

Article

Life Cycle Assessment of the Closed-Loop Recycling of Used Disposable Diapers

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Received: 31 January 2020; Accepted: 12 March 2020; Published: 17 March 2020



Abstract: In Japan, approximately 23.5 billion paper diapers are produced annually (total of diapers for infants and adults produced in 2018). The majority of used paper diapers are disposed of through incineration; in certain regions, some paper diapers are recycled, mostly by open-loop recycling or thermal recycling. To date, several methods of recycling used paper diapers have been proposed and developed, but these methods are considered to have different types and amounts of recycled materials and different environmental performances. In this study, a new technology was developed for the closed-loop recycling of used paper diapers, and the use of the recycled pulp and superabsorbent polymer (SAP) as materials for paper diapers was evaluated via the environmental impact using the life cycle assessment (LCA) method, using data obtained from experimental facilities for recycling. The results between the comparison of the new method with the landfill and incineration processes demonstrate a greenhouse gas reduction of 47% and 39%, respectively. The results also show that such recycling is expected to reduce land-use occupation and water consumption, closely related to the pulp, main raw material of paper diapers.

Keywords: disposable paper diaper; material recycling; closed-loop recycling; life cycle assessment (LCA)

1. Introduction

Paper diapers are roughly divided into two types: those for infants and those for adults. Paper diapers for infants, which are highly convenient as they do not require laundering like cloth diapers, are essential for daily life in Japan. Paper diapers for adults have also become indispensable, given the increasing number of persons requiring nursing care and the shortage of caregivers, in line with the progressive aging of society. In 2018, in Japan, the annual production of paper diapers for infants was approximately 15.1 billion, equal to 480,000 tonnes, while that of diapers for adults mainly used in nursing care facilities and medical institutions stood at about 8.4 billion, equal to about 390,000 tonnes [1]. The production volume has been increasing for 10 years, since 2010: 1.7 times for diapers for adults and 1.9 times for those for infants. Paper diapers for adults, in particular, are expected to further increase in the future, due to the rise in the elderly population [2].

Paper diapers consist of pulp or superabsorbent polymer (SAP) used as a moisture absorber, exterior materials, waterproof materials, and plastic materials such as polyethylene or polypropylene used in internal nonwoven fabric material. Pulp, which accounts for the majority of the materials,

is made of virgin materials for needle bleached kraft pulp (NBKP, or nadelholz bleached kraft pulp in German). The annual consumption of materials for NBKP, SAP, and plastics is estimated at approximately 330,000, 230,000, and 250,000 tonnes, respectively, based on the annual production [1] and the material composition of paper diapers (study by Unicharm Corp.).

The majority of used paper diapers from general households are collected and incinerated by local governments as combustible waste in the category of domestic general waste [3]. Paper diapers are considered to cover 6%–7% of the total volume of household combustible waste, and the high moisture content due to excreta included in used paper diapers leads to a low calorific value, inhibiting heat recovery efficiency during combustion [4]. Used paper diapers from business operators such as nursing care facilities and hospitals are not collected by local governments in principle but instead are entrusted to special disposal companies who collect and incinerate them as general waste from business activities or specially controlled waste [5].

As such, used paper diapers are mostly incinerated in Japan, but there are also some efforts and study cases on the recycling of paper diapers. Fujiyama et al. [6] conducted an analysis and a comparison with incineration processing of the material recycling of recovered recycled pulp to be used for fireproof plates, in addition to the manufacture of refuse paper and plastic fuel (RPF) from the thermal recycling of used paper diapers. They reported that greenhouse gas (GHG) emissions from recycling can be reduced by about 37% compared with incineration. A study related to the recycling of water absorptive sanitary products [7,8] also discussed thermal recycling treatment systems for processing used paper diapers recovered as they are, without separating or cleaning them, for conversion into solid fuel. Quantification of environmental loads adopting the life cycle assessment (LCA) is not confirmed, but reference was made to the possibility of reducing CO₂ emissions by using them as boiler fuel instead of fossil fuel. In the recycling of used paper diapers targeted for studies reported by Itsubo et al. [9], the preceding report of this paper revealed that recycled pulp has the same quality as NBKP, the virgin material that is the main component of paper diapers, which shows that pulp can be closed-loop recycled. It is also indicated that GHG emissions can be reduced by about 26% compared with incineration, as well as significant reductions in water consumption and land use occupation, areas where the pulp is considered to have high potential effects.

The present study introduces a new recycling technology that achieves the closed-loop recycling of SAP. This new recycling technology adopts a new crushing/cleaning/separating technology and improves the recycling rate for pulp, etc., and recycles SAP to the same quality as virgin materials, where SAP was thermally recycled with the preceding recycling technology. The environmental load over the entire life cycle of paper diapers from the acquisition of raw materials to the disposal/recycling phases is quantified.

There have been several reports on the recycling of used disposable diapers overseas [7,10–13]. An LCA report [12], which collected data from an experimental-scale recycling plant, stated that plastics could be recycled and pulp containing SAP could be used to generate the steam needed for the sterilization process, which indicates that the environmental impact is reduced compared to landfill disposal.

