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Environmental Impact Assessment of Bioplastic and Melamine-based Coffee Cup Production

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Abstract: The environmental impacts and energy consumption for polylactic acid (PLA) and melamine coffee cup were studied by applying the life cycle assessment approach. The functional unit of coffee cup was a cup used to contain 180 mL of coffee to be used for 1 time/day for 2 years. The results show that up to the use phase, global warming, abiotic depletion, freshwater and terrestrial ecotoxicity were 1,041.14 gCO_2-eq/cup, 6.02 g Sb-eq/cup, 41.53 g 1,4-DB-eq/cup and 6.73 g 1,4-DB-eq/cup for PLA cup, and 1,595.67 gCO_2.eq/cup, 14.23 g Sb-eq/cup, 51.36 g 1,4-DB-eq/cup and 8.31 g 1,4-DB-eq/cup for melamine cup. These clearly indicate that production and use of PLA cup have less environmental impacts when compared to that of melamine cup. The impacts of whole life cycle, however, significantly depended on the waste disposal scenario. Disposal of PLA cup through landfill with energy recovery would emit 251.46 gCO_2-eq/cup, while that without energy recovery this would be 2,065.24 gCO_2-eq/cup. On the other hand, the greenhouse emission from disposal of melamine cup through incineration with and without energy recovery would be 1,601.05 gCO_2-eq/cup and 1,601.96 gCO_2-eq/cup, respectively.

Keywords: Bioplastic, melamine, coffee cup, environmental impacts, energy consumption, greenhouse gas.

1. Introduction

In the recent decades there has been a significant increase in the amount of plastics being used in various sectors, particularly in food packaging applications [1]. This is mainly because plastics have many advantages when compared to the traditional materials such as metals, alloys and ceramics. These advantages include high thermo-stability, high thermal and mechanical flexibility, the ability to be integrated in various production processes steps (i.e. plastic packages can be formed, filled and sealed in a continuous manner within the production line), light weight and low price [1]. However, environmentally these conventional plastics do also have a number of disadvantages. They are made from fossil fuels and thus contribute to depletion of non-renewable resources. They persist over a long time period due to low degradability (up to several hundred years). Release of some toxic substances during degradation or incineration also occurs [2]. Consequently, large volumes of plastic wastes are produced and cannot be degraded within a reasonable time period. In Thailand, there were 14.4 million tons of plastic wastes in 2003, but only 11% of these were recycled [3]. Besides more waste disposal area requirements, this could also lead to other environmental problems and management as land resources become limiting.

Requirement for large amount of fossil fuels as feedstock and contributions to various environmental problems by the conventional plastics have driven the invention of other alternatives. In this regard, biomass-based plastics have been developed and are becoming widely accepted for use. Current technology advancements have allowed the production of biomass-based plastics at commercial scale [4]. The cost associated with production is still relatively high when compared to the conventional petroleum-based ones [5]. However, bio-based plastics have various advantages over the conventional ones [6]. For instance, because the carbon is originally fixed from the atmosphere through photosynthesis, use of biomass-based plastic is considered environmentally friendly. In addition, their production process can reduce fossil energy use and greenhouse gas (GHG) emissions when compared to the conventional plastics [6]. Bioplastics are also bio-degradable. Because of these advantages and of the large biomass stocks available within the country, Thailand has issued several key policies to promote the development of domestic bioplastic industry. Such include the development of road maps, establishment of pilot plants and institutional arrangements [7-8]. Although there have been several studies trying to compare the environmental advantages of bio-based and conventional plastics for various products, the study on cassava-based bioplastic products has not been evaluated. Since cassava is one of the potential raw materials for bioplastic production and it is wildly grown in Thailand, its environmental impacts should be evaluated. Accordingly, the objective of the present study is to estimate and analyze the cradle-to-grave environmental impacts of cassava-based and fossil-based plastic products by using a coffee cup as the model product.

2. Experimental

This study applies life cycle assessment (LCA) concept to estimate the environmental impacts associated with a coffee cup produced from polylactic acid (PLA) and melamine. The main tasks include the collection of inventory data through field surveys (questionnaires), laboratory experiments and literature review and synthesis.

2.1 Goal and scope definition

2.1.1 Goal definition

Goals of this work are to estimate and to compare the greenhouse gas emissions, abiotic depletion and ecotoxicity (when applicable) through the life time of PLA and melamine coffee cup. Results from these impact evaluations will provide information on sustainability of the two products produced from completely different resources. It is expected that the results is useful for improving the production process of product to reduce the environmental impacts.

2.1.2 Scope definition

Life cycle of the coffee cup is studied from cradle to grave. The study boundary for PLA cup includes cassava growing, dextrose production, lactic acid-lactide production-PLA polymerization, product use, and final disposal at the end of useful life. Study of the melamine cup includes production of melamine, formaldehyde and pulp, melamine resin, melamine cup production, use phase, and disposal of the cup. The disposal of both product types is categorized into two scenarios; landfill for PLA cup and incineration for melamine cup, both with and without energy recovery. The data were collected from field surveys, factory visits and literature review for both PLA and melamine cups.

The information available for assessment under the scope described above in Thailand is very limited. The study is thus in parts based on the information available in literature that does not necessarily represent the manufacturing conditions in Thailand. It is primarily scoped to cover the process from feedstock to PLA or melamine production and disposal. The functional unit of coffee cup is a cup used to contain 180 mL of coffee and to be used for 1 time/day for 2 years. In fact, PLA cup could be used for more than 2 years and melamine cup could even last longer. However, this is very much dependent on the cup-use conditions and many other factors. Provided that the exact life time of both types of cup could not be determined, we therefore decide to use 2-year time for analysis and comparison purpose. Schematic production chains from cradle to grave of PLA and melamine cup are given in Figures 1 and 2, respectively. The weight of PLA and melamine is 86.22 g and 85 g/cup, respectively.

2.2 Life cycle of PLA cup

The first process of PLA cup production (Figure 1) is cassava cultivation that consumes fertilizers, herbicide and diesel which are sources of greenhouse gas emissions. Later cassava roots are sent to the dextrose plant, and then dextrose is fermented to lactic acid. Lactide production is followed by polymerization to PLA resin which is then transported by trucks to the PLA cup manufacturing plant. All production processes consume fuels, electricity and auxiliary chemicals which are the causes of global warming, abiotic depletion and ecotoxicity. Besides, other causes of the environmental impacts are wastewater from dextrose and lactic acid production and emissions from transportation.

