t), S_F(t))$	$S_F(t)$: Capacity of sales for formaldehyde product (Tonnes year ⁻¹)
$A_S(t)$	Ammonia stock	Tonnes	$\int_{t_0}^t (P_{A_R}(t) - S_{22}(t)) dt + A_S(t_0)$	
$F_S(t)$	Formaldehyde stock	Tonnes	$\int_{t_0}^t (P_{F_R}(t) - S_{21}(t)) dt + F_S(t_0)$	

$TP_S(t)$	Torrefied pellet stock	Tonnes	$\int_{t_0}^t (P_{TP_R}(t) - P_{Ga2_R}(t) - P_{BiC3_R}(t) - P_{Py2_R}(t) - S_{29}(t)) dt + TP_S(t_0)$	
$BS_S(t)$	Bio-syngas stock	Tonnes	$\int_{t_0}^t (P_{Ga1_R}(t) - P_{Ga2_R}(t) - P_{FTL1_R}(t) - P_{FTL2_R}(t) - P_{S_R}(t) - P_{M_R}(t) - S_{23}(t)) dt + BS_S(t_0)$	
$S_{17}(t)$	Sales of HP steam product	Tonnes year ⁻¹	$min(HPS_S(t), S_{HPS}(t))$	$S_{HPS}(t)$: Capacity of sales for HP steam product (Tonnes year ⁻¹)
$P_{P1_R}(t)$	Power production rate toward electricity stock	Tonnes year ⁻¹	$HPS_S(t) * C_{33}$	C_{33} : Conversion factor for power production toward electricity stock (Dimensionless)
$S_{18}(t)$	Sales of electricity	Tonnes year ⁻¹	$min(E_S(t), S_E(t))$	$S_E(t)$: Capacity of sales for electricity (Tonnes year ⁻¹)
$P_{P2_R}(t)$	Power production rate toward MP Steam stock	Tonnes year ⁻¹	$HPS_S(t) * C_{34}$	C_{34} : Conversion factor for power production toward MP Steam stock (Dimensionless)
$S_{19}(t)$	Sales of MP steam	Tonnes year ⁻¹	$min(MPS_S(t), S_{MPS}(t))$	$S_{MPS}(t)$: Capacity of sales for MP steam (Tonnes year ⁻¹)
$P_{P3_R}(t)$	Power	Tonnes year ⁻¹	$LPS_S(t) * C_{35}$	C_{35} : Conversion factor for power production toward LP

	production rate toward LP Steam stock			Steam stock (Dimensionless)
$S_{20}(t)$	Sales of LP steam	Tonnes year ⁻¹	$min(LPS_S(t), S_{LPS}(t))$	$S_{LPS}(t)$: Capacity of sales for LP steam (Tonnes year ⁻¹)
$HPS_S(t)$	HP steam stock	Tonnes	$\int_{t_0}^t (P_{BiC1_R}(t) + P_{BiC2_R}(t) + P_{BiC3_R}(t) - P_{P1_R}(t) - P_{P2_R}(t) - P_{P3_R}(t) - S_{17}(t)) dt + HPS_S(t_0)$	
$E_S(t)$	Electricity stock	Tonnes	$\int_{t_0}^t (P_{P1_R}(t) - S_{18}(t)) dt + E_S(t_0)$	
$MPS_S(t)$	MP steam stock	Tonnes	$\int_{t_0}^t (P_{P2_R}(t) - S_{19}(t)) dt + MPS_S(t_0)$	
$LPS_S(t)$	LP steam stock	Tonnes	$\int_{t_0}^t (P_{P3_R}(t) - S_{20}(t)) dt + LPS_S(t_0)$	
III. Production stage emissions				
$CO_{2_DLF_P}(t)$	GHG emissions (carbon dioxide equivalent) from dry long fiber	Tonnes year ⁻¹	CO ₂ e $P_{DLF_R}(t) * e_1$	e_1 : emission coefficient of dry long fiber production (Dimensionless)

$CO_{2_BC_P}(t)$	production GHG emissions (carbon dioxide equivalent) from bio composite production	Tonnes year ⁻¹	CO ₂ e	$P_{BC_R}(t) * e_2$	e_2 : emission coefficient of bio composite production (Dimensionless)
$CO_{2_BCO_P}(t)$	GHG emissions (carbon dioxide equivalent) from bio compost production	Tonnes year ⁻¹	CO ₂ e	$P_{BCO_R}(t) * e_3$	e_3 : emission coefficient of bio compost production (Dimensionless)
$CO_{2_AC_P}(t)$	GHG emissions (carbon dioxide equivalent) from activated carbon production	Tonnes year ⁻¹	CO ₂ e	$P_{AA_R}(t) * e_4$	e_4 : emission coefficient of activated carbon production (Dimensionless)
$CO_{2_L_P}(t)$	GHG emissions (carbon dioxide equivalent) from lignin production	Tonnes year ⁻¹	CO ₂ e	$P_{L_R}(t) * e_6$	e_6 : emission coefficient of lignin production (Dimensionless)
$CO_{2_BR_P}(t)$	GHG emissions (carbon dioxide equivalent) from bio resin production	Tonnes year ⁻¹	CO ₂ e	$P_{BR_R}(t) * e_{14}$	e_{14} : emission coefficient of bio resin production (Dimensionless)
$CO_{2_C_P}(t)$	GHG emissions (carbon dioxide equivalent) from Cellulose production	Tonnes year ⁻¹	CO ₂ e	$P_{C_R}(t) * e_{10}$	e_{10} : emission coefficient of cellulose production (Dimensionless)
$CO_{2_CMC_P}(t)$	GHG emissions (carbon dioxide	Tonnes year ⁻¹	CO ₂ e	$P_{CMC_R}(t) * e_{11}$	e_{11} : emission coefficient of carboxymethyl cellulose production (Dimensionless)

	equivalent) from CMC production				
$CO_{2_HC_P}(t)$	GHG emissions (carbon dioxide equivalent) from Hemicellulose production	Tonnes year ⁻¹	CO ₂ e	$P_{HC_R}(t) * e_5$	e_5 : emission coefficient of hemicellulose production (Dimensionless)
$CO_{2_GS_P}(t)$	GHG emissions (carbon dioxide equivalent) from Glucose production	Tonnes year ⁻¹	CO ₂ e	$(P_{AH1_R}(t) + P_{AH2_R}(t)) * e_{12}$	e_{12} : emission coefficient of glucose production (Dimensionless)
$CO_{2_Xy_P}(t)$	GHG emissions (carbon dioxide equivalent) from xylose production	Tonnes year ⁻¹	CO ₂ e	$(P_{EH1_R}(t) + P_{EH2_R}(t)) * e_{13}$	e_{13} : emission coefficient of xylose production (Dimensionless)
$CO_{2_Xi_P}(t)$	GHG emissions (carbon dioxide equivalent) by xylitol production from xylose stock or glucose stock	Tonnes year ⁻¹	CO ₂ e	$P_{Xi_R}(t) * e_j$	i represents the xylitol production index ($i = 1,2$) e_j : emission coefficient of xylitol production from stock j , where $j = 1,2$ represents glucose and xylose stock (Dimensionless)
$CO_{2_ADi_P}(t)$	GHG emissions (carbon dioxide equivalent) by bio gas production from anaerobic digestion	Tonnes year ⁻¹	CO ₂ e	$P_{ADi_R}(t) * e_i$	i represents the anaerobic digestion index ($i = 1,2$)