Many previous studies have focused on climate change. Disposable diapers use paper as the main material, and the supply of chips, the main raw material for paper, requires a lot of land use and water consumption. Recycling of disposable diapers is expected to contribute to reducing the burden on water consumption and land use but has not been evaluated in previous studies. In this study, in addition to climate change, water consumption and land use are evaluated.

2. Materials and Methods

2.1. Objective

This study assesses the life cycle of paper diapers, including the closed-loop recycling that recycles pulp and SAP from used paper diapers into a quality product to be used as the raw material for paper

diapers. The quantified environmental impacts are discussed and compared with those for incineration and landfill. In performing the LCA, an inventory analysis and impact assessment were conducted for the production, transportation, recovery, recycling, and disposal of disposable diapers in accordance with the international standard for ISO 14040 [14].

2.2. Scope of This Study

2.2.1. Overview of Key New Technologies for Closed-Loop Recycling

1. Crushing, Washing, and Separation Technologies

Used paper diapers are required to be degraded into composition materials such as pulp, SAP, and plastics for recycling. The crushing process is characterized by dissolving the diapers in an organic acid solution of pH 2.5 or less, which prevents a reduction in treatment efficiency as there is no loss of liquidity in the treatment tank caused by the swollen highly water absorptive polymer [15]. It also has the effect of continuously securing hygiene in the facility, using a safe organic acid to enable safe treatment and to prevent odor and contamination. In conventional techniques using a water solution for the basic cleaning/separating process [9], SAP absorbs a large amount of moisture to become gel-like, losing its liquidity. This, in turn, greatly reduces the performance of the treatment equipment, making it necessary to use a large amount of lime to inactivate the SAP. Moreover, the use of hypochlorite as a disinfectant generates a highly alkaline environment in the treatment tank, which degrades the pulp fibers and lowers the pulp recovery rate and quality. Conventional techniques also require lengthy agitation and heating for separation, making it difficult to improve treatment efficiency. The process in this study, that is, applying the new technology, improved the recycling rate of SAP to about 80% and that of pulp also to about 80% compared to around 40% with conventional techniques [9].

2. Ozone Treatment Technology

Reusing the pulp recovered from the crushing/cleaning/separating process as raw materials for paper diapers requires that the pulp be recycled to a sufficient quality usable for sanitary materials. Ozone treatment uses ozone water to dissolve and solubilize SAP contained in the recovered pulp as residue, then discharges the ozone water to remove the SAP from the pulp, thereby extracting pulp ingredients only [16]. Ozone treatment also thoroughly sterilizes the pulp, eliminating the need for disinfectant. Moreover, ozone is returned to oxygen after use, without generating resistant bacteria, which improves the safety of recycled pulp.

3. SAP Reactivation Technology

As the SAP recovered from the crushing/cleaning/separating process is inactivated, it is necessary to recover the water absorption performance so that it can be used instead of virgin SAP [17]. Conventional techniques [9] use acid or alkaline treatment, which leaves the possibility of acid or alkaline residue in recycled SAP if not completely neutralized. Using such recycled SAP as raw materials for paper diapers may cause skin irritation, making it difficult to reuse as sanitary materials. However, the process targeted in this study makes it possible to recover the water absorption performance of SAP by neutralizing the SAP that has been inactivated by the organic acid solution.

4. Verification of the Quality and Safety of Recycled Products

The present study targeted closed-loop recycling, where pulp and SAP are recycled to a quality equal to that of virgin materials, and thus are usable as raw materials for paper diapers. The quality of the pulp was confirmed by consigning inspections about the standards stipulated by the Ministry of Health, Labour, and Welfare (MHLW) [18] to a third-party inspection organization. Inspection items and results are summarized in Table 1. The recycled SAP was also confirmed to have a water

absorption performance equal to that of SAP in virgin materials, and thus can be used as raw materials for paper diapers.

Table 1. Quality inspection results of recycled pulp.

Quality Inspection Items		Criteria	Inspection Results
Purity	Appearance and Properties	Color is white, no odor, no foreign substances	conform
	Color elution	No color is exhibited when observing the eluate from above and from the side	conform
	pH	4.5~8	conform
	Fluorescence	No fluorescence	conform
	Ash content	0.65% or less	conform
	Kjeldahl nitrogen	50 mg/kg or less	conform
Cleanliness	Bacteria	Not more than 1000 per 1 gram	conform
	<i>Escherichia coli</i>	Not detected	conform

2.2.2. Functional Unit

The functional unit is assumed as the “provision of one paper diaper and its disposal.” Paper diapers have different material compositions and composition ratios depending on the manufacturer and the shape. The individual material composition ratios for paper diapers for adults and infants (study by Unicharm Corp.) were calculated by weighing them with the individual production volumes [1] to determine the average material composition ratio (see Table 2). In this study, 40.5 g per paper diaper was adopted for the average weight of all paper diapers, including those for adults (except underwear liners or pads), based on diaper production statistics (2019) [1] (see Table 3). Furthermore, the composition of excreta included in used paper diapers is based on studies by Unicharm Corp. and literature values [19] (see Table 4).