2.2.1 Cassava cultivation

Data collection for cassava cultivation in Thailand includes the steps from preparing cassava planting site, cassava growing, harvesting and preserving before use. The information was collected from various sources including literatures and field surveys by interviews of 20 farmers in 2009, who had cassava cultivation farms located near the starch and dextrose plants in Rayong province. Greenhouse gas emissions from fertilizer were estimated from the emissions in production process (1.47 kgCO_2eq/kg fertilizer; [9]), direct N_2O emissions from nitrification and denitrification processes in soil and indirect emissions from deposition of NH_3+NOx, and leaching and runoff using the method recommended by IPCC [10].

2.2.2 Dextrose production

The amounts of electricity use, fuel use, distance between cassava growing fields and factory, and operating supplies of dextrose production were collected from one dextrose and five starch production plants in Chonburi and Rayong province (P.S.C. Starch Products PCL) by interviews in 2009 and 2010. GHG emission from wastewater is calculated using Eq. (1) [10].

$$E_{ww} = Q_{ww} \bullet COD_{removed} \bullet B_{o,ww} \bullet MCF_{ww,treatment} \bullet GWP\_CH_4 \tag{1}$$

where E_{ww} is greenhouse gas emissions from wastewater treatment (tCO_2e), Q_{ww} is quantity of wastewater treated, $COD_{removed}$ is COD removed by the wastewater treatment system (90% of COD inlet value), $B_{o,\ ww}$ is methane producing capacity of the wastewater (0.21kg CH_4/kg COD, [10]), and $MCF_{ww,\ treatment}$ is methane correction factor for the existing wastewater treatment systems (0.8, [10]). The wastewater treatment system identified from interview data is open lagoon.

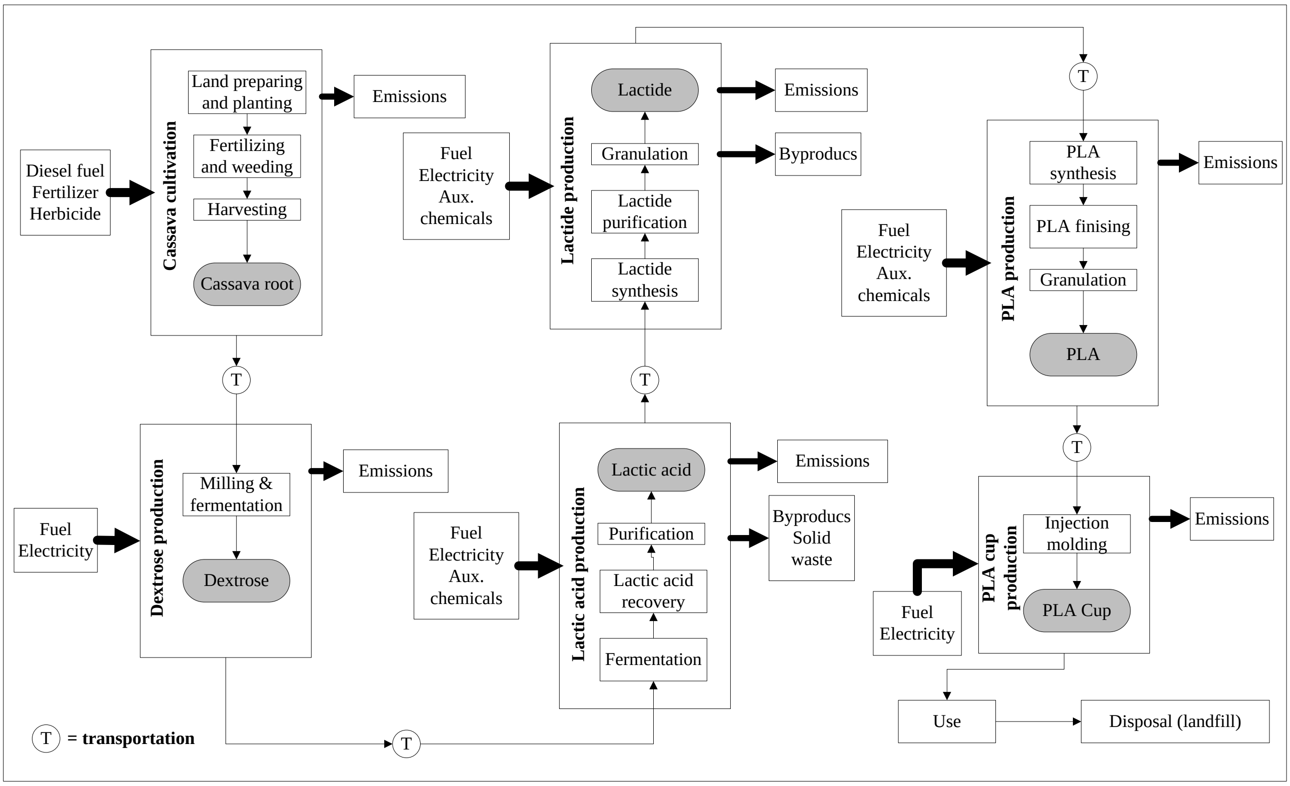

Figure 1. Flow diagram and system boundary from cultivation of feedstock to disposal of PLA.

2.2.3 Lactic acid, lactide and PLA production

The summary of energy consumption and value of greenhouse gas emission from each stage of lactic acid, lactide and PLA production (auxiliary chemicals production, electricity and steam consumption, and amount of wastewater) were obtained with some adjustments for Thailand conditions from Groot and Borén [11]. The impacts of lactic acid production were estimated based on the information from PURAC (Thailand) Ltd. lactide plant [11]. Data of PLA were obtained from the Sulzer Chemtech design for Synbra as described by Groot and Borén [11]. Lime, sulfuric acid, and other auxiliary chemicals are the input for lactic acid production. The greenhouse gas emissions of electricity and steam are calculated from energy consumption needed in lactic acid production through PLA plant.

