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Progress towards Sustainable Production: Environmental, Economic, and Social Assessments of the Cellulose Nanofiber Production Process

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Abstract: We assessed the environmental, economic, and social impacts of the process for producing cellulose nanofibers (CNFs), which are considered to be a valuable sustainable woody biomass feedstock. The greenhouse gas (GHG) emissions associated with CNF production are greater than the emissions associated with producing most plastic materials used in vehicle components because the grinding process during CNF production generates significant GHG emissions. The cost of CNF production is also higher than the cost of producing comparable plastics for automotive use because of the high cost of the pulverization process. The sensitivity analysis in this study suggested that GHG emissions and manufacturing costs could be reduced by 19.1–76.4% and 3.6–12.2%, respectively, by improving the energy efficiency of CNF production by two to five times. We compared the potential social risks associated with CNF production between Japan and Vietnam using a product social impact life cycle assessment database. It is desirable to reduce the social risk on the fair salary and child labor, and to improve the safe and healthy living conditions in the local communities that import wood chips harvested in Vietnam.

Keywords: cellulose nanofibers (CNFs); greenhouse gas (GHG) emissions; social risk; woody biomass

1. Introduction

The utilization of unused logging residues as a type of woody biomass in the forest sector can have environmental effects related to the improvement of energy efficiency and the slowing of global warming. Using logging residues also has economic effects, such as the revitalization of regional economies and industrial development. Many local governments in Japan have started to develop plans for the use of logging residues as woody biomass. Moreover, demand for the use of unused logging residues as a source of energy for generating electricity has increased drastically since a feed-in tariff (FIT) scheme was implemented in Japan in 2014. Under the FIT scheme, electricity produced from applicable renewable energy sources such as solar, wind, geothermal, hydrologic, and biomass must be purchased by power companies at a fixed price within a particular period [1]. In 2015, the local governments of Japan were certified or scheduled to start the test operation of 68 power plants, which will produce yearly 335 million kilowatts of electricity, using approximately 610 million tons of woody biomass [2]. Although the utilization of woody biomass as a new renewable energy source has become mainstream in Japan, woody biomass has also been proposed as a material feedstock to secure the diversity of methods to use the resources. The production of cellulose nanofibers (CNFs), a high-value-added product, is one way to expand the material use of woody biomass. CNFs obtained from woody biomass are fibrous materials consisting of nanosized cellulose with diameters ranging from 1 to 100 nm and aspect ratios (length/diameter) greater than 100 [3,4]. CNFs are light, with one-sixth to one-fifth the weight of steel, and possess bending strength equivalent to that of mild steel [5–7]. Due to these advantages, CNFs have been applied in a wide range of industries such as the paper, electronic parts and devices, pharmaceutical, medicine manufacturing, cosmetics, food, and automotive parts industries [8]. In the automotive parts industry, replacing the plastic resin currently used in vehicles with CNFs could reduce the total weight of the vehicle. The reduction in total vehicle weight resulting from the use of CNFs can be linked with economic and environmental benefits, including increased fuel economy and reduced greenhouse gas (GHG) emissions. Moon et al. studied the economic effects of producing CNFs from logging residues [9]. They determined that the process of CNF production can have net benefits and create jobs in various sectors of industry. Moon et al. also calculated the effect of using CNFs as substitutes for plastic resins on GHG emissions throughout the life cycle of the vehicle [10].

The above studies focused on how to maximize the economic and environmental efficiency of the CNF manufacturing process. To assess the feasibility for implementing a sustainable business, it is necessary to consider the social risks for a certain region in which the business is going to be operated.

In Japan, the use of local resources is a key aspect of basic plans for promoting the utilization of biomass. The use of local resources is expected to benefit rural regions, which are relatively deprived from the viewpoint of sustainable production compared to urban regions [11]. Thus, the benefits of using woody biomass include enhanced opportunities for local community members along with profit and reductions in GHG emissions. Therefore, assessing the economic, social, and environmental effects of CNF production is meaningful for stakeholders associated with all stages of CNF manufacturing and is the focus of this study. First, the environmental impact of CNF production in terms of GHG emissions was assessed, and the manufacturing cost for the entire process of CNF production was calculated using a life cycle assessment (LCA) approach. Second, to assess the effects of improvements in manufacturing technology, the GHG emissions and cost associated with CNF production in 2015 were comparing with those in 2012, the year that CNF manufacturing began. Third, the potential social risk to the community of producing CNF was estimated by applying product social impact life cycle assessment database (PSILCA) methodology as a tool for social LCA (SLCA).

2. Methodology

2.1. Process Boundaries

The process boundaries for the CNF life cycle were divided into four stages, as shown in Figure 1: (1) planting and logging; (2) chipping; (3) transportation; and (4) CNF manufacturing. The stage of CNF manufacturing using the mechanochemical method can be further divided in three sub-stages: (1) preliminary grinding; (2) fine grinding; and (3) classifying.

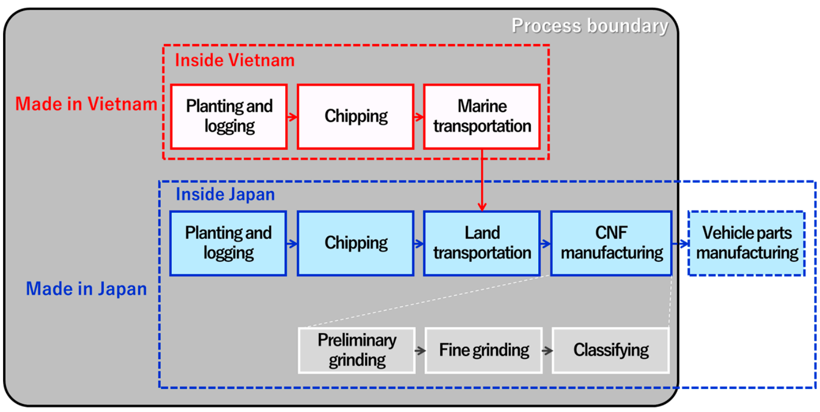

Figure 1. Process boundaries for the life cycle of CNF production.

To estimate social risk, the marine transport stage required to import the raw material from Vietnam is added as an additional stage.