Table 2. Material composition ratio of paper diapers. SAP, superabsorbent polymer.

Materials	Composition Ratio (%)			
	Average	for Adult	for Infant	
Pulp	40.9	52.2	33.3	
SAP	27.9	19.8	33.3	
Plastics	Polyethylene	6.2	5.6	6.7
	Polypropylene	18.7	16.8	20.0
	Polystyrene	6.2	5.6	6.7
Total	100.0	100.0	100.0	

Table 3. Average weight of paper diapers.

Type	Production Weight (tonne)	Production Quantity (1000 pieces)	Average Weight (g)
for Adult	365,804	5,864,108	62.4
for Infant	484,079	15,094,904	32.1
Total	849,883	20,959,012	40.5

Table 4. Composition of 1 tonne of used paper diapers.

Composition	Weight (kg)	Composition Ratio (%)
Paper diaper	383	38.3
Collection bag made of polyethylene	4	0.4
Human excreta	Moisture content	598
	Solid content	15
Total	1000	100.0

2.2.3. System Boundary

The scope from the acquisition of raw materials to the production, distribution, and disposal/recycling of paper diapers was selected as the system boundary. For the use phase, non-use of electric power, fuel, and other utilities were assumed, thus these processes were excluded from the scope of the assessment. Figure 1 illustrates the life cycle flow. As comparable systems, two models using incineration and landfill to treat waste in the disposal/recycling phase were set. For incineration, the combustible general domestic waste treatment currently used in Japan was assumed. For waste power generation, the power generated was assumed to substitute the average purchased power in Japan. For landfill, general waste landfilling was assumed. In this paper, the systems for recycling, landfilling, and incinerating waste in the disposal/recycling phase are called RE, LF, and IN, respectively (see Table 5). Table 6 shows the recycled products and alternative products.