The impact of transportation included the greenhouse gas emissions from transport of dextrose and auxiliary chemicals to lactic acid plant in Thailand. The weight of dextrose and lactic acid are estimated based on required raw material for one ton of PLA which are 1.36 tons dextrose [12] and 1.25 tons lactic acid (stoichiometrically one kg of lactic acid yields 0.8 kg PLA).

2.2.4 PLA cup production

For this step the PLA resin is the main raw materials, with energy inputs in the form of electricity and fossil fuels. The information obtained during the PLA cup manufacturing plant visit indicates that 0.27 kWh is consumed per cup [13]. The PLA resin is assumed to be produced by PURAC Ltd. in Thailand. Transportation distance of raw material from PURAC Ltd. to cup production plant is 174 km.

2.3 Life cycle of Melamine cup

For melamine cup, the raw materials of melamine resin are melamine, formaldehyde, and pulp (Figure 2). Melamine and formaldehyde production utilizes crude oil and methanol as the feedstock, respectively. Pulp is produced from eucalyptus. Those three materials are mixed to produce melamine-formaldehyde (melamine) resin that is used for compression molding of melamine cup. All production processes of melamine cup consume fuel and electricity, and emit air and water pollutants which contribute to global warming, abiotic depletion and ecotoxicity. Besides the production process of feedstock through melamine cup, use and disposal stages are also considered.

2.3.1 Melamine production

Melamine is the main raw material of melamine-formaldehyde resin. It is synthesized from urea that is the product of ammonia and nitrogen reaction which are obtained from the liquefied petroleum gas (LPG) and air, respectively. Although the air is a raw material for melamine, it has no environmental impact so it is excluded from the impact calculation [14]. When impacts are estimated, crude oil is considered as a feedstock while natural gas and electricity are considered as fuels.

2.3.2 Formaldehyde and pulp production

Formaldehyde is used to mix with melamine for melamine-formaldehyde resin production which will be used to produce melamine cup. Natural gas is used as only raw material of formaldehyde to produce methanol. Data for 1 kg of each material production consist of materials, fuels, and emission to air from Remmerswaal [14].

2.3.3 Melamine-formaldehyde resin production

This resin is used as a raw material of melamine cup production. Melamine and formaldehyde are transported by ship from China (4,961 km) and Japan (3,957 km) to Thailand, respectively while pulp is transported by truck from pulp factory in Prachinburi province to melamine resin plant in Rayong province, with a distance of about 157 km. The return trip of the truck is assumed to be empty-loaded.

2.3.4 Melamine cup production

Available data for this step are the amount of electricity for melamine cup production and fossil fuel use for transport. The environmental impact estimate is based on the information that one cup consumes 1.30 kWh of electricity [15]. The distance of transportation of raw material from Rayong province to cup production plant in Samutprakarn province is 133 km.

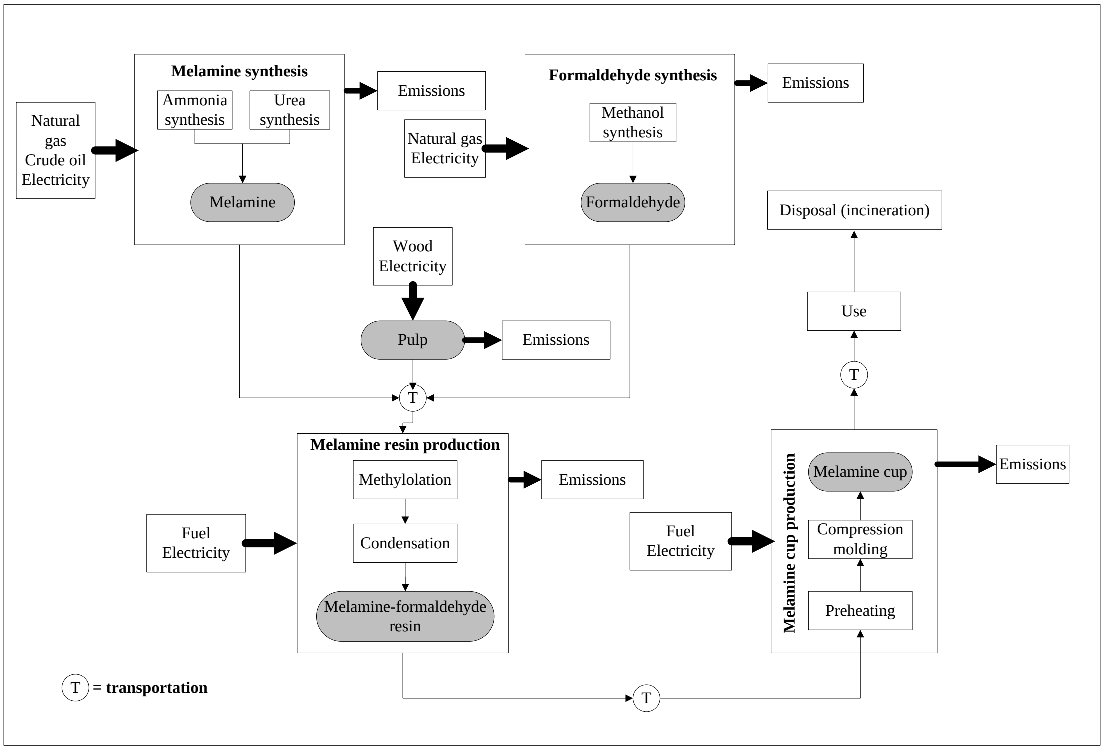

Figure 2. Flow diagram and system boundary from synthesis of feedstock to disposal of melamine cup.

Table 1. Characterization equivalency factor and greenhouse gas emission factors for calculating the environmental impacts of PLA and melamine coffee cup.