2.2. Preconditions

Table 1 shows the amount of logging residues needed for the manufacturing of 1 kg of dried CNF (1 dry kg) and the set as a basic unit for quantifying environmental, economic, and social impact in this study. Related information such as moisture content and yield rate was obtained from company executives and from Moon et al. [9]. To produce 1 kg of CNFs, approximately 2.9 wet ton of logging residue is needed as a feedstock. This amount was calculated considering the moisture content of the logging residue, yield rate of wood chips made from the logging residue, and yield rate of CNFs made from the wood chips. The calculations assumed that the plant producing the CNFs to have a production capacity of 40 tons.

Table 1. Amount of logging residue required for manufacturing 1 kg of CNFs.

Items		Amount		Required Condition		
		Figure	Unit	Substance	Figure	Source
CNF	$Q_{dry-CNF}$	1 *	dry kg			
Chip (dry)	$Q_{dry-chip}$	1.3 *	dry kg	Yield rate	80	-
Chip (wet)	$Q_{wet-chip}$	2.6 *	wet kg	Moisture content	52%	Moon et el. [9]
Logging Residues	$Q_{residues}$	2.9 *	wet kg	Yield rate	89%	Moon et al. [9]

* Figures used in the table above rounded off to the nearest hundredth (or where appropriate).

2.3. Estimating GHG Emissions

LCA was used as to estimate the GHG emissions associated with the manufacturing of CNFs from logging residues. Total GHG emissions (Ghg_T), including the emissions during planting and logging (Ghg_1), chipping (Ghg_2), transportation (Ghg_3), and CNF manufacturing (Ghg_4), was calculated as:

$$Ghg\_T = \sum_{s=1}^{n} Ghg\_S \text{ (S} = 1,\ 2,\ 3,\ 4) \tag{1}$$

where Ghg_T is the total GHG emissions per kg of CNF production (kg CO_2eq/kg CNF); Ghg_S is the amount of GHG emissions per kg of CNF production during stage S of CNF production ($S = 1,\ 2,\ 3,$ and 4 are the planting and logging, chipping, transport, and CNF manufacturing stages, respectively).

The amount of GHG emissions in the planting and logging stage (Ghg_1) was calculated by multiplying the quantity of logging residues use ($Q_{residues}$) by the unit energy consumption in the planting and logging stage ($EC_{logging}$) and the GHG emissions efficient for diesel, which is the main energy source in the planting and logging stage (c_ghg^{diesel}):

$$Ghg\_1 = Q_{residues} \times \left(\frac{EC_{logging}}{1000}\right) \times c\_ghg^{diesel} \tag{2}$$

where Ghg_1 is the amount of GHG emissions per kg of CNF production in the planting and logging stage (kg CO_2eq/kg CNF); $Q_{residues}$ is the quantity of logging residues used to generate 1 kg of CNFs (wet kg/kg CNF); $EC_{logging}$ is the unit energy consumption in the planting and logging stage (L/kg); c_ghg^{diesel} is the GHG emissions coefficient of diesel (kg CO_2eq/L) based on the Japan Environmental Management Association for Industry (JEMAI) [12].

The amount of GHG emissions in the chipping stage (Ghg_2) was calculated as shown in Equation (3):

$$Ghg\_2 = Q_{residues} \times \left(\frac{EC_{chipping}}{1000}\right) \times c\_ghg^{diesel} \tag{3}$$

where Ghg_2 is the amount of GHG emissions per a kg of CNF production in the chipping stage, and $EC_{chipping}$ is the unit energy consumption in the chipping stage. The main source of energy during chipping is diesel, as for planting and logging.

The amount of GHG emissions in the transportation stage (Ghg_3) was calculated using Equation (4):

$$Ghg\_3 = Q_{wet-chip} \times TD_{ftf} \times (\frac{EC_{transportation}}{1000}) \times c\_ghg^{diesel} \quad (4)$$

where Ghg_3 is the amount of GHG emissions per kg of CNF production in the transportation stage; $Q_{wet-chip}$ is the quantity of wood chips required for the production of 1 kg of CNF production (wet kg/kg CNF); TD_{ftf} is the transportation distance from forest to factory (km); and $EC_{transportation}$ is the unit energy consumption of CNF production during the transportation stage (0.059 L/ton CNF km [13]). Ghg_3 was evaluated using the TON-KM method suggested by the Japanese government (METI and MLTI, 2006). The TON-KM method is a standard way to estimating CO_2 emissions caused by truck transport. TD_{ftf} was based on a NEDO research report [14]. $EC_{transportation}$ was determined assuming an eight-ton dump truck at 60% loading rate [13].

The amount of GHG emissions in the CNF manufacturing stage was calculated by summing the GHG emissions of the three stages of CNF manufacturing (preliminary grinding, fine grinding, and the classifying), as shown in Equation (5):

$$Ghg\_4 = \sum_{l=1}^{n} Ghg_4^l \ (l = 1,\ 2,\ 3), \quad (5)$$

where Ghg_4 is the amount of GHG emissions per kg of CNF production during CNF manufacturing (kg CO_2eq/kg CNF); Ghg_4^l is the amount of GHG emissions per kg of CNF production at stage l of the CNF manufacturing stage (l = 1, 2 and 3 correspond to preliminary grinding, fine grinding, and classifying, respectively). Ghg_4^1, Ghg_4^2, and Ghg_4^3 were calculated by multiplying the quantity of wood chips used by the unit energy consumption of each manufacturing level ($EC_{CNF\_manufacturing}^{preliminary}$, $EC_{CNF\_manufacturing}^{fine\ grinding}$, and $EC_{CNF\_manufacturing}^{classifying}$) and the GHG emissions coefficient for electricity ($c\_ghg^{electricity}$):

$$Ghg_4^1 = Q_{dry-chip} \times (\frac{EC_{CNF_{manufacturing}}^{preliminary}}{1000}) \times c_{ghg}{}^{electricity} \quad (6)$$

$$Ghg_4^2 = Q_{dry-chip} \times (\frac{EC_{CNF_{manufacturing}}^{fine\ grinding}}{1000}) \times c_{ghg}{}^{electricity} \quad (7)$$

$$Ghg_4^3 = Q_{dry-CNF} \times (\frac{EC_{CNF_{manufacturing}}^{classifying}}{1000}) \times c_{ghg}{}^{electricity} \quad (8)$$

where $Q_{dry-chip}$ is the quantity of wood chips used to generate 1 kg of CNFs (dry kg/kg CNF), and $Q_{dry-CNF}$ is the quantity of CNFs produced (kg).