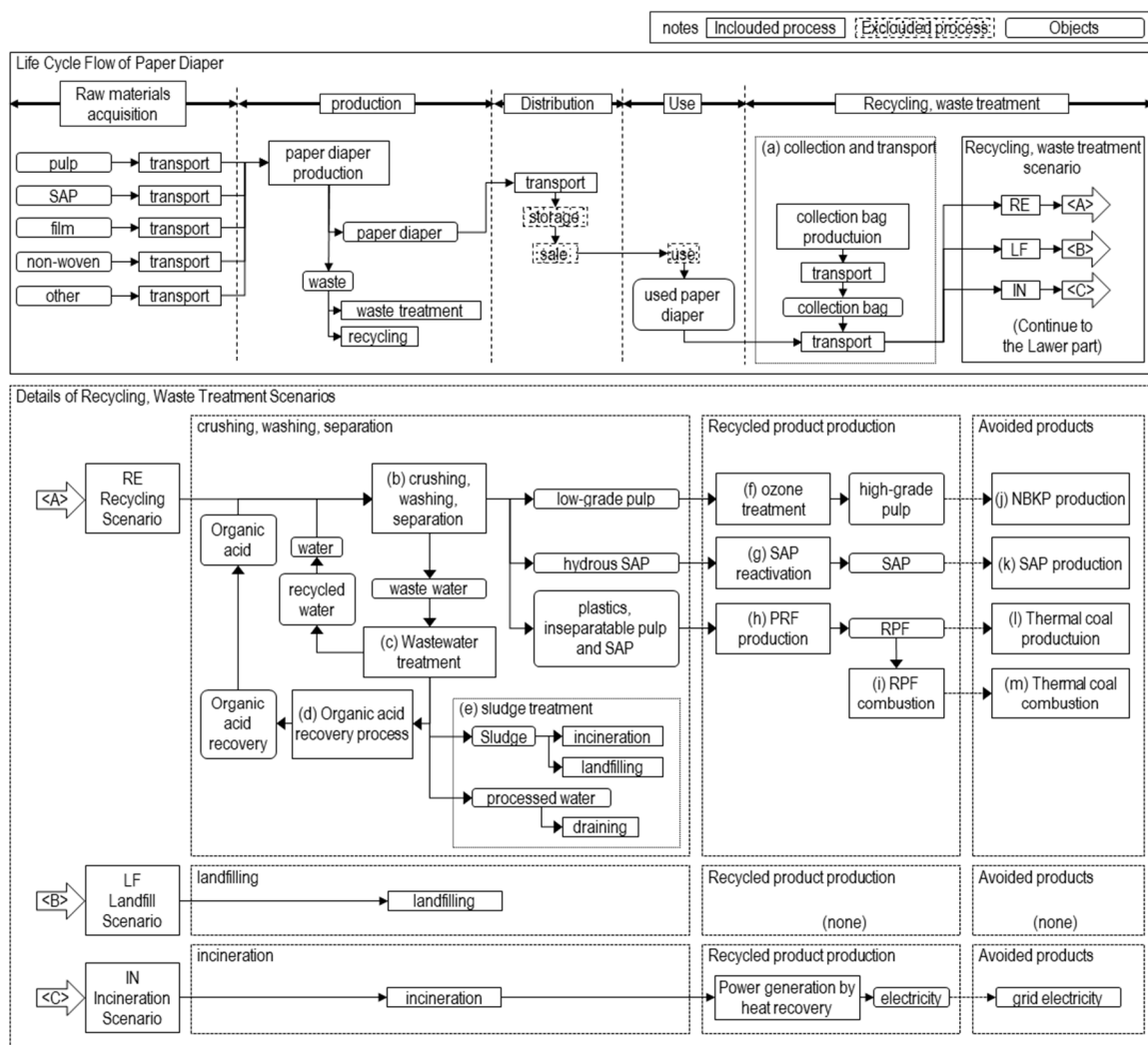


Figure 1. Life cycle flow chart. The upper part shows the life cycle of paper diapers, and the lower part shows details of recycling, waste treatment scenarios. The system boundary is from raw material production, disposable diaper production, transportation, disposal/recycling, production of recycled products, and production of alternative products (excluding storage, sales and use of disposable diapers). RE, recycling; LF, landfill; IN, incineration; RPF, refuse paper and plastic fuel; NBKP, needle bleached kraft pulp.

Table 5. Scenarios in this study and their differences.

Scenario	Abbreviations in This Study	Life Cycle Stage	
		Raw Materials Acquisition ~ Production ~ Distribution ~ Use	Recycling, Waste Treatment
Recycling	RE	Common for all scenarios	Recycling
Landfill	LF		Landfilling
Incineration	IN		Incineration

Table 6. Recycled products and alternative products.

Scenario	Recycled Products	Alternative Criteria	Alternative Products
RE	Pulp	Mass equivalent	NBKP
	SAP	Mass equivalent	SAP
	RPF	Heat value equivalent	Thermal coal
LF	(none)	-	-
IN	Electricity	Electric power equivalent	Public power

2.2.4. Impact Categories

Table 7 shows the impact categories and evaluation methods for the targets. In addition to global warming, land use occupation (maintaining) and water consumption were also included as impact categories closely related to pulp, the main raw material of paper diapers. Furthermore, blue water was considered as the target for water consumption.

Table 7. Environment impact categories and methods in this study.

Impact Category	Unit	Evaluation Method
Global warming	kg-CO ₂ e	IPCC 2013 GWP 100a
Land use occupation	m ² a	LIME2 [20]
Water consumption (blue water)	m ³	water consumption inventory

2.3. Inventory Analysis

2.3.1. Data Collection

1. Raw materials acquisition stage

The input amount of each raw material was determined by multiplying the average material composition ratio for paper diapers for adults and for infants, calculated from their respective composition ratios, by the average weight of paper diapers (see Table 8). For transport, the scenario of importing NBKP from North America via marine transport, and procuring other materials in Japan via land transport using trucks (see Table 9), was used.

2. Production stage

For energy input related to paper diaper production, primary data were collected from the paper diaper plants of Unicharm Corp. Raw material residue generated in the production processes was used as raw materials for pet goods and other products within the same plant; thus, it was assumed that no material loss occurs (see Table 8).

Table 8. Main collected data and collection methods.

Life Cycle Stage	Data Item	Data Type	Collected Data	Data Collection Method
Raw materials acquisition	Input amount of various raw materials	foreground	Pulp, SAP, Film, Non-woven fabric, others	Collected from Unicharm's paper diaper factory
Production	Energy consumption Waste amount	foreground foreground	Electricity Residue material	
Recycling, waste treatment	Input amount of Energy, utilities and auxiliary materials	foreground	Electricity, LPG, Industrial water, Organic acid, others	Demonstration experiment data
	Pulp recycling rate	foreground	80%	
	SAP recycling rate	foreground	80%	
	Plastics recycling rate	foreground	100%	
	RPF heat value	foreground	36.3 MJ/kg	

Table 9. Transport scenarios.

Life Cycle Stage	Transport Object	Transport Route	Distance	Mode of Transportation
Raw materials acquisition	Raw materials and auxiliary for paper diapers	Domestic land transportation	500 km	10 t truck, loading ratio of 50%
		Ocean freight (From North America to Japan)	18,707 km	Container transport ship, >4000 TEU
Distribution	Product (paper diaper)	Domestic land transportation	555 km	10 t truck, loading ratio of 50%
Recycling, waste treatment	Used paper diaper Auxiliary materials Waste	Domestic land transportation	100 km	2 t truck, loading ratio of 50%
			200 km	
			100 km	

3. Distribution stage

Paper diapers are generally distributed from the manufacturers to the stores, nursing care facilities, etc., through many distribution channels, which makes it difficult to determine the actual distribution amounts and distribution routes in detail. Therefore, in this study, it was assumed that the diapers are distributed from the paper diaper plants of Unicharm Corp to all 47 prefectures nationwide, with the distribution amounts proportional to the population of individual prefectures. The transport distances for individual prefectures were determined using Google Maps and were then weighed by the transport amount for individual prefectures. For the vehicle class and loading ratio, general domestic transport was assumed (see Table 9).