$CO_{2_FPi_P}(t)$	GHG emissions (carbon dioxide equivalent) by bio ethanol production from fermentation plant	Tonnes year ⁻¹	CO ₂ e	$P_{FPi_R}(t) * e_i$	i represents the plant index ($i = 1,2$)
$CO_{2_BET_P}(t)$	GHG emissions (carbon dioxide equivalent) by bio ethylene production	Tonnes year ⁻¹	CO ₂ e	$P_{BET_R}(t) * e_{41}$	e_{41} : emission coefficient of bio ethylene production (Dimensionless)
$CO_{2_Br_P}(t)$	GHG emissions (carbon dioxide equivalent) by briquette production	Tonnes year ⁻¹	CO ₂ e	$P_{Br_R}(t) * e_7$	e_7 : emission coefficient of briquette production (Dimensionless)
$CO_{2_HPS_P}(t)$	GHG emissions (carbon dioxide equivalent) by boiler combustion1, boiler combustion2 and boiler combustion3 toward HP steam production	Tonnes year ⁻¹	CO ₂ e	$\sum_{i=1}^3 (P_{BiCi_R}(t) * e_i)$	i represents the boiler combustion index ($i = 1,2,3$)
$CO_{2_LPS_P}(t)$	GHG emissions (carbon dioxide equivalent) by LP steam	Tonnes year ⁻¹	CO ₂ e	$P_{LPS_R}(t) * e_{34}$	e_{34} : emission coefficient of LP steam production (Dimensionless)

$CO_{2_MPS_P}(t)$	production GHG emissions (carbon dioxide equivalent) by MP steam production	Tonnes year ⁻¹	CO ₂ e	$P_{MPS_R}(t) * e_{33}$	e_{33} : emission coefficient of MP steam production (Dimensionless)
$CO_{2_E_P}(t)$	GHG emissions (carbon dioxide equivalent) by electricity production	Tonnes year ⁻¹	CO ₂ e	$P_{P1_R}(t) * e_{42}$	e_{42} : emission coefficient of electricity production (Dimensionless)
$CO_{2_BS_P}(t)$	GHG emissions (carbon dioxide equivalent) by gasification1 and gasification2 toward bio- syngas production	Tonnes year ⁻¹	CO ₂ e	$\sum_{i=1}^2 (P_{Gai_R}(t) * e_i)$	i represents the boiler gasification index ($i = 1,2$)
$CO_{2_BM_P}(t)$	GHG emissions (carbon dioxide equivalent) by Bio-Methanol production	Tonnes year ⁻¹	CO ₂ e	$P_{BM_R}(t) * e_{35}$	e_{35} : emission coefficient of bio-methanol production (Dimensionless)
$CO_{2_BH_P}(t)$	GHG emissions (carbon dioxide equivalent) by separation plant and steam reforming toward bio-hydrogen production	Tonnes year ⁻¹	CO ₂ e	$\sum_{i=1}^2 (P_{SP_R}(t) * e_i)$	i represents the separation plant index ($i = 1,2$)

$CO_{2_BD_P}(t)$	GHG emissions (carbon dioxide equivalent) by FTL and bio-oil upgradings toward bio-diesel production	Tonnes year ⁻¹	CO ₂ e	$\sum_{i=1}^2 (P_{FTLi_R}(t) * e_i) + (P_{BOUj_R}(t) * e_j)$	i represents the FTL index ($i = 1,2$) j represents the bio-oil upgradings index ($i = 1,2$)
$CO_{2_A_P}(t)$	GHG emissions (carbon dioxide equivalent) by ammonia production	Tonnes year ⁻¹	CO ₂ e	$P_{A_R}(t) * e_{40}$	e_{40} : emission coefficient of ammonia production (Dimensionless)
$CO_{2_F_P}(t)$	GHG emissions (carbon dioxide equivalent) by formaldehyde production	Tonnes year ⁻¹	CO ₂ e	$P_{F_R}(t) * e_{39}$	e_{39} : emission coefficient of formaldehyde production (Dimensionless)
$CO_{2_Pe_P}(t)$	GHG emissions (carbon dioxide equivalent) by pellet production	Tonnes year ⁻¹	CO ₂ e	$P_{Pe_R}(t) * e_8$	e_8 : emission coefficient of pellet production (Dimensionless)
$CO_{2_TPe_P}(t)$	GHG emissions (carbon dioxide equivalent) by torrefied Pellet production	Tonnes year ⁻¹	CO ₂ e	$P_{TPe_R}(t) * e_9$	e_9 : emission coefficient of torrefied pellet production (Dimensionless)
$CO_{2_BO_P}(t)$	GHG emissions (carbon dioxide equivalent) by fast pyrolysis from pellet and torrefied pellet	Tonnes year ⁻¹	CO ₂ e	$\sum_{i=1}^2 (P_{Pyi_R}(t) * e_i)$	i represents the Fast Pyrolysis index ($i = 1,2$)