The values of unit energy consumption and the GHG emissions coefficient used in all calculations are shown in Table 2. Data related to the energy consumption coefficient for the CNF manufacturing stage were obtained from the executives of companies that produce CNFs. The GHG emissions produced by light diesel oil and electricity were obtained from the Inventory Database for Environmental Analysis (IDEA). IDEA is a total database of GHG emissions from different raw materials and was developed by the National Institute of Advanced Industrial Science and Technology in coordination with JEMAI [12]. In IDEA, the six primary Kyoto GHGs, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs), are translated into CO_2equivalents (CO_2eq) using global warming potential values provided by the Intergovernmental Panel on Climate Change in 1995.

Table 2. Values of unit energy consumption and GHG emission coefficient for each stage.

Items	*Ghg_1*	*Ghg_2*	*Ghg_3*	*Ghg_4*		
				Ghg_4^1	Ghg_4^2	Ghg_4^3
Energy	Light diesel oil			Electricity		
The unit energy consumption	2.5	5	0.059	2000	6400	400
Unit	L/wet ton		L diesel/ton km	kWh/dry ton		
Sources	NEDO (2010)		METI and MLIT (2006)	Measured value (2015)		
The GHG efficient	3.21			0.69		
Unit	kg CO_2eq/L			kg CO_2eq/kWh		
Sources	IDEA					

2.4. Calculating Manufacturing Cost

The total manufacturing costs associated with planting and logging $(Cost\_1)$, chipping $(Cost\_2)$, transportation $(Cost\_3)$, and CNF manufacturing $(Cost\_4)$ were calculated as in Equation (9):

$$Cost\_T = \sum\nolimits_{s=1}^{n} Cost\_S \ (\mathrm{S} = 1,\ 2,\ 3,\ 4) \tag{9}$$

where $Cost\_T$ is the total cost in Japan Yen (JPY) per kg of CNF production (JYP/kg CNF), and $Cost\_S$ is the cost in stage S of CNF production.

The manufacturing costs in the planting and logging stage ($Cost\_1$), chipping stage ($Cost\_2$), and transportation stage ($Cost\_3$; JPY/kg CNF) were computed by multiplying the quantity of logging residue needed to produce one kg of CNFs by the unit cost for each stage ($UC_{logging}$, $UC_{chipping}$, and $UC_{transportation}$, respectively; JPY/kg), as shown Equations (10)–(12):

$$Cost\_1 = Q_{residues} \times UC_{logging} \tag{10}$$

$$Cost\_2 = Q_{residues} \times UC_{chipping} \tag{11}$$

$$Cost\_3 = Q_{wet-chip} \times UC_{transportation} \tag{12}$$

where $Q_{residues}$ is the quantity of logging residue used to generate 1 kg of CNF production (wet kg/kg CNF), and $Q_{wet-chip}$ is the quantity of wet wood chips used to generate 1 kg of CNFs (wet kg/kg CNF).

In the CNF manufacturing stage, the manufacturing cost ($Cost\_4$; JPY/kg CNF) was calculated by summing the manufacturing costs of the above three stages, as shown in Equation (13):

$$Cost\_T = \sum\nolimits_{l=1}^{n} Chg_4^l \ (l = 1,\ 2,\ 3) \tag{13}$$

where GHG_4^l is the amount of GHG emissions per kg of CNF production during level l of CNF manufacturing (l = 1, 2, and 3 correspond to preliminary grinding, fine grinding, and classifying, respectively).

The manufacturing costs for each process of CNF manufacturing ($Cost_4^1$, $Cost_4^2$, and $Cost_4^3$) were calculated by dividing the expense for each level of stage 4 (E_4^1, E_4^1, and E_4^3; JPY/kg CNF) by the total quantity of CNFs produced, as shown in Equations (14)–(16):

$$Cost_4^1 = E_4^1 / PQ_{CNF} / 1000 \tag{14}$$

$$Cost_4^2 = E_4^2 / PQ_{CNF} / 1000 \tag{15}$$

$$Cost_4^3 = E_4^3 / PQ_{CNF} / 1000 \tag{16}$$

where PQ_{CNF} is the total quantity of CNFs produced (ton). The expense for each level of stage 4 was determined by summing eight individual expenditures: the cost of raw materials, cost of fuel (e.g., light diesel oil and electricity), depreciation, personnel expenses, maintenance costs, cost of debt redemption, annual fixed asset costs, and general management costs. These costs were obtained from the executives of companies that produce CNFs. The calculations assumed that CNF manufacturing hours were eight hours a day for 250 days a year.

The fixed expenses (depreciation, personnel expenses, maintenance costs, cost of debt redemption, annual fixed asset costs, and general management costs) account for approximately 82% of total expenditures. The fixed expenses were not divided into each level of the CNF production stage as were the variable costs (the cost of raw materials and cost of fuel expenses). The fixed expenses for each level was determined by dividing the total fixed expense by the number of level of stage. Table 3 shows the cost for each stage used to calculate the expenditures.

Table 3. Unit cost for each CNF production stage.

Categories and Items		Figure	Unit	Source
*Cost*_1	Unit cost of production	3625	JPY/ton	NEDO Research report [14]
*Cost*_2	Unit cost of production	5263	JPY/ton	
*Cost*_3	Unit cost for delivery (in the case of 30 km)	2815	JPY/ton	The average by 14 delivery companies
	Purchase unit cost	20,000	JPY/ton	Measured data in 2015
*Cost*_4	Unit cost of electric power	22	JPY/kWh	Unit price offered by EFTC [15]
	Personnel expenses	20,000	JPY/day	Measured data in 2015

2.5. Assessing Potential Social Impact

SLCA is a social impact or potential impact assessment technique that evaluates the social and socio-economic aspects of products and their potential positive and negative effects along the product's life cycle, including the extraction and processing of raw materials [16]. However, the assessment ability of SLCA is limited because of the lack of information to organize, measure, and quantify the various social phenomena. Despite these difficulties, assessing the social impacts of products can be a valuable tool to understand the effect of a product on society.