Item	Unit	Impact Category			
		Global warming (kg CO_2 eq/Unit)	Abiotic depletion (kg Sb eq/Unit)	Fresh water aquatic ecotoxicity (kg 1,4-DB eq/Unit)	Terrestrial ecotoxicity (kg 1,4-DB eq/Unit)
For PLA cup production					
Fertilizer 15-15-15 production$^{a)}$	kg	1.4700$^{b)}$	0.0125	0.0029	0.0001
Herbicide (Paraquat) $^{c)}$	kg	25.00	0.00	0.92	0.10
Fuel oil$^{f)}$	L	3.010	0.020	0.001	0.001
Diesel for tractor$^{g)}$	L	3.3500	0.0185	0.0000	0.0000
For Melamine cup production					
Natural gas (excluding combustion)$^{d)}$	L	$0.1986\times10^{-3d)}$	0.0153×10^{-3}	0.0441×10^{-3}	0.0003×10^{-3}
Natural gas (with combustion)$^{f)}$	L	$1.89\times10^{-3\ b,d)}$	0.0212×10^{-3}	0.0035×10^{-3}	0.0001×10^{-3}
Crude oil (excluding combustion)$^{h)}$	kg	0.18	0.022	0.0002	0.0005
For both PLA and melamine cups					
Transport by truck 16t$^{g)}$	tkm	0.2380	0.0015	0.0035	0.0001
Transport by ship$^{g)}$	tkm	0.1160	0.0008	0.0002	0.0000
Electricity production$^{d)}$	MWh	581.20$^{e)}$	5.63	6.63	1.36

Data sources: $^{a)}$Produktie, 1995 [20]; $^{b)}$Konshaug, 1998 [21]; $^{c)}$Seabra, et al., 2007 [22]; $^{d)}$Ökoinventare, 1996 [23] and Phumpradab et al., 2009 [24]; $^{e)}$TGO, 2010 [25]; $^{f)}$Franklin Associates, 1998 [26]; $^{g)}$IDEMAT, 2001 [27], $^{h)}$Boustead, 1993 [28]

2.4 Use phase and disposal

An experiment of cup washing is used as a basis to estimate the value of COD and BOD from wastewater of cup washing. Both cups with and without coffee stain were tested and the wastewater resulting from such washing was analyzed for COD and BOD values. For each washing, 2.1 liters of water and 1 ml of detergent were used.

For cup disposal, landfill and incineration with and without energy recovery are chosen for end-of-life scenarios of PLA and melamine coffee cup, respectively. Furthermore, only greenhouse gas emissions and energy consumption of disposal steps are reported. The transportation for PLA and melamine cups waste is assumed over 90 km and 30 km, respectively by 16-ton truck. For landfill, PLA cup is degraded into carbon dioxide (CO_2), methane (CH_4), water and biomass [16]. Since CO_2 will be trapped by next cycle of cassava cultivation it can be ignored in the estimation, but CH_4 is taken into account in this phase. The basic data for energy recovery are derived from Suwanmanee et al. [17]. Generally, electricity can be generated from landfill gas (CH_4) which would result in reduction of greenhouse gas emissions and displacement of fossil electricity.

2.5 Abiotic depletion (ADP) and ecotoxicity

ADP is calculated from extraction of elements and fossil fuels and subsequently multiplied with the characterization factor (in kg antimony (Sb) equivalents/kg extraction), according to CML2 baseline 2000 method [18]. Freshwater aquatic and terrestrial ecotoxicity are calculated from toxic substances emitted to those ecosystems (in kg) and multiplied with the characterization factor (in kg 1,4-dichlorobenzene (1,4-DB) equivalents/kg emission). Factors that are applied for calculations in this study are shown in Table 1. For electricity calculation, it is assumed that all comes from grid, which has a fossil mix as followed; 67% of natural gas and 23% of lignite [19].

3. Results and Discussion

3.1 Impacts evaluation of PLA cup production

3.1.1 Cassava Cultivation

In this study, cassava was used as raw materials for starch and PLA production. For the environmental impact evaluations at this step, the required data were the amount of fertilizer, herbicide, and diesel used for cassava growing and harvesting. From literature and field surveys, it was found that the mixed fertilizer 15-15-15 (N-P-K) was the most commonly used in most areas of cassava growing in Thailand. The range of use in the north, northeast and east area was 10-12 kg/ton yield. The area-weight average of 11.29 kg/ton yield was used for impact estimate in this study.

Using the factors given in Table 1, N_2O by means of direct and indirect emission associated with N fertilizer application and CO_2 emission from N, P and K production were estimated. It was found that N_2O emission from fertilizer (production and application) was 0.81 kgN_2O/ha or equivalent to 239.75 kgCO_2-eq/ha or 16.03 kgCO_2-eq/ton cassava (yield of cassava root per ha was about 14.96 tonnes). Among emission sources from cassava cultivation, fertilizer was the most important (73%, Table 2). Another important source GHG emission was the production and utilization of diesel fuel (24%). The total global warming for this step was 22.11 kgCO_2-eq/ton cassava. On the other hand, the total abiotic depletion and ecotoxicity were 0.17 kgSb-eq/ton cassava and 0.068 kg 1,4-DB-eq/ton cassava, respectively.

3.1.2 Dextrose Production

The data on dextrose production and material uses were available from the plant surveys in Chonburi province [29]. This plant used cassava roots as the raw material to produce dextrose and cassava pulps. For one ton of dextrose, 1.73 ton of cassava root, 160 L of fuel oil and 76 kWh of electricity from the grid were consumed. This process generated 16.55 m^3 of wastewater which was assumed to be 80% to the input water because the accurate quantity of wastewater was not available. The dextrose production plant used an open anaerobic lagoon without methane recovery for water treatment. Thus, methane emission needs to be accounted. Diesel consumption for transportation of cassava roots from planting site to dextrose plant was collected from field surveys and plant visits. The average value was 7.42 L/ton starch. This was converted to 8.02 L/ton dextrose as one ton of dextrose was produced from 1.08 ton of starch.

The results in Table 2 show that the energy use and wastewater treatments were the main sources of environmental impacts. The disaggregated sources of greenhouse gas emissions shown in Table 2 indicate that there may be some opportunities to reduce greenhouse gas emission and therefore the impacts during dextrose production. The possibility, for example, to use renewable energy and the recovery of methane as biogas may serve as a good strategy since this could lead to the reduced use of fuel oil, electricity and emission from wastewater itself [30].

3.1.3 Lactic acid, lactide and polylactic acid production

Since the information on material use for producing PLA was not available publicly, only global warming potential was

Table 2. Materials, fuels use and the estimated environmental impacts for PLA cup production.