	toward Bio-Oil production				
$CO_{2_Bch_P}(t)$	GHG emissions (carbon dioxide equivalent) by slow pyrolysis toward bio-char production	Tonnes year ⁻¹	CO ₂ e	$P_{Bch_R}(t) * e_{19}$	e_{19} : emission coefficient of slow pyrolysis toward bio-char production (Dimensionless)
IV. Transportation emissions					
$CO_{2_DLF_TSi}$	GHG emissions from train transportation between EFB collection by supplier i and dry long fiber production	Tonnes (tonne of biomass transported) ⁻¹	CO ₂ e	$P_{DLF_R}(t) * D_i * T_i$	i represents the supplier Johor, Perak or Pahang index ($i = 1,2,3$) D_i : Distance between EFB collection by supplier i and dry long fiber production (Kilometer) T_i : CO ₂ emission factor of train transportation between EFB collection by supplier i and dry long fiber production (tonne CO ₂ equivalent /tonne of biomass transported)
$CO_{2_BC_T}$	GHG emissions from truck transportation between dry long fiber production and bio composite production	Tonnes (tonne of biomass transported) ⁻¹	CO ₂ e	$P_{BC_R}(t) * D_4 * T_4$	D_4 : Distance between dry long fiber production and bio composite production (Kilometer) T_4 : CO ₂ emission factor of truck transportation between dry long fiber production and bio composite production (tonne CO ₂ equivalent /tonne of biomass produced)
$CO_{2_AA_TSi}$	GHG emissions from train transportation between EFB collection by supplier i and activated carbon	Tonnes (tonne of biomass transported) ⁻¹	CO ₂ e	$P_{AA_R}(t) * D_i * T_i$	i represents the supplier Johor, Perak or Pahang index ($i = 1,2,3$) D_i : Distance between EFB collection by supplier i and activated carbon production (Kilometer) T_i : CO ₂ emission factor of train transportation between EFB collection by supplier i and activated carbon production (tonne CO ₂ equivalent /tonne of biomass

	production			transported)
$CO_{2_L_TSi}$	GHG emissions from train transportation between EFB collection by supplier i and lignin production	Tonnes of biomass transported) ⁻¹	$P_{L_R}(t) * D_i * T_i$	i represents the supplier Johor, Perak or Pahang index ($i = 1,2,3$) D_i : Distance between EFB collection by supplier i and lignin production (Kilometer) T_i : CO ₂ emission factor of train transportation between EFB collection by supplier i and lignin production (tonne CO ₂ equivalent /tonne of biomass transported)
$CO_{2_BR_T}$	GHG emissions from train transportation between lignin production and bio resin production	Tonnes of biomass transported) ⁻¹	$P_{BR_R}(t) * D_{11} * T_{11}$	D_{11} : Distance between lignin production and bio resin production (Kilometer) T_{11} : CO ₂ emission factor of train transportation between lignin production and bio resin production (tonne CO ₂ equivalent /tonne of biomass produced)
$CO_{2_C_TSi}$	GHG emissions from train transportation between EFB collection by supplier i and cellulose production	Tonnes of biomass transported) ⁻¹	$P_{C_R}(t) * D_i * T_i$	i represents the supplier Johor, Perak or Pahang index ($i = 1,2,3$) D_i : Distance between EFB collection by supplier i and cellulose production (Kilometer) T_i : CO ₂ emission factor of train transportation between EFB collection by supplier i and cellulose production (tonne CO ₂ equivalent /tonne of biomass transported)
$CO_{2_HC_TSi}$	GHG emissions from train transportation between EFB collection by supplier i and hemicellulose	Tonnes of biomass transported) ⁻¹	$P_{HC_R}(t) * D_i * T_i$	i represents the supplier Johor, Perak or Pahang index ($i = 1,2,3$) D_i : Distance between EFB collection by supplier i and hemicellulose production (Kilometer) T_i : CO ₂ emission factor of train transportation between EFB collection by supplier i and hemicellulose production (tonne CO ₂ equivalent /tonne of biomass transported)

$CO_{2_G_T}$	production GHG emissions from train transportation between glucose production and acid hydrolysis production	Tonnes of biomass transported) ⁻¹	$\sum_{i=1}^2 (P_{AHi_R}(t) * D_i * T_i)$	i represents the acid hydrolysis production index ($i = 1,2$) D_i : Distance between glucose production and acid hydrolysis production i (Kilometer) T_i : CO ₂ emission factor of train transportation between glucose production and acid hydrolysis production i (tonne CO ₂ equivalent /tonne of biomass produced)
$CO_{2_Xy_T}$	GHG emissions from train transportation between xylose production and enzymatic hydrolysis production	Tonnes of biomass transported) ⁻¹	$\sum_{i=1}^2 (P_{EHi_R}(t) * D_i * T_i)$	i represents the enzymatic hydrolysis production index ($i = 1,2$) D_i : Distance between xylose production and enzymatic hydrolysis production i (Kilometer) T_i : CO ₂ emission factor of train transportation between xylose production and enzymatic hydrolysis production i (tonne CO ₂ equivalent /tonne of biomass produced)
$CO_{2_X_T}$	GHG emissions from train transportation between xylitol production and xylose production	Tonnes of biomass transported) ⁻¹	$\sum_{i=1}^2 (P_{Xi_R}(t) * D_i * T_i)$	i represents xylitol production index ($i = 1,2$) D_i : Distance between xylitol production i and xylose production (Kilometer) T_i : CO ₂ emission factor of train transportation between xylitol production i and xylose production (tonne CO ₂ equivalent /tonne of biomass produced)
$CO_{2_ADi_T}$	GHG emissions from train transportation between bio gas production and anaerobic digestion production	Tonnes of biomass transported) ⁻¹	$P_{ADi_R}(t) * D_i * T_i$	i represents the anaerobic digestion index ($i = 1,2$) D_i : Distance between bio gas production and anaerobic digestion i production (Kilometer) T_i : CO ₂ emission factor of train transportation between Bio Gas production and anaerobic digestion i production (tonne CO ₂ equivalent /tonne of biomass produced)

$CO_{2_FPi_T}$	GHG emissions from train transportation between bio ethanol production and fermentation plant i production	Tonnes CO ₂ e (tonne of biomass transported) ⁻¹	$P_{FPi_R}(t) * D_i * T_i$	i represents the plant index ($i = 1,2$) D_i : Distance between bio ethanol production and anaerobic digestion i production (Kilometer) T_i : CO ₂ emission factor of train transportation between bio ethanol production and fermentation plant i production (tonne CO ₂ equivalent /tonne of biomass produced)
$CO_{2_HC_Ti}$	GHG emissions from train transportation between EFB collection by supplier i and briquette production	Tonnes CO ₂ e (tonne of biomass transported) ⁻¹	$P_{Br_R}(t) * D_i * T_i$	i represents the supplier Johor, Perak or Pahang index ($i = 1,2,3$) D_i : Distance between EFB collection by supplier i and briquette production (Kilometer) T_i : CO ₂ emission factor of train transportation between EFB collection by supplier i and briquette production (tonne CO ₂ equivalent /tonne of biomass transported)
$CO_{2_BiCi_T}$	GHG emissions from truck transportation between briquette, pellet or torrefied pellet production and boiler combustion production	Tonnes CO ₂ e (tonne of biomass transported) ⁻¹	$P_{BiCi_R}(t) * D_j * T_j$	i represents the boiler combustion index ($i = 1,2$) j represents the production index where $j = 1,2,3$ corresponds briquette, pellet and torrefied pellet
$CO_{2_Gai_T}$	GHG emissions from truck transportation between Pellet production and	Tonnes CO ₂ e (tonne of biomass transported) ⁻¹	$P_{Gai_R}(t) * D_i * T_i$	i represents the gasification production index ($i = 1,2$) D_i : Distance between pellet production and gasification i production (Kilometer) T_i : CO ₂ emission factor of train transportation between pellet production and gasification i production (tonne CO ₂