The United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) produced guidelines for SLCA assessment (SLCA guidelines). The SLCA guidelines propose a methodology for assessing the social and socio-economic impacts of a product, process, or activity throughout its life cycle, from the extraction of raw materials to processing, transport, use, and disposal. In the SLCA guidelines, stakeholders and its impact categories are set as socio-economic subcategories of inventory indicators to support further the identification of stakeholders [16]. Particularly, stakeholder categories, i.e., the parent category that includes the child category, are divided into the following five categories: worker, consumer, local community, society, and value chain actors that do not include consumers (value chain actors). The impact categories, i.e., the child category belonging to stakeholder category of the parent category, is divided into 31 subcategories.

Based on the SLCA guidelines, the social hotspots database (SHDB) and PSILCA were developed as comprehensive databases for evaluating the social impacts of products throughout their life cycles [17,18]. To provide insights into the global supply chain related to a product's life cycle, SHDB and PSILCA are commonly used as global input–output (IO) databases that are linked to information on all countries of the world's economy. Through the IO database, it is possible to trace the worker hours and social risks associated with global industrial activities. In addition, potential social impacts related to industrial activities can be deduced based on information from various world agencies, international statistics, and other documents. Although the methodologies used to analyze SHDB and PSILCA are similar, the social indicators and the evaluation criteria for assessing potential social impacts differ slightly. For the SHDB developed by New Earth, 22 social theme tables by country and economic sector, along with 134 social indicators have been established for determining potential social impacts based on over 200 reputable sources of statistical (e.g., the World Health Organization and International Labor Organization) [17]. Potential social impacts can be graded on a five-tier scale: undefined risk level (URL), low risk (LR), medium risk (MR), high risk (HR), and very high risk

(VHR). PSILCA, produced by Green Delta, with four affected stakeholder groups, 17 subcategories for social topics, and 55 qualitative and quantitative indicators has been composed as social indicators for potential social impacts used from the raw data like as the UN's system of national accounts and COMTRADE databases, Eurostate, IDE/JETRO, and numerous national agencies [18]. Here, potential social impact is categorized into two large divisions: (1) potential risk, which is divided into six risk levels (no risk, very low risk, low risk, medium risk, high risk, and very high risk); and (2) potential opportunity, which is classified into three opportunity levels (high opportunity, medium opportunity, and low opportunity).

The social impact categories used in SHDB and PSILCA are compared with the social indicators in the SLCA guidelines of UNEP/SETAC in Table 4. The social indicators categorized in SHDB emphasize the living conditions for human beings, particularly workers. Thus, the contents are related to all aspects of society, including labor rights, human rights for the weak in society, health and safety, transparency of the administrative procedure and the legal system, and community infrastructure. In PSILCA, the social indicators are mainly based on the SLCA guidelines and focus on social issues affecting stakeholders such as workers, value chain actors, the local community, and society. Social indicators related to the local community include the socio-economic contributions to the local community in terms of the use of local resources and local employment.

Table 4. Social impact categories according to SHDB and PSILCA in comparison to the SLCA guidelines of UNEP/SETAC.

Stakeholder Categories and Subcategories (UNEP, 2009)		SHDB	PSILCA
Stakeholder Categories	**Impact Categories**		
Worker	Freedom of association and collective bargaining	○	○
	Child labour	○	○
	Fair salary	○	○
	Working hours	○	○
	Forced labour	○	○
	Equal opportunities/Discrimination	○	○
	Healthy and safety	○	○
	Social benefits/Social security	○	○
Consumer	Health & safety	○	○
	Feedback mechanism		
	Consumer privacy		
	Transparency		
	End of life responsibility		
Local community	Access to material resources		○
	Access to immaterial resources		
	Delocalization and migration	○	○
	Cultural heritage		
	Safe & healthy living conditions	○	○
	Respect of indigenous rights	○	○
	Community engagement		
	Local employment	○	○
	Secure living conditions	○	

Table 4. *Cont.*

Stakeholder Categories and Subcategories (UNEP, 2009)		SHDB	PSILCA
Stakeholder Categories	**Impact Categories**		
Society	Public commitments to sustainability issues		
	Contribution to economic development	○	○
	Prevention & mitigation of armed conflicts	○	
	Technology development		
	Corruption	○	○
Value chain actors not including consumers	Fair competition	○	○
	Promoting social responsibility		○
	Supplier relationships		
	Respect of intellectual property rights		

The definition of classifying the social impact categories are slightly differences between SHDB, and PSILCA.

This study aims to assess the impacts of CNFs along their entire life cycle on local communities in which a woody biomass material, such as logging residue, can be harvested. Therefore, PSILCA was used to assess the social impacts to the local community.

3. Results and Discussion

3.1. Environmental Impact: GHG Emissions

The amount of GHG emissions in each stage of CNF production is shown in Figure 2. The GHG emissions for the planting and logging stage, chipping stage, and transportation stage were 0.023, 0.047, and 0.015 kg CO_2eq/kg, respectively. The emissions for the three sub-stages of the CNF manufacturing stage (preliminary grinding, fine grinding, and classifying) were 1.723, 5.513, and 0.276 kg CO_2eq/kg, respectively. This study assessed GHG emissions for CNFs produced by the mechanochemical methods; in this production methodology, the greatest GHG emissions are associated with preliminary grinding, fine grinding, and electricity consumption.

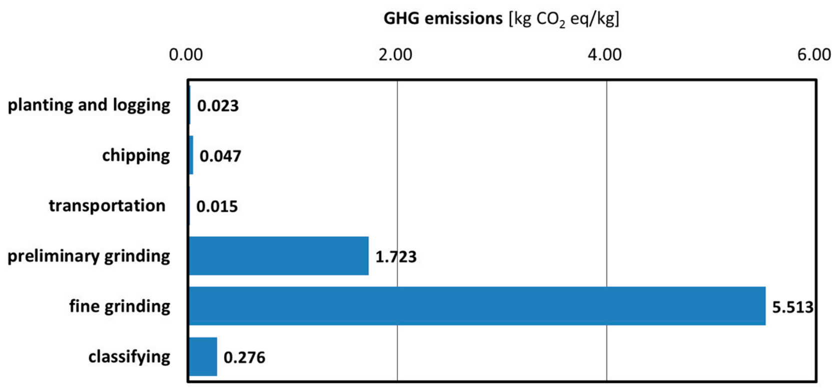

Figure 2. GHG emissions for each stage of CNF production.