Raw material or product	Production input		Global Warming (kg CO_2-eq/ton of raw material or product)	Abiotic depletion (kgSb-eq/ ton of raw material or product)	Ecotoxicity (kg 1,4-DB-eq/ ton of raw material or product)	
	Material	Quantity used			Freshwater	Terrestrial
Cassava	Fertilizer (kg/ton cassava)	11.29	16.03	0.141	0.033	0.001
	Herbicide (kg/ton cassava)	0.03	0.85	0.000	0.031	0.003
	Diesel (L/ton cassava)	1.56	5.23	0.029	0.000	0.000
	Total		**22.11**	**0.17**	**0.064**	**0.004**
Dextrose	Fuel oil (L/ton dextrose)	160.00	481.60	3.200	0.160	0.160
	Electricity (kWh/ton dextrose)	76.00	44.17	0.428	0.504	0.103
	Diesel for transportation (L/ton dextrose)	3.00	10.08	0.056	0.000	0.000
	Water (L/ton dextrose)	16,552	1,215.18	0.000	0.000	0.000
	Total		**1,751.03**	**3.684**	**0.664**	**0.263**
PLA resin (include lactic acid and lactide)	Lime production (kg/ton PLA)	-	553.00	-	-	-
	Sulfuric acid production (kg/ton PLA)	-	89.00	-	-	-
	Auxiliary chemicals (kg/ton PLA)	-	222.00	-	-	-
	Electricity (kWh/ton PLA)	-	610.00	-	-	-
	Steam (kg/ton PLA)	-	689.00	-	-	-
	Wastewater (L/ton PLA)	-	2.00			
	Transportation (tkm/ton PLA)	-	67.00	-	-	-
	Total		**2,232.00**			
PLA cup	Electricity (kWh/ton cup)	3,139.53	1,824.70	17.676	20.815	4.270
	Transportation by truck (tkm/ton cup)	348.84	83.02	0.523	1.214	0.019
	Total		**1,907.72**	**18.20**	**22.03**	**4.29**

estimated. The data from Groot and Borén [11] were used for this purpose. Lime, sulfuric acid, and other auxiliary chemicals which are shown in Table 2 were the inputs for lactic acid production. The global warming of electricity and steam were calculated from energy consumption. The impact of transportation was somehow complicated. This included the data on transport for dextrose to lactic acid plant in Thailand by truck (74 km). Lactic acid and lactide were imported from U.S.A. by ship, thus the distance between these two destinations were used (13,297 km).

Out of total greenhouse gas emission per ton of PLA produced, steam, electricity and lime production combined contributed 83% (31%, 27%, and 25% respectively). The rest mainly came from auxiliary chemicals (10%), and transportation contributed only marginally (Table 2).

Since various raw materials could be used to produce PLA, and some data are not made public, comparing the impacts resulting from PLA cup production obtained from this study with other studies could not be made except for global warming potential (Table 3). For comparison purpose, carbon fixation in PLA was taken into account for the value of PLA production phase. The value was 1,833 kg CO_2-eq/ton PLA. This was calculated from stoichiometry: 6 moles CO_2 (MW 44 g/mol) is fixed per 1 mole of lactide (MW 144 g/mol) which is the same for PLA [11]. PLA that was evaluated for its environmental impacts in other studies were produced from corn. Their assessment started from cradle to gate, and carbon fixation of corn was included as well. PLA of Groot and Borén [11] study was made from sugarcane in Thailand. The energy credit for electricity production from bagasse in the sugar mill was taken into account in their study, so global warming potential of PLA for their study was relatively low (0.50 kg CO_2-eq/kg PLA). In this study the greenhouse gas emission of 2.84 kg CO_2-eq/kg PLA was relatively high but within the same range (0.5-5.16 kg CO_2-eq/kg PLA) when compared to other studies. The main reason was due to high impacts from fuel oil and CH_4 from wastewater of dextrose plant, and a relatively high emission factor of electricity in Thailand (581.20 kgCO2-eq/MWh). The high value reported by Johansson (2005) was due to the fact that energy recovery is not taken into account.

3.1.4 Production of PLA cup

One PLA cup was produced from 86.22 g of PLA and this consumed 0.27 kWh [13]. The impacts were evaluated for electricity consumed within PLA plant and the transportation of PLA resin from PURAC Ltd (174 km). Compared to other steps, cup production so far contributed relatively high for impact categories, i.e. 27%, 77%, 95%, 93% of the total global warming, abiotic depletion, freshwater and terrestrial ecotoxicity, respectively. In most case, electricity use during cup production was the highest contributor to each impact category.

3.1.5 Impact summary for a PLA cup production

One PLA cup was produced using materials mass as followed; 0.086 kg PLA which was made from 0.108 kg lactic acid, 0.117 kg dextrose, and 0.203 kg cassava roots. Thus, the impacts for one PLA cup production contributed by each of these production steps could be summarized as 164.06, 192.44, 204.87, 4.49 g CO_2-eq for global warming, 1.57, 0.43, 0.03 g Sb-eq for abiotic depletion (excluding PLA resin production step), and 2.26, 0.11, 0.01 g 1,4-DB-eq for ecotoxicity (excluding PLA resin production step), respectively.

Table 3. Comparison of the greenhouse gas emissions of PLA resin production between those obtained from this study and those from other studies.

Source	Raw material of PLA	kg CO_2-eq/kg PLA
This study	Cassava	2.84
Chiarakorn et al. (2011) [31]	Cassava	2.62
Groot and Borén (2010) [11]	Sugarcane	0.50
Suwanmanee et al. (2010) [17]	Corn	2.53
Vink et al. (2007) [32]	Corn	2.02
Hisun Co., Ltd. (2006) [33]	Corn	1.62
Johansson (2005) [12]	Corn	5.16
Bohlmann (2003) [34]	Corn	2.71

3.2 Impacts evaluation of melamine cup production

3.2.1 Melamine production

Melamine is the main raw material of melamine-formaldehyde resin production. It is generally synthesized from urea that is a product of ammonia and nitrogen, which in turn is produced from liquefied petroleum gas (LPG) and air, respectively. Although air was used as one of the raw materials but it has no impact so excluded from the impact calculation.