4. Use stage

In this stage, no additional energy was used, so it was excluded from the assessment of environmental impact.

5. Recycling, waste treatment stage

For RE or recycling processing, primary data were collected from simulated demonstration experiments at a recycling plant being developed by Unicharm Corp. in Shibushi City, Kagoshima Prefecture that processes about 500 tonnes of waste annually (see Table 8). Eighty percent of the SAP and pulp included in the used paper diapers is recycled, and part of the unrecycled content is mixed with plastics to produce RPF. The plastics are completely recovered and then mixed with part of the unseparated pulp and SAP to produce RPF. For LF and IN, it was assumed that one tonne of used

paper diapers with the same composition as in RE is processed. Since waste is separately recovered in a polyethylene collection bag of 20 g per 5 kg of used paper diapers in RE, it was assumed that the same bags are used in LF and IN and that the scenarios for transport related to waste materials and collection are common to RE, LF, and IN (see Table 9).

2.3.2. Background Data and Software

Background data from the Life Cycle Inventory (LCI) database IDEAv2 [21] were mainly used, with missing data complemented by the GHG Emissions Accounting and Reporting Manual [22], and SimaPro 8.5 was used for the calculation.

3. Results

3.1. LCA Results and Comparison between the Three Scenarios

The LCA results of the system targeted in this study, which assumes the disposal/recycling phase as “recycling processing” in the life cycle, as well as the results for landfill and incineration are shown in Figure 2 and Table 10. The system boundary is the life cycle, including the individual phases from the acquisition of raw materials to the production, use, and disposal/recycling of paper diapers, and the functional unit is the provision of one paper diaper (40.5 g).

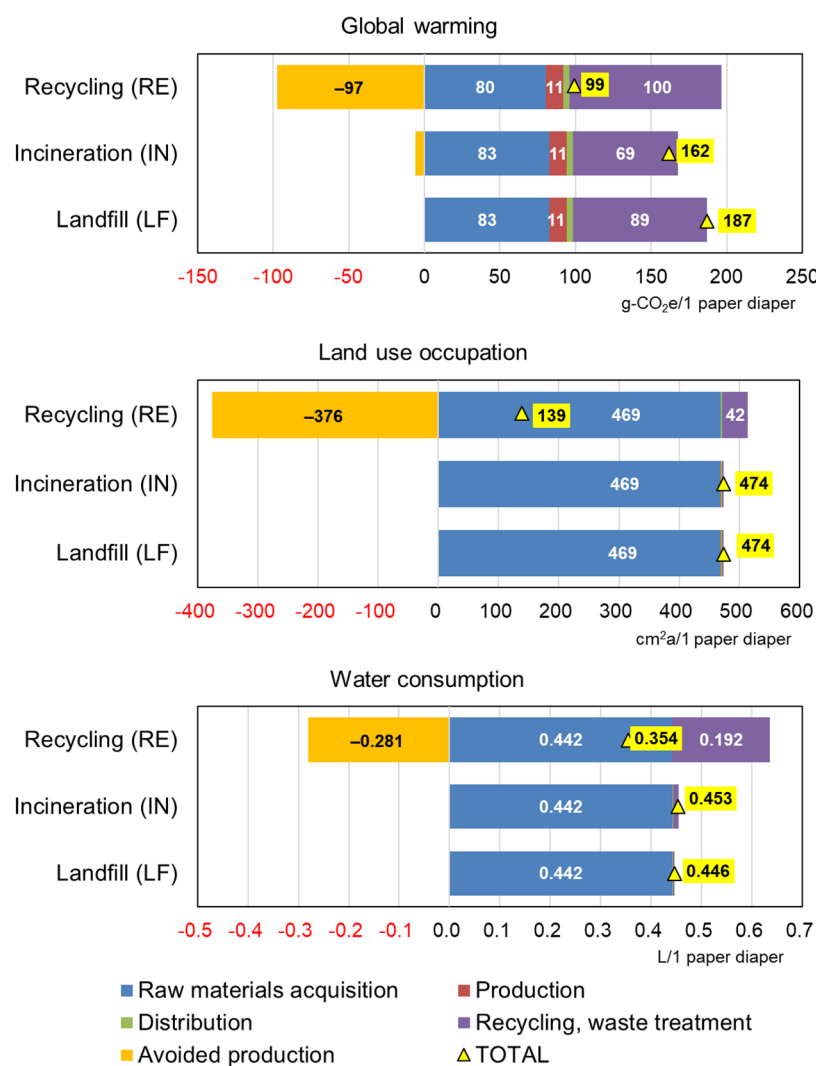


Figure 2. Life cycle assessment (LCA) results and comparison between the three scenarios.

Table 10. LCA results for each scenario and reduction effect rate.