The total amount of GHG emissions for the entire manufacturing process of 1 kg of CNFs was approximately 7.597 kg CO_2eq/kg, as shown in Figure 3. The total amount of GHG could be 5.76 kg CO_2eq/CNF kg, by excluding the approximate value of 1.83 kg CO_2eq/kg, which are examined under the assumption that the carbon content is 50% from the total weight of CNF (Figure 3) [6,19].

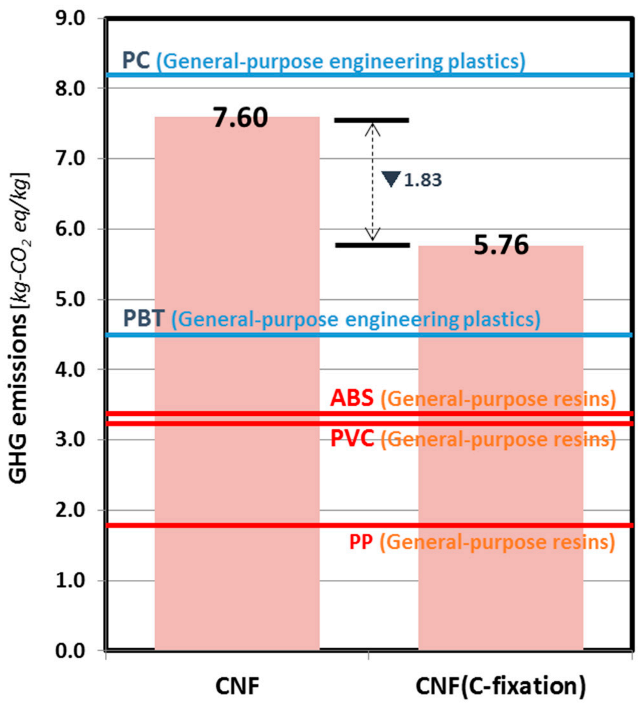

Figure 3. GHG emissions from CNF production (base case) in comparison with plastic materials used in vehicle components.

Figure 3 compares the GHG emissions from CNFs and five plastic resins, polypropylene (PP), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polyvinyl chloride (PVC), and polybutylene terephthalate (PBT), which are the most commonly used in plastic parts in automobiles [20]. The consumption rates of PP, ABS, PC, PVC, and PBT in automobiles are 42.7%, 7.3%, 4.5%, 3.1%, and 2.9%, respectively [20].

The GHG emissions from PP, ABS, PC, PVC, and PBT were 1.782, 3.277, 8.207, 3.389, and 8.207 kg CO_2eq/kg, respectively [12]. The GHG emissions of CNFs were higher than those of the plastic resins except PC, even though C-fixation is considered as one of the factors for determining the GHG emissions of CNFs.

However, because CNFs are used to reinforce plastic resins, the total amount of plastic components can be decreased by adding CNFs instead of a certain amount of plastic resins [20]. Moreover, the reduction in the total amount of plastic component is linked to a reduction in the total volume of the vehicle; thus, a decrease in GHG emissions resulting from an increase in fuel economy can be expected [10].

3.2. Economic Impact: Manufacturing Cost

The manufacturing cost of each stage of CNF production is shown in Figure 4. The total manufacturing cost was 1615.6 JPY/CNF kg. The costs for the planting and logging stage, chipping stage, and transportation stage were 10.6, 15.4, and 7.3 JPY/CNF kg, respectively. The costs of the three sub-stages of CNF manufacturing (preliminary grinding, fine grinding, and classifying) were 298.3, 1029.7, and 254.3 JPY/CNF kg, respectively. As for the environmental impacts in Section 3.1, the manufacturing costs were the highest in the preliminary grinding and fine grinding stages.

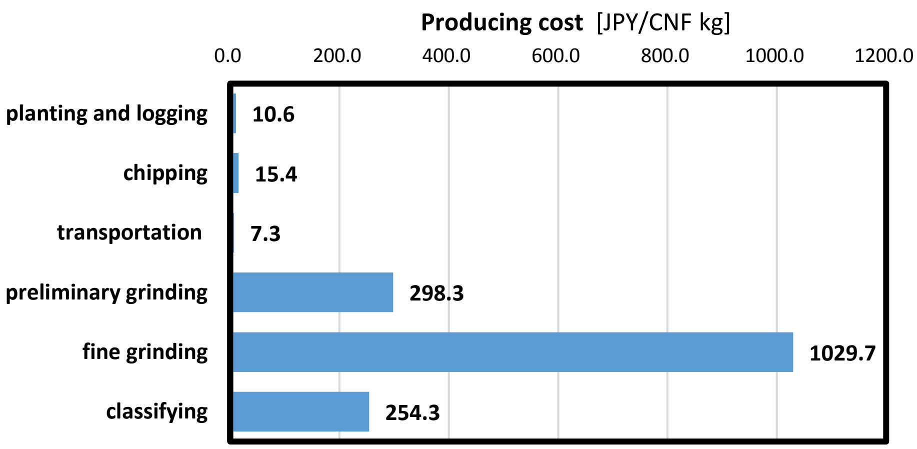

Figure 4. The manufacturing cost of each stage of CNF production.

The production unit prices and shipping unit prices for PP, ABS, PC, PVC, and PBT based on 2015 METI statistics [21] are shown in Figure 5. The shipping unit prices ranged from 138.42 to 342.79 JPY/CNF kg, and the range of production unit prices was 126.98 to 339.01 JPY/CNF kg, accounting for approximately 8.6–21.2% of the total production price for CNF, which is not as stable as the specific markets that are established.

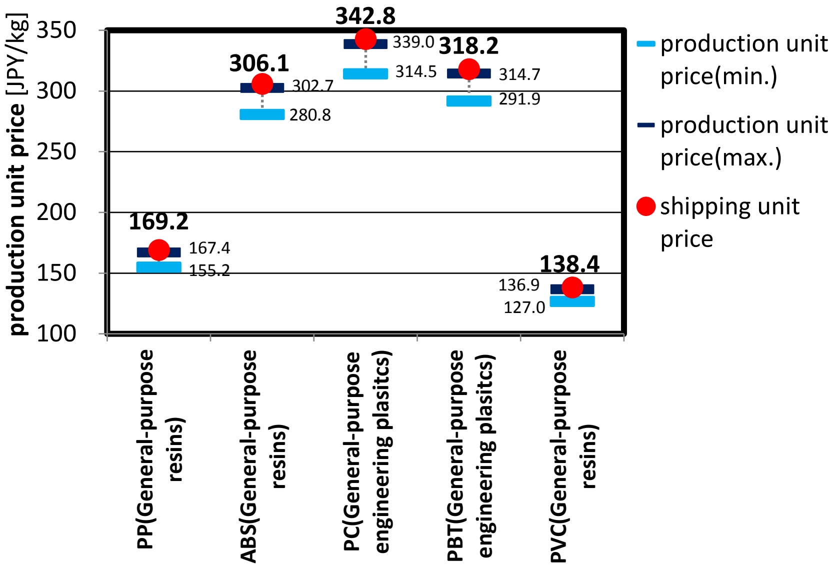

Figure 5. Production unit prices and shipping unit prices for five plastic resins.