Table 4. Materials, fuels use and the estimated environmental impacts for melamine cup production.

Raw material or product	Production inputs			Global Warming (kg CO_2-eq/ton of raw material or product)	Abiotic depletion (kgSb-eq/ ton of raw material or product)	Ecotoxicity (kg 1,4-DB-eq/ton of raw material or product)	
	Material/Fuel	Quantity used	Unit			Aquatic	Terrestrial
Melamine	Crude oil	1,000.00	kg/ton melamine	180.00	22.00	0.23	0.49
	Natural gas (Fuel)	396,000.00	L/ton melamine	827.08	8.40	1.40	0.02
	Electricity	1,000.00	kWh/ton melamine	844.78	5.63	6.63	1.36
	CO_2	460.00	kg/ton melamine	460.00	0.00	0.00	0.00
	CO	0.10	kg/ton melamine	0.15	0.00	0.00	0.00
	CH_4	0.01	kg/ton melamine	0.32	0.00	0.00	0.00
	Total			**2,312.33**	**36.03**	**8.26**	**1.87**
Formaldehyde	Natural gas	63,000.00	MJ/ton formaldehyde	594.72	36.54	105.21	0.77
	Electricity	200.00	kWh/ton formaldehyde	83.71	1.12	1.33	0.27
	Formaldehyde	0.10	kg/ton formaldehyde	0.00	0.00	18.18	0.03
	CO	12.00	kg/ton formaldehyde	18.36	0.00	0.00	0.00
	Total			**696.79**	**37.66**	**124.72**	**1.07**
Pulp				**327.00**	**-**	**-**	**-**
Melamine-formaldehyde resin	Electricity	1,000.00	kWh/ton melamine resin	581.20	5.63	6.63	1.36
	Transport by ship	3,270.00	tkm/ton melamine resin	379.32	2.62	0.65	0.07
	Transport by truck	160.00	tkm/ton melamine resin	38.08	0.24	0.56	0.01
	Total			**998.6**	**8.49**	**7.84**	**1.44**
Melamine cup	Electricity	15,243.08	kWh/ton cup	8,859.28	85.82	101.06	20.73
	Transport by truck	265.88	tkm/ton cup	63.28	0.40	0.93	0.01
	Total			**8922.56**	**86.22**	**101.99**	**20.74**

LPG used for urea production was produced from crude oil, therefore the impact estimation included crude oil as a feedstock was considered [14]. CO_2, CO and CH_4 were emitted to the air contributing to global warming [14]. Information used in the calculation was adopted from Remmerswaal [14]. The production of 1 kg of melamine consumed 1 kg of crude oil, 396 L of natural gas, and 1 kWh of electricity (Table 4).

The total impacts per ton melamine production were 2,312.33 CO_2-eq, 36.03 kg Sb-eq, and 10.13 kg 1,4-DB-eq for global warming, abiotic depletion and ecotoxicity, respectively (Table 4). Global warming was mainly contributed by consumption of natural gas and electricity (72%). Abiotic depletion was mainly caused by use of crude oil (61%), and ecotoxicity by electricity consumption (79%).

3.2.2 Formaldehyde and pulp production

Formaldehyde (20% by weight) was used to mix with melamine and pulp for melamine-formaldehyde resin production. The amount of materials used is shown in Table 4. Natural gas and electricity was the raw materials and fuel that were used to produce formaldehyde, respectively. Natural gas was used as only raw material of formaldehyde so the impact for combustion of natural gas was not taken into account that resulted to low impact value of formaldehyde. For one ton of formaldehyde produced, 696.89 CO_2-eq, 37.66 kg Sb-eq and 125.79 kg 1,4-DB-eq of impacts were produced. Most of the global warming, abiotic depletion and ecotocixity were the results from consumptions of natural gas. Of particular importance was the relatively high impact for aquatic ecotoxicity resulting from use of natural gas.

3.2.3 Melamine-formaldehyde resin production

The materials used in this step were melamine, formaldehyde and pulp. The resin was produced through the condensation reaction of melamine and formaldehyde with pulp as reinforcement material. Therefore, the impacts in this step were resulted from the use of energy as electricity and fossil fuels for transportation (Table 4). The global warming, abiotic depletion and ecotocixity for this step were 998.60 CO_2-eq, 8.49 kg Sb-eq, 9.28 kg 1,4-DB-eq, respectively. The transportation of melamine from aboard (China and Japan) and the electricity consumptions were the main sources of impacts for this step.

3.2.4 Melamine cup production

Using the raw materials mentioned above, in this step melamine cup was produced by compression molding. The resin was heated until it was melted using primarily the electricity-heated mold. Another source of impacts came from fossil fuel uses for transportation. The data per ton melamine cup production and the impacts are provided in Table 4. The main source of impacts was from electricity consumption.

3.2.5 Impact summary for a melamine cup production

One melamine cup production consumed 0.085 kg melamine resin which is made from 0.043 kg melamine, 0.017 kg formaldehyde, and 0.025 kg pulp. Thus, the impacts of one melamine cup production for the step of cup production, MF resin, pulp, formaldehyde and melamine can be summarized as followed; 758.42, 84.88, 8.18, 11.85, 99.43 g CO_2-eq for global warming, 7.33, 0.72, 0.00, 0.64 and 1.55 g Sb-eq for abiotic depletion, and 10.43, 0.79, 0.00, 2.13, 0.44 g 1,4-DB-eq for ecotoxicity, respectively.

3.3 Use phase

For the use phase, only global warming category was evaluated. In this phase, laboratory experiments were conducted in which the coffee cups were washed and the wastewater resulting from such washing was measured for its COD and BOD contents. As can be expected, the results indicate that both BOD and COD contents of wastewater resulting from PLA and melamine cups were not different ($p \leq 0.05$). Therefore, greenhouse gas emissions of both cup types in this phase were assumed to be the same. The COD and BOD values of wastewater were 251.60 and 113.11 mg/L, respectively. Comparing between with and without coffee stain indicated that most of COD and BOD were contributed by the use of detergent.