Scenario		Global Warming (g-CO ₂ e)	Land Use Occupation (cm ² a)	Water Consumption (L)
RE	Recycling	99	139	0.354
	Reduction rate	IN Δ	39%	71%
		LF Δ	47%	71%
IN	Incineration	162	474	0.453
LF	Landfill	187	474	0.446

3.1.1. Global Warming

GHG emissions of IN and LF were calculated as 162 and 187 g-CO₂e, respectively, while that of RE was estimated at 99 g-CO₂e, a reduction of 39% and 47% compared with IN and LF, respectively. In RE, the amount in the disposal/recycling phase was 100 g-CO₂e, larger by 11%–45% compared with IN and LF. However, a significant reduction effect compared with IN and LF is expected in the entire life cycle, with the contribution of the total deduction at 97 g-CO₂e due to the substitution effect of recycled pulp, SAP, and RPF.

3.1.2. Land Use Occupation

The land use occupation values for IN and LF were almost the same at 474 cm²a, while that for RE was estimated at 139 cm²a, a reduction of 71% compared with IN and LF. About 99% of the loads from IN or LF are due to pulp production included in the raw materials acquisition phase, while RE has a lower value in this phase due to the substitution effect of recycled pulp. Thus, for RE, the load is expected to be reduced in the life cycle.

3.1.3. Water Consumption

Water consumption values for IN and LF were calculated at 0.453 and 0.446 L, respectively, about 97% of which is the contribution from the raw materials acquisition phase, and about 75% in this phase is the contribution from pulp production and SAP production. The value for RE was 0.354 L, although the ratio in the disposal/recycling phase for RE was 0.19 L, accounting for 53% of the total compared to 2%–3% for IN and LF, due to the contribution of 0.069 L of cleaning water and 0.10 L related to the production of organic acid for cleaning chemicals. Meanwhile, the value for RE in the entire life cycle was estimated to be 21% and 22% lower than that for IN and LF, respectively, with the contribution from the substitution effects of recycled pulp and SAP.

3.2. Detailed LCA Results at Recycling, Waste Treatment Stage of the Recycling Model

The treatment scenarios targeted in this study are characterized by recycling in the disposal/recycling phase, so the LCA results for disposal/recycling, ranging from collection/transport to production of the recycled products and using the substitution effect (deduction) with the recycled products as the system boundary, are presented in detail (see Table 11). The process IDs in the table correspond to the symbols in (a) to (m) described in the individual processes in Figure 1. The functional unit was the disposal/recycling of one used paper diaper.

3.2.1. Global Warming

GHG emissions were calculated at 3.18 g-CO₂e. Emissions related to the phases from the collection/transport of used paper diapers to the production of recycled products were 100 g-CO₂e (subtotal-1), due to a significant contribution of 97.2 g-CO₂e (subtotal-2) from the deduction total as a result of NBKP production (j), SAP production (k), as well as thermal coal production and combustion (l), (m), substituted by recycled pulp, SAP, and RPF. Details of the recycling are as follows: 7.8% for collection/transport (a); 22.7% for crushing/cleaning/separating (b, c, d, e); and 69.5% for recycled products production (f, g, h, i). The substitution effects for NBKP production and SAP production were

19.3% and 20.2%, respectively, while that for thermal coal production/combustion was the highest at 60.4%, due to a significant contribution from CO₂ direct emissions caused by combustion.

Table 11. Detailed life cycle assessment (LCA) results at the recycling, waste treatment stage.

	Process	Process ID	Global Warming (g-CO ₂ e)	Land Use Occupation (cm ² a)	Water Consumption (L)
Collection and transport	Collection and transport	(a)	7.83	1.48	0.00282
Crushing, washing, and separation	Crushing, washing, and separation	(b)	9.63	39.7	0.182
	Waste water and sludge treatment	(c, e)	9.53	0.320	0.00143
	Organic acid recovery	(d)	3.68	0.0628	0.000298
Recycled product production	Ozone treatment	(f)	5.55	0.104	0.00100
	SAP reactivation	(g)	17.0	0.307	0.00243
	RPF production and combustion	(h, i)	47.2	0.233	0.00252
Subtotal-1, (a)~(i)			100	42.2	0.192
Avoided products	NBKP production	(j)	-18.8	-375	-0.100
	SAP production	(k)	-19.7	-0.324	-0.180
	Thermal coal production and combustion	(l, m)	-58.7	-0.00654	-0.000690
Subtotal-2, (j)~(m)			-97.2	-376	-0.281
Total			3.18	333	-0.0886

3.2.2. Land Use Occupation

The land use occupation was $-333 \text{ cm}^2\text{a}$, considered as a negative load in the entire process, due to the contribution from the deduction by the substitution effect. Details are as follows: the total of the recycling, from collection/transport to recycled products production (subtotal-1), was $42.2 \text{ cm}^2\text{a}$; and the total of the deduction from the substitution effect by recycled products (subtotal-2) was $376 \text{ cm}^2\text{a}$. In recycling, the crushing/cleaning/separating phase (b) accounted for the majority at about 94%, which was largely due to the contribution from land use in the plant culturing phase, as the organic acid used was plant-based. Meanwhile, the substitution effect of NBKP production (j) was $375 \text{ cm}^2\text{a}$, accounting for almost 100% of the total at $376 \text{ cm}^2\text{a}$, which was due to the significant contribution from land use related to the production of forest resources (softwood) used as materials for virgin pulp, which was avoided by using recycled pulp.