3.3. Sensitivity Analysis: Potential Improvements in Environmental and Economic Efficiency

The changes in GHG emissions and manufacturing cost between 2012, the year when CNF manufacturing began, and 2015 are shown in Figure 6. The GHG emissions and manufacturing cost decreased by approximately 13.0% and 1.7%, respectively, from 2012 to 2015 as a result of eliminating the hot-compressed water treatment stage from the CNF production process.

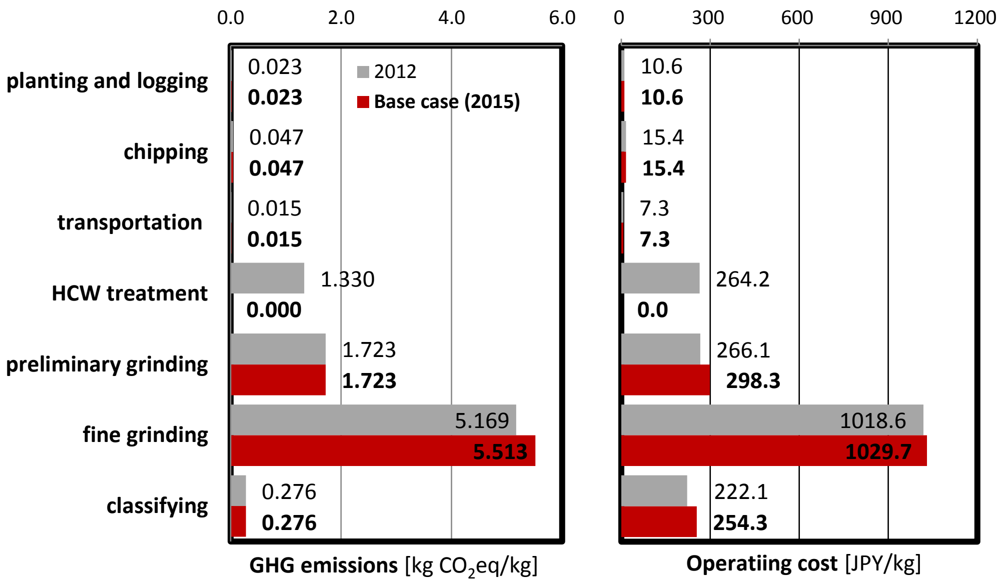

Figure 6. GHG emissions and manufacturing costs for CNFs in 2012 and 2015.

The efficiency of GHG emissions and manufacturing cost also can be improved by 0.2% and 0.4%, respectively, compared to the base year of 2015, by increasing the yield rate from 0.8 to 1.0. Moreover, greater reductions in GHG emissions and manufacturing cost can be expected by improving the energy consumption efficiency in the preliminary and fine grinding stages by two to five times, as shown in Figure 7.

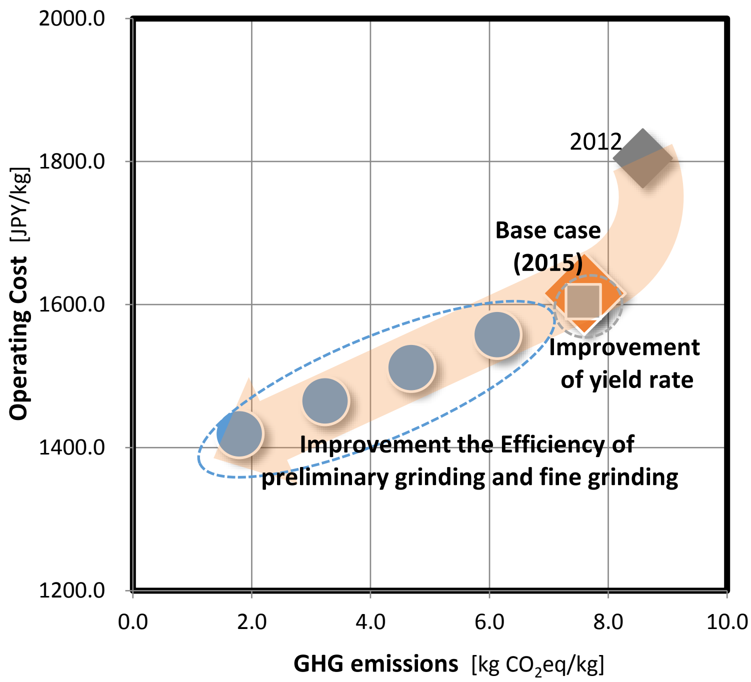

Figure 7. Operating cost and GHG emissions by sensitivity analysis of the yield rate and the energy consumption efficiency.

By increasing the energy consumption efficiency from two to five times in the two stages, the GHG emissions can be decreased by between 19.1% and 76.4% compared to 2012 levels, in which the maximum emission level was similar to that of PP (1.8 kg CO_2eq/CNF kg). At the same time, the manufacturing cost can be expected to be reduced between 3.6% and 12.2% from 1419.1 JPY/CNF kg in 2015 by enhancing the energy consumption efficiency by two to five times. Since fixed costs account for ca. 80% of the total manufacturing cost, it is difficult to achieve large reductions in manufacturing costs without large-scale CNF production.

3.4. Social Impact: Potential Social Risk

The above results show that environmental and economic efficiency can be improved by technological advances in the process of CNF production. In an attempt to increase the profit from the business for CNF manufacturing, budget reduction with lower raw material costs by looking for other sources of wood chip instead of their own local resources can be considered. However, an effort to improve the environmental and economic efficiency can lead to other social consequences.