Based on this COD and BOD and by assuming that the source of water as tap water [35], impacts of wastewater generated from the use phase of cups were evaluated. Throughout the life time (730 times of use), use of coffee cup emitted 632.91 gCO_2eq, 3.99 g Sb-eq of abiotic depletion, 39.55 g 1,4-DB-eq of aquatic ecotoxicity and 6.33 g 1,4-DB eq of terrestrial ecotoxicity, respectively. The main contribution was the impacts generated during tap water production, rather than from wastewater itself (Table 5).

Table 5. Life time impacts evaluation for the use phase of PLA and melamine cups.

Source	Quantity	Global warming (gCO_2-eq)	Abiotic depletion (g Sb-eq)	Ecotoxicity (g 1,4-DB)-eq
Tap water	2.10 L	594.8	3.99	45.88
Wastewater				
COD	251.6 mg/L	18.3	-	-
BOD	113.11 mg/L	19.81	-	-
Total		632.91	3.99	45.88

3.4 Disposal of coffee cup

In this study landfill and incineration with and without energy recovery were chosen for an end-of-life scenario of PLA and melamine coffee cups, respectively. Greenhouse gas emissions and energy consumption were estimated. For landfill scenario, PLA cup was assumed to be degraded into carbon dioxide, methane, water and biomass [16]. Suwanmanee *et al.* [17] found that electricity can be generated from landfill with energy recovery from CH_4 collection. Thus, energy recovery for cup disposal could result in reduction of greenhouse gas emissions and energy consumption for whole life cycle of PLA cup. This study applied the greenhouse gas emission reduction and energy consumption of 9.16 kg CO_2-eq and 13.81 MJ per kg PLA of Suwanmanee *et al* [17] to evaluate the impacts for this step. It was found that greenhouse gas emissions of landfill phase for one PLA cup was -789.68×10^{-3} $kgCO_2$-eq/cup (-9.16 kg CO_2-eq/kg PLA × 0.086 kg PLA/cup), and energy consumption was -1.19 MJ/cup (13.81 MJ/kg PLA × 0.086 kg PLA/cup) (Table 6). The negative values indicate emission reduction and net energy generation, respectively. Without energy recovery, the net emissions of 11.87 $kgCO_2$-eq/kg PLA would occur. Environmentally, therefore, the better alternative for PLA cup disposal was landfill with energy recovery from CH_4 collection.

Table 6. Global warming and energy consumption for disposal phase of PLA and melamine cups.

Cup type	Disposal scenarios	Global warming (kg CO_2-eq/cup)	Energy consumption (MJ/cup)
PLA cup	Landfill without energy recovery [a)]	1.02	-
	Landfill with energy recovery [a)]	-0.79	-1.19
Melamine cup	Incineration without energy recovery [b)]	0.01	0.003
	Incineration with energy recovery [b)]	0.005	-0.01

[a]adjusted from Suwanmanee et al. (2010) [17], [b]adjusted from Liamsanguan and Gheewala (2008) [36]

For estimate of emission and energy consumption of melamine cup disposal, the data of Liamsanguan and Gheewala (2008) [36] were applied. GHG emissions and energy consumption of melamine cup incineration were estimated from carbon content of melamine which was 30.77% in its chemical structure. The municipal solid waste carbon content was about 85.7%, estimated from polyethylene (PE) which was representation of plastic waste (27.72%) in MSW. The impact for GWP was about 63.38×10^{-3} kg CO_2-eq/kg melamine (5.39×10^{-3} kg CO_2-eq/cup). The net energy consumption of incineration with energy recovery for melamine was -104.27×10^{-3} MJ/kg melamine (-0.009 MJ/cup) [36]. Additionally, for the incineration without energy recovery 0.01 $kgCO_2$-eq was emitted and 0.003 MJ of energy were consumed. These results demonstrate that the end-of-life disposal scenarios have significant impacts of the greenhouse gas emission and energy balance of both PLA and melamine cups.

4. Comparison of environmental impacts from whole cycle of PLA and melamine cups

The comparison of greenhouse gas emissions from PLA and melamine coffee cups are shown in Figures 3 and 4, respectively. Up to use phase, the impacts for both PLA and melamine cups were the same. For PLA cup, carbon fixed through photosynthesis serving as the building block of PLA was taken into account. Stoichiometrically this value is -157.63 g CO_2-eq/cup (1,833 kg CO_2-eq/ton PLA). The total greenhouse gas emission up to use phase was 1,198.77 CO_2-eq/cup. Considering the amount of CO_2 absorbed through photosynthesis as mentioned, the net greenhouse gas emission was 1,041.14 CO_2-eq/cup (Figure 3). For melamine cup production and use phase, the total emission was 1,595.67 CO_2-eq/cup. Therefore it can be said that the production and use of PLA cup contributes much lesser greenhouse gas emission than melamine cup.

The contribution of PLA cup to global warming throughout the life cycle of PLA cup, however, is significantly dependent on the disposal scenarios. Since PLA cup is biologically degradable, anaerobic degradation could result in the production and emission of greenhouse gas methane. In the scenario that this methane gas is collected for energy generation and this subsequently utilized to replace the fossil fuel, the life cycle greenhouse gas emission was only 251.46 CO_2-eq/cup (Figure 3b). In contrast, if there is no methane collection for energy production, there would be the net emission of 2,065.24 CO_2-eq/cup (Figure 3a).

The effects of disposal scenario of melamine cup were not as significant as the case of PLA cup. Since melamine is not biologically degradable and its incineration does not generate much of useful energy as that in the case of PLA cup's methane collection, disposal with and without energy recovery did not result in the significant different in total greenhouse gas emission (Figure 4). The life time emission for the scenario of with and without energy recovery was 1,601.05 CO_2-eq/cup, and 1,601.96 CO_2-eq/cup, respectively.

Table 7 summarizes and compares the impacts of PLA and melamine cup for the whole life cycle. In addition to greenhouse emissions as mentioned above, energy consumption is another important aspect. In general, production of PLA is less energy intensive when compared with melamine cup. Again, the disposal scenario is the important indicator for energy intensity value, especially for PLA cup. For other impact categories, since the calculation results were not complete, it is still difficult to compare. However, the calculation results indicate that melamine production produces higher impacts (one order of magnitude) for abiotic depletion, freshwater and terrestrial ecotoxicity.