	gasification production				equivalent /tonne of biomass produced)
$CO_{2_Pe_TSi}$	GHG emissions from train transportation between EFB collection by supplier i and Pellet production	Tonnes (tonne of biomass transported) ⁻¹	CO ₂ e of	$P_{Pe_R}(t) * D_i * T_i$	i represents the supplier Johor, Perak or Pahang index ($i = 1,2,3$) D_i : Distance between EFB collection by supplier i and Pellet production (Kilometer) T_i : CO ₂ emission factor of train transportation between EFB collection by supplier i and pellet production (tonne CO ₂ equivalent /tonne of biomass transported)
$CO_{2_TPe_TSi}$	GHG emissions from train transportation between EFB collection by supplier i and torrefied pellet production	Tonnes (tonne of biomass transported) ⁻¹	CO ₂ e of	$P_{TPe_R}(t) * D_i * T_i$	i represents the supplier Johor, Perak or Pahang index ($i = 1,2,3$) D_i : Distance between EFB collection by supplier i and torrefied pellet production (Kilometer) T_i : CO ₂ emission factor of train transportation between EFB collection by supplier i and torrefied pellet production (tonne CO ₂ equivalent /tonne of biomass transported)
$CO_{2_Py_T}$	GHG emissions from train transportation between torrefied pellet production and fast pyrolysis production plus Carbon dioxide emissions from truck transportation between torrefied pellet production and fast pyrolysis production	Tonnes (tonne of biomass transported) ⁻¹	CO ₂ e of	$\sum_{i=1}^2 (P_{Pyi_R}(t) * D_i * T_i)$	i represents the fast pyrolysis index ($i = 1,2$) D_i : Distance between torrefied pellet production and fast pyrolysis i production (Kilometer) T_i : CO ₂ emission factor of train transportation between torrefied pellet production and fast pyrolysis i production (tonne CO ₂ equivalent /tonne of biomass produced)

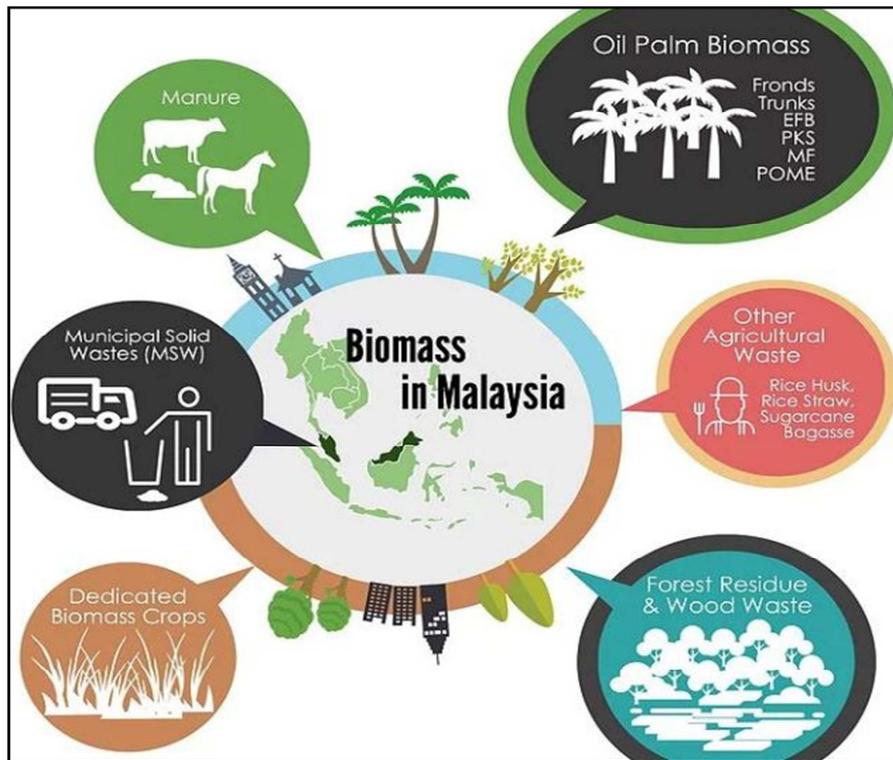


Fig. 1. Biomass resources in Malaysia (Agensi Inovasi Malaysia, 2011)