In this chapter, the potential social risk of implementing CNF manufacturing was estimated by PSILCA. The various potential social risks related with the terms of employment, working conditions, and human rights within a certain region where people work can be assumed through this tool. To better understanding the social risks in Japan, the following two scenarios were evaluated: RM-J and RM-V. The RM-J scenario corresponds to the entire process of CNF production as it is implemented in Japan. In contrast, the RM-V scenario assumes that the wood chips in Vietnam are used for CNF production (Figure 1) because the price of wood chips is relatively cheap than that of those found in Japan. Thus, the social risk for labor activities of the planting and logging, and the chipping stage for collecting raw material of CNF production between two countries could be evaluated. To estimate potential social risks, the detailed costs for manufacturing CNF that are used for evaluating economic impacts were reorganized by industrial sectors for use as social parameter values in PSILCA (the calculation results for potential social risks are expressed in the unit of worker hours and social impacts for the manufacturing CNF process of global industrial activities) as shown in Table 5.

Table 5. Detailed cost for the social parameter value in PSILCA (Unit: USD/CNF 1 USD).

Industrial Sector	Scenario	
	RM-J	**RM-V**
Wooden chips JP	0.01057	-
Forestry VN	-	0.00531
Transport VN	-	0.00421
Travel agency and other services relating to transport JP	0.00298	0.00298
Real estate rental service JP	0.03386	0.03390
Water supply JP	0.01170	0.01171
Other business services JP	0.02018	0.02020
Electric power for enterprise use JP	0.26221	0.26249
Manufacture of other products of wood JP	0.65851	0.65921
Total	1.00000	1.00000

As shown in Figure 8, the relative social risk distribution by the input costs in both scenarios have similar results because only the wood chip harvesting-related process from the total process is different between the two scenarios. In the RM-J scenario, the highest potential social risk caused by CNF manufacturing was in the worker sector, which accounted for approximately 46.0% of total risk in the five stakeholder categories, which ratio is similar to the RM-V scenario. The local community, society, and value chain actor sectors had the next highest levels of risk, accounting for approximately 29.7%, 16.1%, and 8.1% of total risk, respectively. In the consumer sector, no potential social risk was found. In the RM-V scenario, the distribution of potential social risk among the stakeholder categories was similar to in the RM-J scenario. Instead, there was a noticeable discrepancy between the scenarios in the ratio of the subcategories in each category, as shown in Figures 9–12.

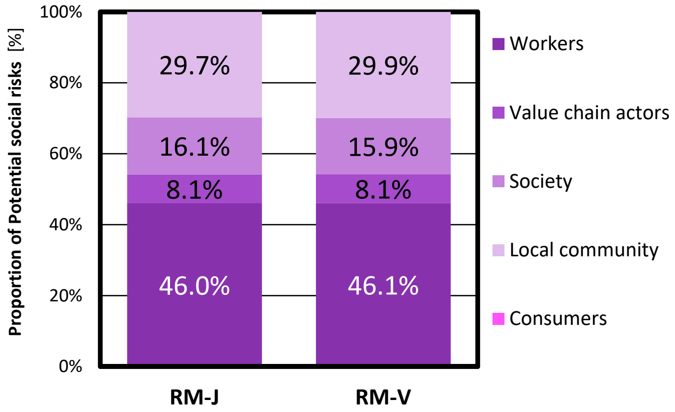

Figure 8. Potential social risks of CNF production determined using PSILCA.

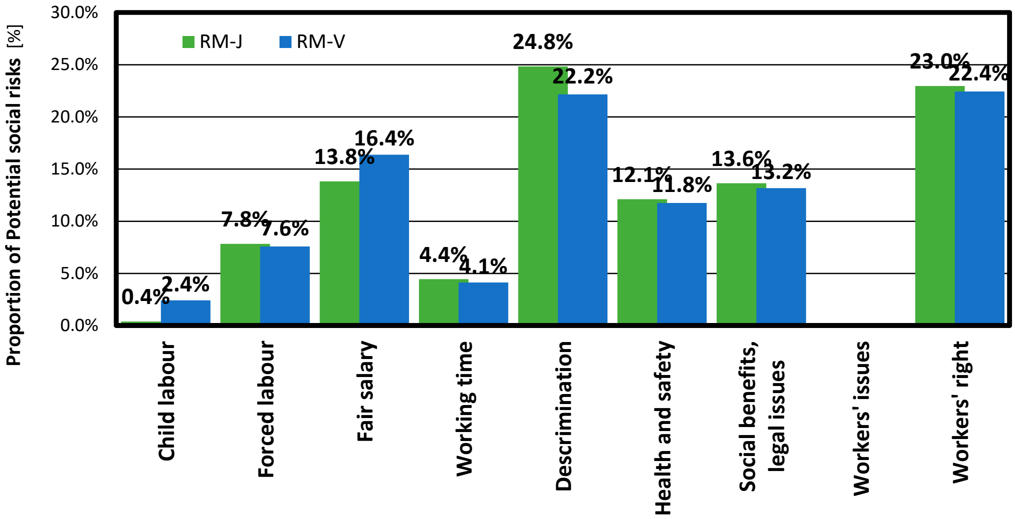

Figure 9. Detailed breakdown of potential social risks in the worker category.

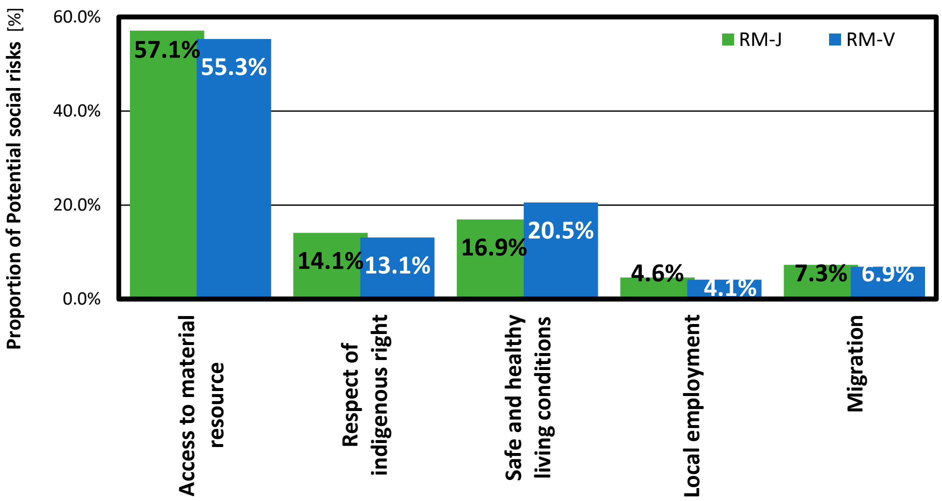

Figure 10. Detailed breakdown of potential social risks in the local community category.