Table 7. Comparison of environmental impact and energy consumption from whole cycle of a PLA and melamine cup.

Impacts	PLA cup	Melamine cup	Unit
Greenhouse gas emissions (cradle to product-gate)	565.86	962.76	kg CO_2-eq/cup
Greenhouse gas (whole cycle included disposal without energy recovery)	2,065.24	1,601.96	kg CO_2-eq/cup
Greenhouse gas (whole cycle included disposal with energy recovery)	251.46	1,601.05	kg CO_2-eq/cup
Energy consumption (cradle to product-gate)	4.35	8.96	MJ/cup
Energy consumption (whole cycle included disposal without energy recovery)	4.35	8.96	MJ/cup
Energy consumption (whole cycle included disposal with energy recovery)	3.16	8.95	MJ/cup
Abiotic depletion	6.02×10^{-3}	1.42×10^{-2}	kgSb-eq/cup
Freshwater aquatic ecotox.	41.53×10^{-3}	5.14×10^{-2}	kg 1,4-DB eq/cup
Terrestrial ecotox.	6.73×10^{-3}	8.31×10^{-3}	kg 1,4-DB eq/cup

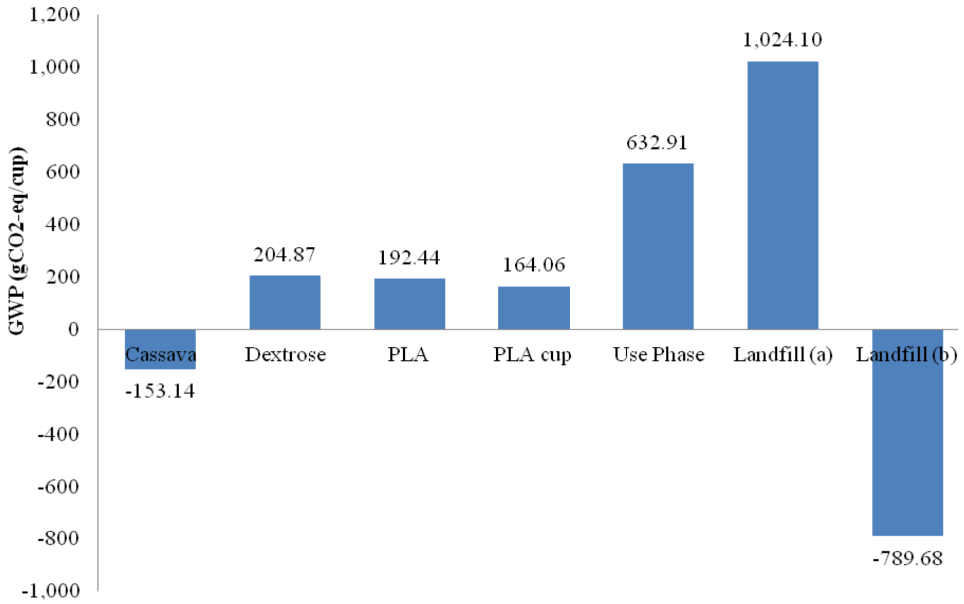

Figure 3. Global warming estimated for the whole life cycle of a PLA cup for the scenario landfill without energy recovery (a), and with energy recovery (b).

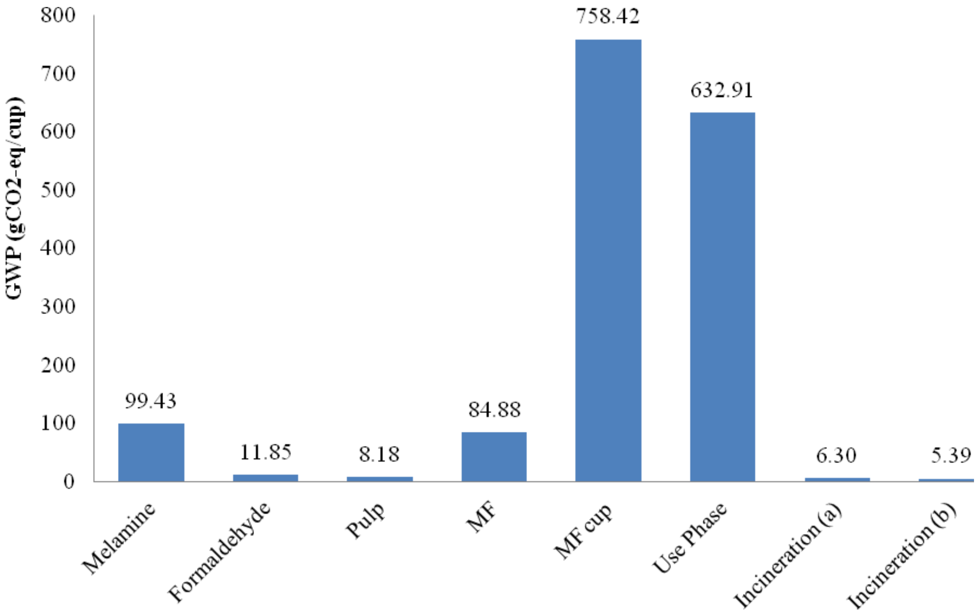

Figure 4. Global warming estimated for the whole life cycle of a melamine cup for the scenario landfill without energy recovery (a), and with energy recovery (b).

5. Conclusion

The results show that greenhouse gas emissions and energy consumption of PLA cup production and use were significantly lower than melamine coffee cup. However, greenhouse gas emission throughout the life time depends very much on disposal scenarios. It was observed that with energy recovery from landfill for PLA cup disposal, greenhouse gas emission could be significantly reduced. In contrast, greenhouse gas emission from PLA life cycle could be higher than that of melamine cup if there is no energy recovery from landfill methane. Comparing to PLA cup production, abiotic depletion and ecotoxicity associated with melamine cup production were higher. The results indicate that use of bio-plastic coffee cup as compared to the conventional plastic like melamine could be one of the effective strategies to reduce the environmental impacts, provided that a proper waste disposal scheme is implemented for the end-of-life management.

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