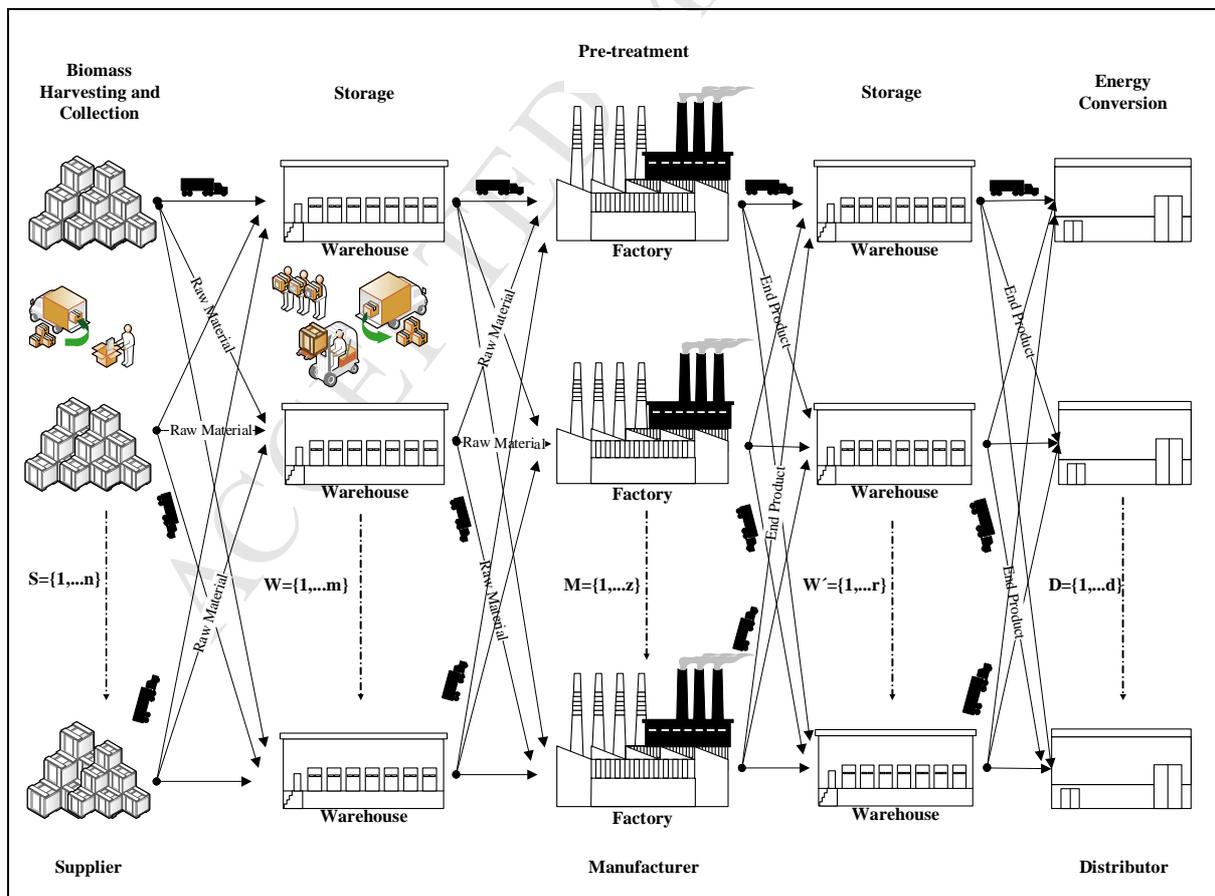
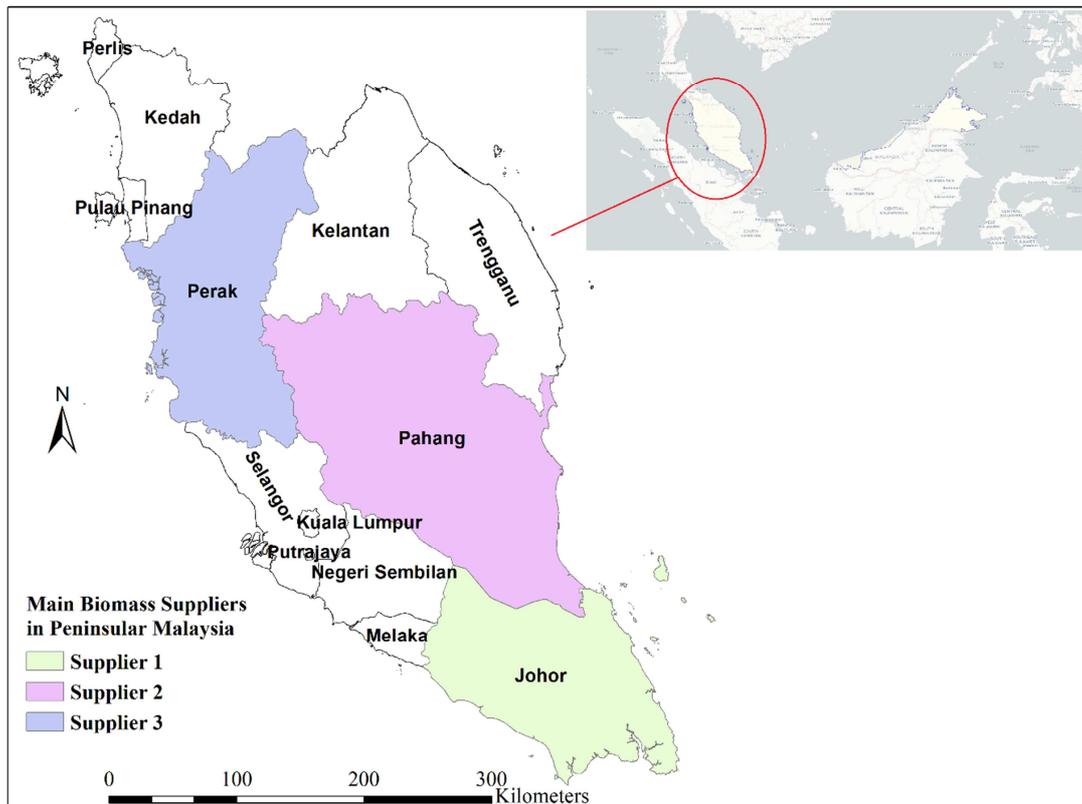
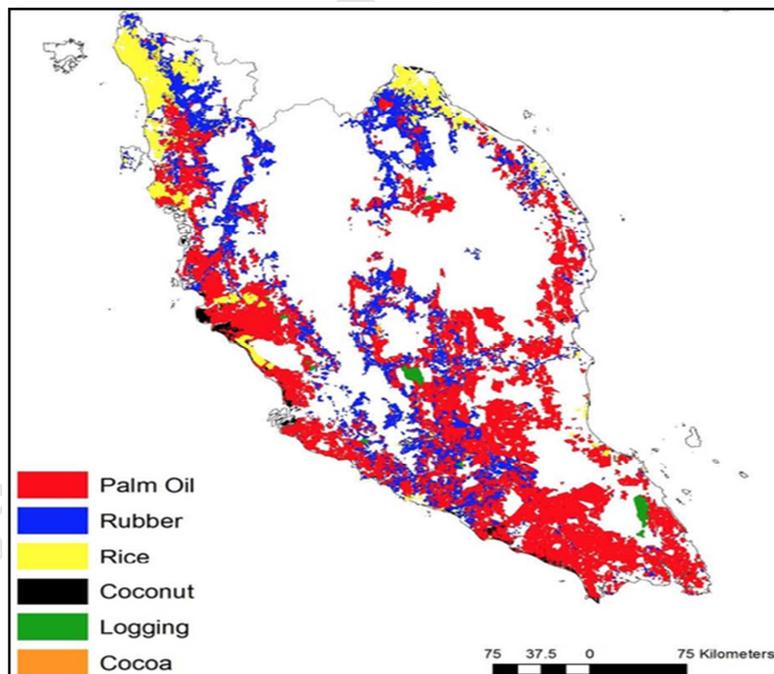


Fig. 2. Biomass supply chain network (Sokhansanj et al., 2009)**Fig. 3.** Map of Malaysia including main biomass supplier in Peninsular Malaysia**Fig. 4.** Distribution of palm plantation in Malaysia