3.2.3. Water Consumption

The water consumption per paper diaper was -0.0886 L as a whole, a negative value calculated by deducting the substitution effect. Details are as follows: the total of the recycling, from collection/transport to recycled products production (subtotal-1), was 0.192 L ; and the total of the deduction from the substitution effect of recycled products (subtotal-2) was 0.281 L . In recycling, the crushing/cleaning/separating phase (b) accounted for the majority at about 94.5%, among which about 40% was due to directly consumed water in the cleaning tank, while about 60% was due to production of the plant-based cleaning agent.

4. Discussion

4.1. Comparison with Previous Studies

The results of previous studies related to the recycling of used paper diapers were reviewed and compared with this study. As previous studies assess only the disposal/recycling phase in the life cycle of paper diapers, the disposal/recycling process from the results of this study were extracted and the system boundary was set to cover “disposal/recycling of one tonne of used paper diapers” only (see Table 12).

Table 12. Comparison with previous studies. The functional unit is recycling, waste treatment of 1 tonne of used paper diapers.

Comparative Studies	GHG Emissions (kg-CO ₂ e)			Total	Recycled Products
	Collection and Transport	Recycling, Waste Treatment	Recycling Effect		
This study					
Recycling	74	875	−919	30	Pulp (127 kg) SAP (91 kg) RPF (155 kg)
Incineration	74	579	−55	598	Electricity (91 kWh)
Landfill	74	764	0	838	(None)
Comparative studies					
Itsubo et al. [8]					
Recycling	55	1132	−821	366	Pulp (89 kg) RPF (306 kg)
Incineration	55	523	−85	493	Electricity (137 kWh)
Fujiyama et al. [6]					
Recycling	(out of boundary)	530	−240	290	Pulp (159 kg) Fermented fertilizer
Incineration	(out of boundary)	432	(none)	432	(None)

Among the domestic studies, Itsubo et al. [9] discuss closed-loop recycling. The paper targeted the closed-loop recycling of recycling pulp as fine pulp usable as raw materials for paper diapers, where plastics and SAP were converted to RPF for thermal recycling. Compared with the present study, this system as characterized by a lower pulp recycling amount by about 30%, but a higher RPF recycling amount of about two-fold. The calorific value for RPF as lower by about 34%, making the total of the substitution effect (deduction) smaller by about 10%. The total GHG emissions related to recycling was about 1.3 times that of the present study, which resulted in a total—including the deduction—at 366 kg-CO₂e, which was about 12 times the value in this study at 30 kg-CO₂e. Compared with the study by Itsubo et al., GHG emissions related to recycling in this study were reduced by 23%, while the recycling ratio of pulp was about 80%. For RPF, the contamination rate of pulp and SAP residues other than plastics was low, resulting in a higher calorific value, and the deduction was higher due to SAP recycling, significantly reducing GHG emissions as a whole.

In the study by Fujiyama et al. [6], the GHG emissions related to recycling were about 60% of the value obtained in the present study, but the substitution effect (deduction) in their study was about a quarter of the value obtained in the present study at 240 kg-CO₂e. This is presumably caused by a lower deduction range per unit of weight of recycled products compared to the present study as Fujiyama et al. used downgrade recycling.

The study report on the processing equipment for thermal recycling of used paper diapers as solid fuel [7] indicates the possible reduction of CO₂ emissions by using such fuel as a substitute for fossil fuel, but that effect was excluded from the comparison as the effect was not quantified.

Note that the values in the present study cannot be directly compared with those in previous studies as the prerequisites differ in the following points.

1. The system boundaries are not always the same in studies, such as the inclusion of the collection/transport process.
2. Individual studies may use different background databases, resulting in different environmental loads, even with the same inventory.
3. The composition of used paper diapers (material composition of used paper diapers, the ratio of excretion in paper diapers, etc.) differs by study, which results in, for example, a different yield in recycled products, even with the same recycling ratio.
4. The suitability of recycled products is not sufficiently assessed. If recycled products substitute virgin materials in equal amounts, the quality of the former should be sufficiently verified. It is also necessary to assess the market demand. Sufficient information on these matters cannot be obtained from a comparison with previous studies.
5. Values not provided in the report by Fujiyama et al. were directly measured using a chart, which may have errors.

4.2. Estimation of the Potential for Environmental Load Reduction

The potential for environmental load reduction by recycling used paper diapers in Japan and the world was estimated from reduction amounts obtained in this study and by applying them to the incineration and landfill baselines of Japan and the world (see Table 13). The annual production volume of paper diapers for adults and infants in Japan was 878,000 tonnes. The waste weight was estimated at 2.294 million tonnes, assuming that the disposal weight increase factor was 2.6; this is due to the increased weight from excretion. Based on this waste amount and the ratio of 98:2 for incineration vs. landfill, the reduction potential nationwide was estimated at about 1.314 million t-CO₂e for GHG emissions, 726 km²a for land use occupation, and 2.149 million m³ for water consumption.