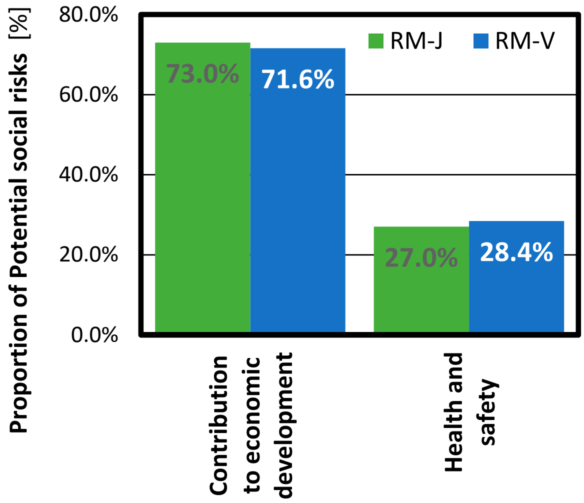

Figure 11. Detailed breakdown of potential social risk in the society category.

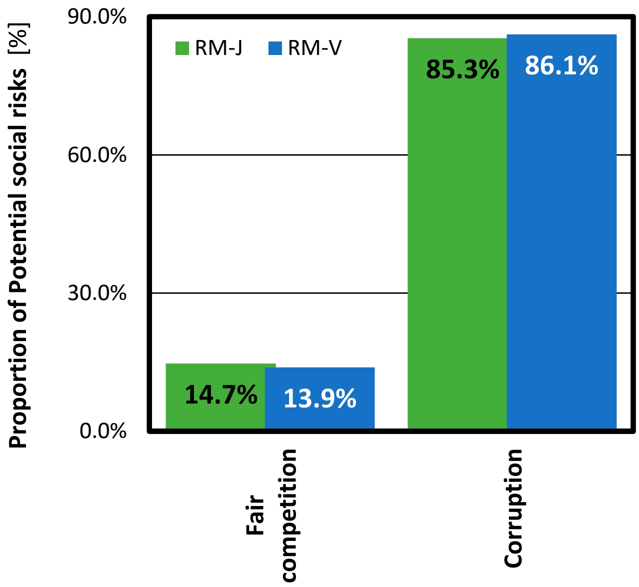

Figure 12. Detailed ratio of potential social risk in the value chain actors category.

In the worker category, discrimination and worker's rights were common potential social risks in both scenarios. In the RM-J scenario, discrimination and worker's rights accounted for 24.8% and 23.0% of social risks in this category, approximately 2.7% and 0.5% higher than in the RM-V scenario (22.2% and 22.4%, respectively). The potential social risks of fair salary and child labor also tended to be higher in the RM-V scenario than in the RM-J scenario (16.4% and 2.4% compared to 13.8% and 0.4%, respectively; Figure 9). In the local community category, the potential social risks of access to material resources and respect of indigenous rights were roughly 1.8% and 1.0% in the RM-J scenario than in the RM-V scenario, while the risk of safe and healthy living conditions was approximately 3.6% lower in the RM-J scenario (Figure 10).

In the society and value chain actors categories, the differences in the distributions of potential social risks between the two scenarios were minor. In the society category, the contribution of economic development to risk in the RM-J scenario was 73.0%, 1.4% higher than in the RM-V scenario; the contribution of the risk to health and safety in the RM-J scenario was 1.4% lower than in the RM-V scenario (Figure 11). In the value chain actors category, the contribution of the potential risk of corruption in the RM-J scenario (85.3%) was slightly smaller than in the RM-J scenario (86.1%).

Meanwhile, the contribution of fair competition in the RM-J scenario was 14.7%, approximately 0.9% higher than in the RM-V scenario (Figure 12).

4. Conclusions and Next Steps

This study was proposed to estimate the social, the environmental and the economic impact associated with CNF manufacturing, which is considered a valuable material in many industries, to clarify the significance of woody biomass as a feedstock from the three dimensions of sustainable development.

The results show that the GHG emissions and manufacturing cost in 2015 were roughly 13.0% and 1.7% lower, respectively, compared to in 2012, the year when CNF manufacturing began. Moreover, the GHG emissions and manufacturing cost can be reduced by up to 76.4% and 12.2%, respectively, by enhancing the efficiency of energy consumption between two and five times. However, this does not necessarily mean that the improvement of the environmental and economic efficiency can be effective in improving social performance. To better understand the social impacts of CNF production in Japan, the potential social risk of CNF manufacturing in Japan and Vietnam were also estimated and compared using PSILCA. Here the proportion of total potential social risk was regarded as a valuable criterion for evaluating social risks of the two countries because of the difficulties of absolute evaluation of the working conditions of employees in the two countries. The importing of wood chips to Vietnam from Japan can cause risks of fair salary and child labor (in the worker category) along with the risk of safe and healthy living conditions (in the value chain actors category) to be high compared to when the wood chips are harvested locally in Japan and used for CNF manufacturing without import. Instead, the potential risk of discrimination and the worker's rights in the worker category, and the access to material resources and the respect of indigenous rights in the local community category can be threatened by the self-sufficiency of raw materials in Japan.

This study examined the environmental, economic, and social impacts associated with the utilization of woody biomass for manufacturing CNFs, which are considered high-value-added products. Opportunities for reducing GHG emissions and manufacturing cost were also suggested via sensitivity analysis. However, empirical analyses to support the results of the theoretical analysis were lacking in this study. The calculation of GHG emissions only focused on CNF manufactured via mechanochemical treatment although there are many types of treatment processes that extract CNF from natural sources [8], which can influence the amount of GHG emitted. Moreover, it is not sufficient to assess sustainability for the relationships between the environmental, economic, and social impacts in the process of manufacturing CNF. A feasible approach for assessing sustainability with effective tools for estimating potential social impacts is needed for future studies.

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