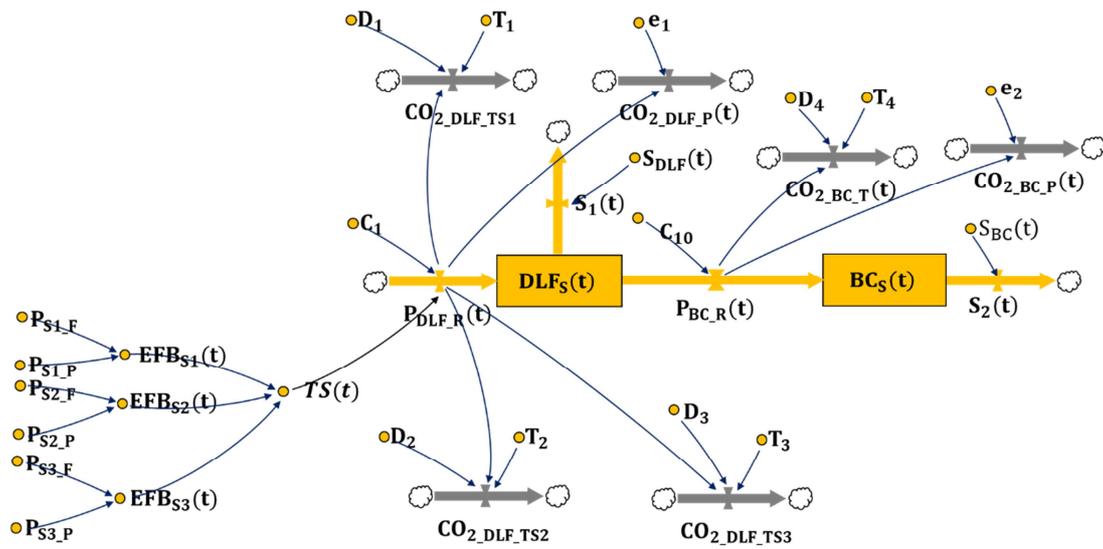


Fig. 5. Simulation model for dry long fiber and bio composite

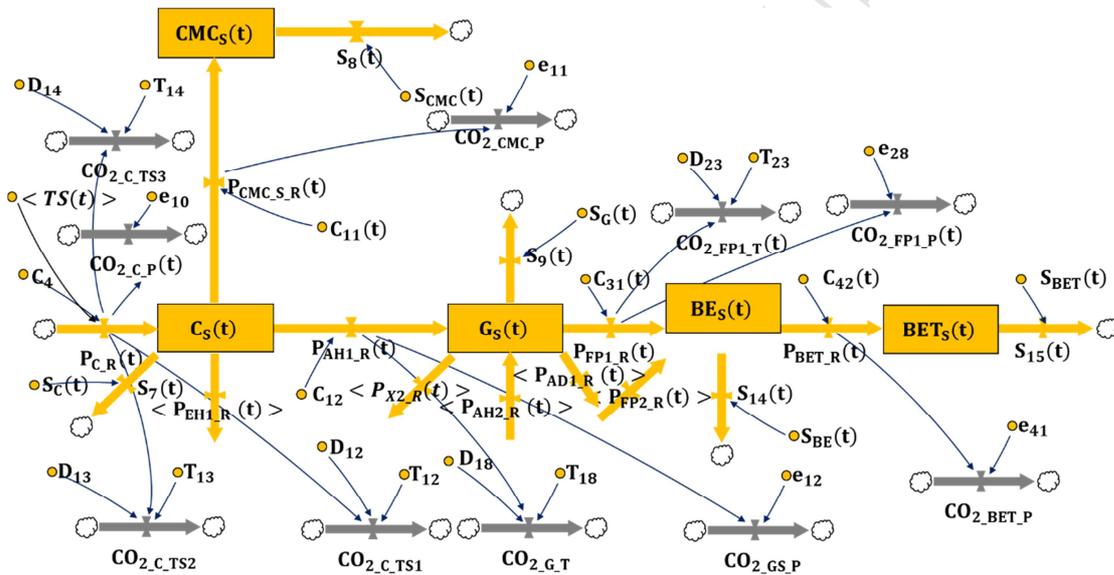


Fig. 6. Simulation model for cellulose, CMC, glucose, bio ethanol and bio ethylene