Table 13. Estimation of the potential for environmental load reduction.

	Unit	Incineration		Landfill		Total Amount of Reduction per Year
		Current Estimates	Apply Recycling	Current Estimates	Apply Recycling	
Japan						
Paper diaper production	Mt/year			0.878		-
Disposal volume	Mt/year			2.294		-
Ratio of disposal method	%		98%		2%	-
Amount by disposal method	Mt/year		2.248		0.046	-
Environmental load per year						-
Global warming	Mt-CO ₂ e	1.344	0.068	0.038	0.001	1.314
Land use occupation	km ² a	4	-708	0.1	14	726
Water consumption	Mm ³	0.222	-1.881	0.006	-0.038	2.149
Global						
Paper diaper production	Mt/year			4.866		-
Disposal volume	Mt/year			12.720		-
Ratio of disposal method	%		37%		63%	-
Amount by disposal method	Mt/year		4.706		8.014	-
Environmental load per year						-
Global warming	Mt-CO ₂ e	2.814	0.142	6.712	0.241	9.143
Land use occupation	km ² a	8	-1482	13	-2524	4027
Water consumption	Mm ³	0.466	-3.938	1.111	-6.706	12.221

Overseas, the annual production volume of paper diapers was estimated at 120 billion [23], but the weight per diaper is unknown. Thus, the production volume for the world was estimated at 4.866 million using the average weight of 40.5 g for diapers for adults and infants produced in Japan. The weight increase factor for disposal was set at the same value as in Japan, or 2.6, and the waste weight was estimated at 12.720 million tonnes. The ratios of the processing methods were set at 63% for landfill and 37% for incineration [24]. Using these prerequisites, it was estimated that the GHG emissions reduction potential was 9.143 million tonnes-CO₂e, land use occupation was 4027 km²a, and water consumption was 12.221 million m³ when applying recycling throughout the world (see Table 13).

The estimates were based on the assumption that all used paper diapers produced in Japan and the world are recycled, which requires the following cautions.

- No comparative study on costs has been conducted, so it is uncertain if economic rationality is achieved in all regions.
- It is uncertain if a system to recover used paper diapers for recycling facilities can be established, as the disposal methods for used paper diapers differ by nation or region.
- It is uncertain if the destinations for using recycled products can be established in all regions.

5. Conclusions

As the production of paper diapers is expected to increase in the future, there is a strong need for an appropriate recycling technology in terms of waste treatment after use and for sustainable use of resources. While previous studies and cases are limited to open-loop recycling, the present study achieved closed-loop recycling of pulp and SAP from “paper diapers to paper diapers” thanks to a new technology, thus clarifying that the environmental load can be further reduced compared to that in the preceding report [9] in the assessment of GHG emissions, water consumption, and land use occupation for the life cycle of recycling used paper diapers (see Table 14). The recycling technology in this study demonstrated a high recycling effect by enabling the recycling of high-quality pulp and SAP. In the future, further reductions in environmental impact are expected through the efficiency of SAP regeneration and the improvement of the recycling rate. On the other hand, in this study, it was considered that uncertainties were included from the following points, but even if these factors are taken into consideration, a significant reduction in environmental load was confirmed.

Table 14. Reduction of environmental load by the recycling technology of this study and other recycling technologies.

System Boundary	Impact Category	This Study		Other Recycling Technologies
		Reduction Rate		
		Compared with Incineration	Compared with Landfill	
Full life cycle *	Global warming	39%	47%	Previous studies in Japan have not evaluated the full life cycle.
	Land use occupation	71%	71%	
	Water consumption	22%	21%	
Recycling, waste treatment stage	Global warming	95%	96%	Itsubo et al. [9] reported a 26% reduction, and Fujiyama et al. [6] reported a 33% reduction in GHG emissions.

* Full life cycle includes all life cycle stages of the paper diaper, from the acquisition of the raw materials to the recycling, waste treatment stage, except for the use stage.

The recycling facility from which the data were collected is a prototype, so its representativeness may be low.

- Japanese data were used for LCA calculations.
- Thermal coal and electricity were set as alternative products for the recycling effect. However, if these are changed to other products, the recycling effect may change.

In addition, it is expected that the recycling process of this study will have great social and economic benefits. Analyses focused on social and economic aspects were also assumed, but were not included in this study due to the difficulty in obtaining data, etc., and the immature evaluation method.

Author Contributions: Conceptualization, N.I., M.W., and K.S.; methodology, N.I., N.M., and K.S.; validation, N.I., N.M., and K.S.; formal analysis, A.M. and N.M.; investigation, M.W., S.I., and A.M.; resources, M.W., S.I., and A.M.; writing—original draft preparation, N.M.; writing—review and editing, N.M.; supervision, M.W.; project administration, M.W. All authors read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

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