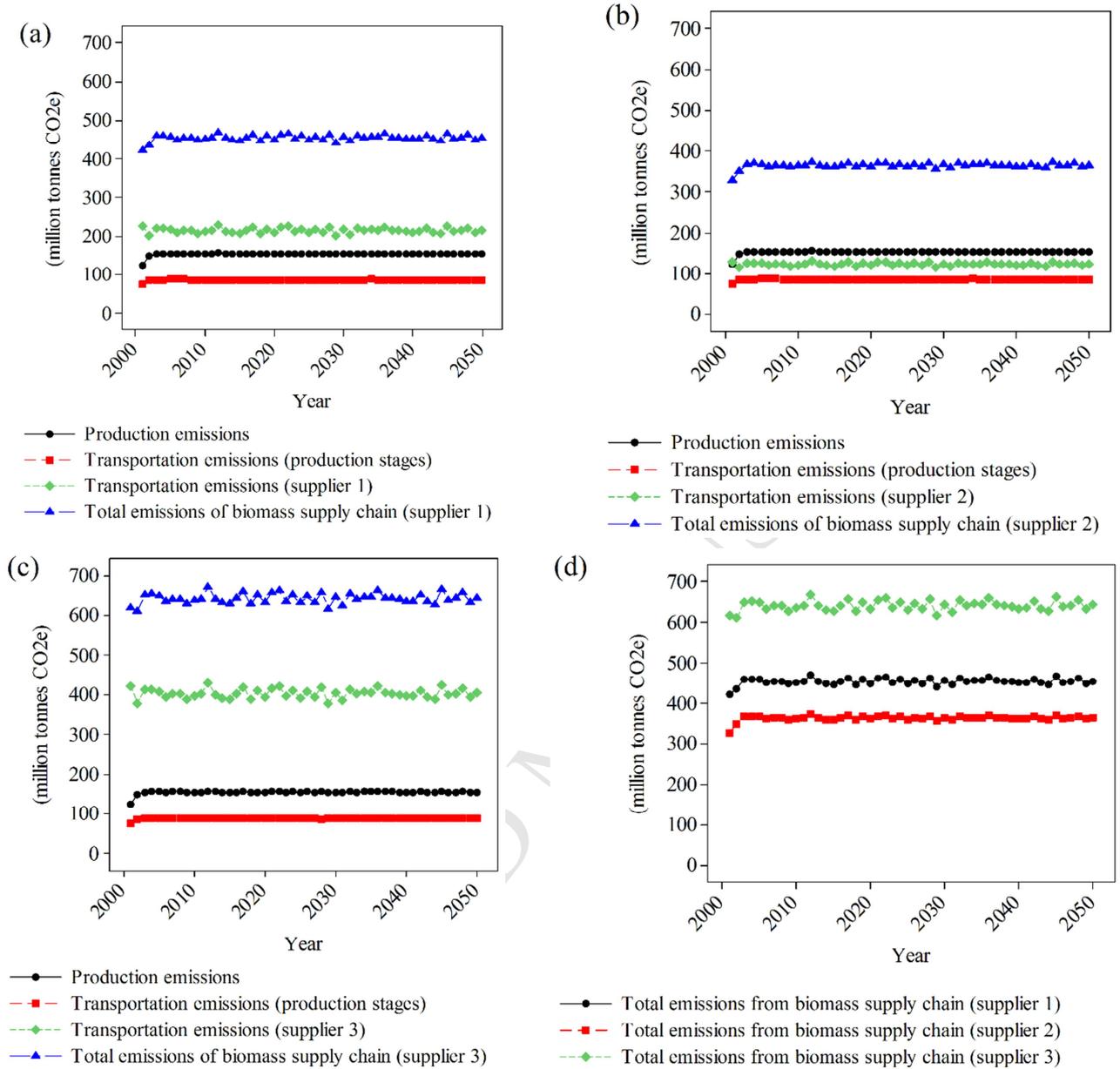


Fig. 9. GHG emissions trend from production and transportation for three suppliers for 50

years

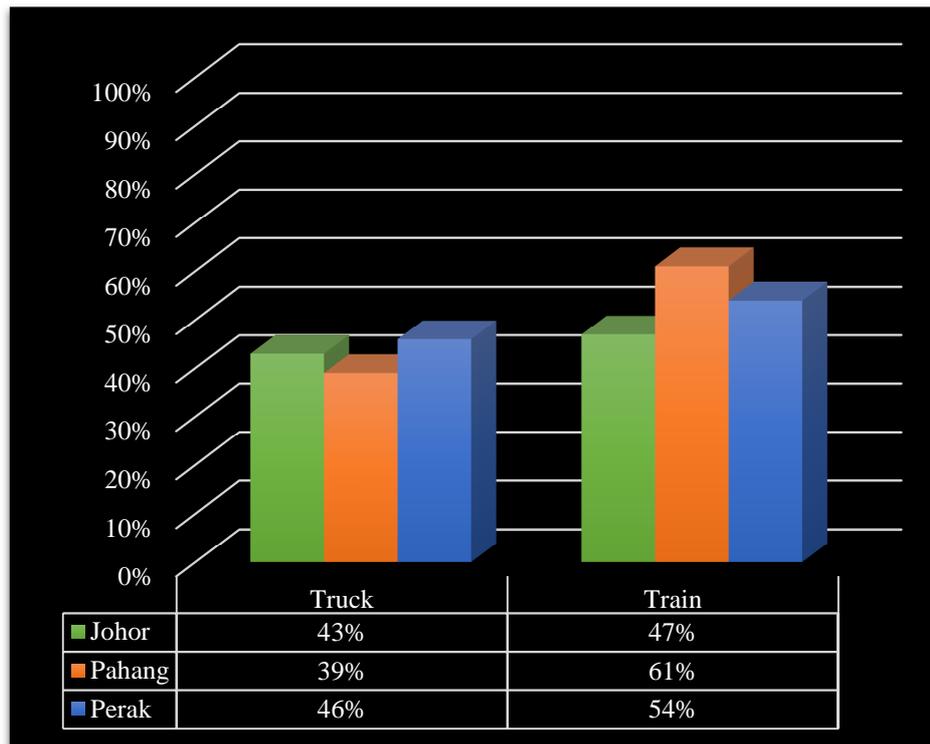


Fig. 10. Average percentage of CO₂ emissions

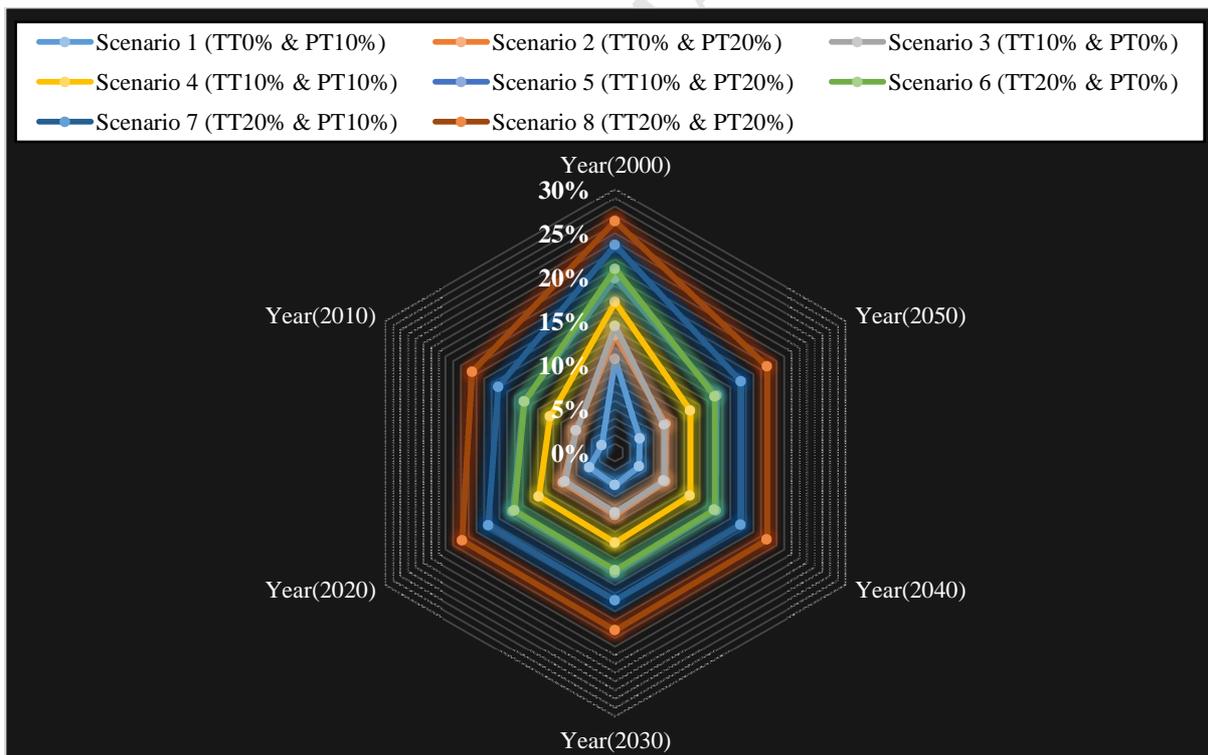


Fig. 11. CO₂ emission changes from 2000 to 2050 for supplier 1

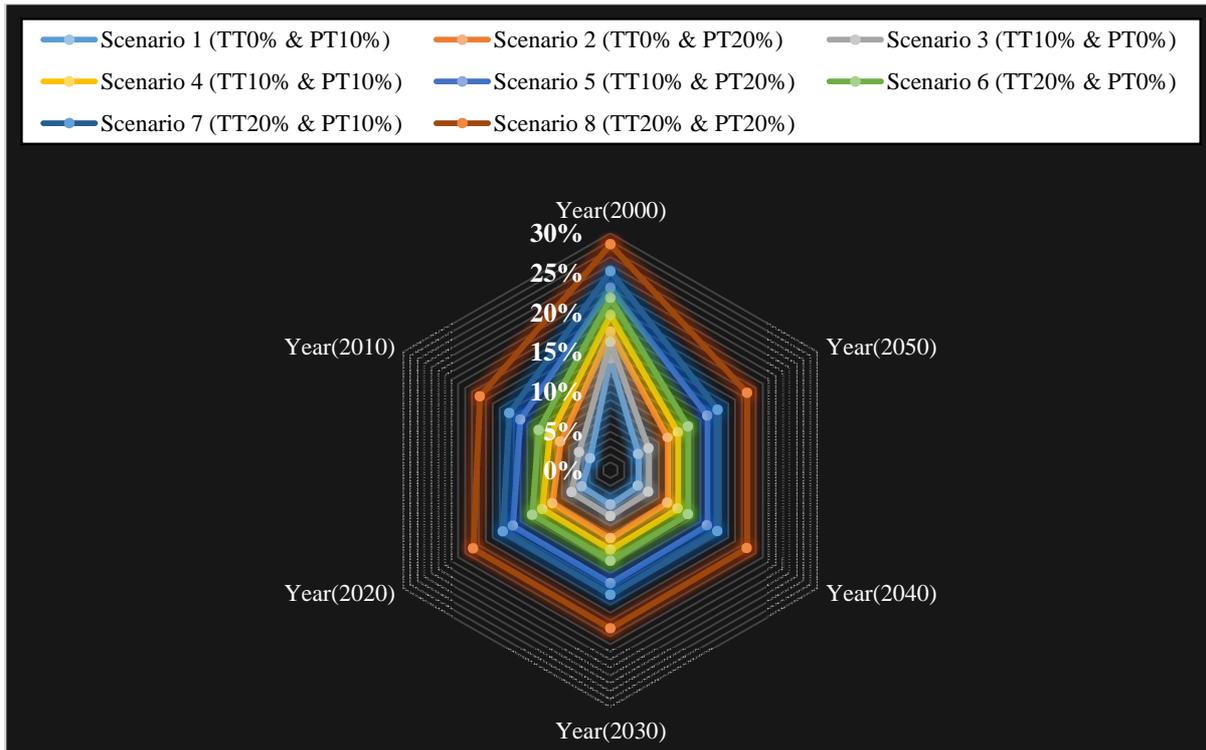


Fig. 12. CO₂ emission changes from 2000 to 2050 for supplier 2

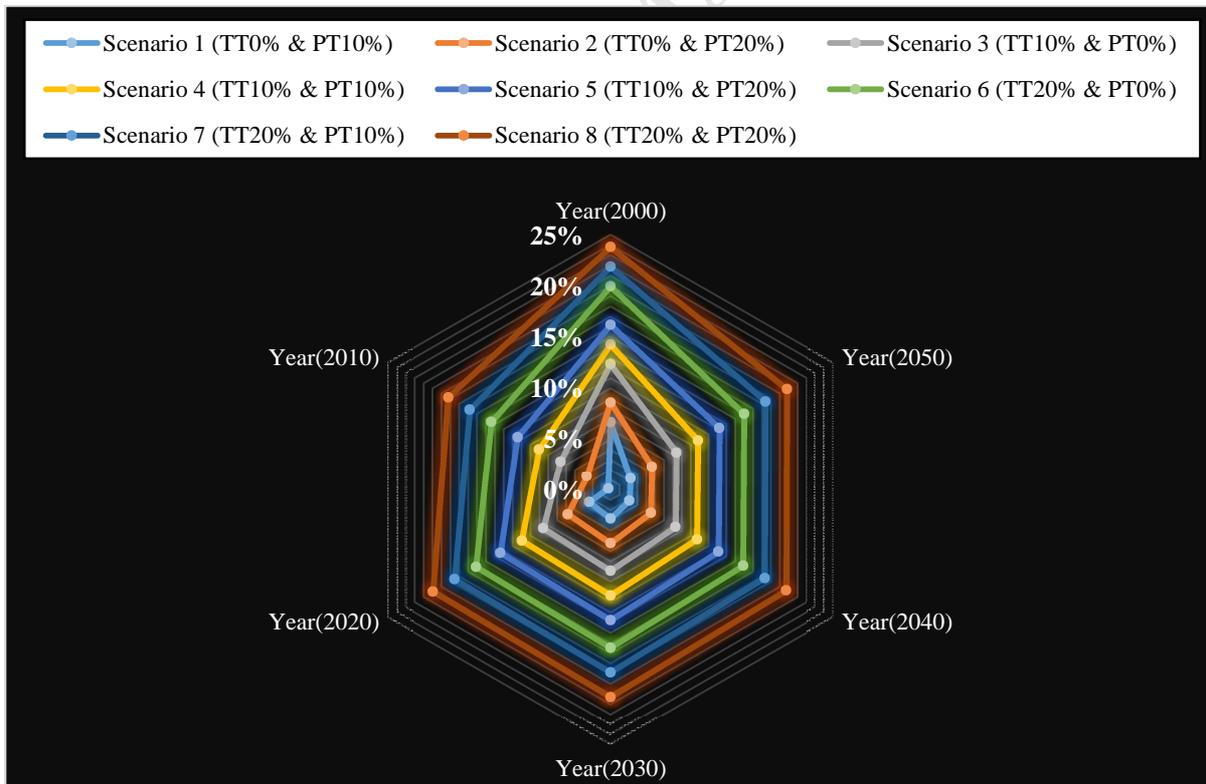


Fig. 13. CO₂ emission changes from 2000 to 2050 for supplier 3

- Ensuring the environmental sustainability of biomass supply chain
- Dynamic simulation model for predicting GHG emissions from biomass supply chain
- Assessment of GHG emissions for palm biomass suppliers in Malaysia (2000-2050)
- Effect of efficiency of transportation and production technology on GHG emissions