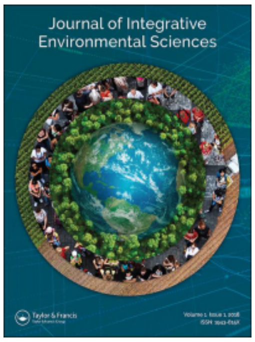

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Evaluation of the potential environmental impacts of condom production in Thailand

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ABSTRACT

This study aims to analyse the potential environmental impact of natural rubber (NR) condoms over its entire life cycle. The environmental performance of the production process of NR condoms is also compared to that of synthetic polyisoprene (PI) condoms. Options to reduce the environmental impact of condom production are proposed and evaluated. The potential environmental impacts are quantified by life cycle assessment (LCA). The study takes a cradle-to-grave approach, and considers six phases: 1) fresh latex production, 2) concentrated latex production, 3) condom production, 4) condom use, 5) condom transportation, and 6) condom disposal. The comparative analysis of NR and PI condom production takes a gate-to-gate scope. The functional unit is one gross condom. The results indicate that the condom production phase has the largest share (34–73%) in the environmental impact during the life cycle of NR condoms, followed by the disposal phase (20–60%). Comparing the production of NR and PI condoms reveals that the production of PI condoms results in a 1.5–2.5 times higher environmental impacts than the NR condom production, due to higher electricity consumption, especially for the compounding, dipping, and leaching processes. Reduction of electricity use is a key measure to reduce the environmental impact. Combining natural gas with electricity for the dipping process is a promising option to reduce the electricity use; it results in ~10–17% reduction in environmental impacts.

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Life cycle assessment; Natural rubber condom; Polyisoprene condom; Rubber; Thailand

1. Introduction

Thailand has been the world's leading producer of natural rubber for the last two decades. Approximately 3.4–3.6 million tons per year of natural rubber were exported worldwide in 2013–2016 (TTRA 2018). Natural rubber products are exported in the form of intermediate products (such as concentrated latex, block rubber, and smoked sheet rubber) and final products (such as gloves, condoms, balloons, soles, belts, and vehicle tires). Condoms are

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a natural rubber dipping product produced from concentrated latex. As awareness of the prevention of unintended pregnancy and sexually transmitted infections increases, condom demand is growing worldwide. The global condom market is expected to grow by ~8% between 2019 and 2025 (GMI 2019). Thailand has been the world's largest producer of condoms since 2004 (DITP 2018). Condoms produced in Thailand are mainly exported to international markets, especially China, the United States, and Europe. Although the majority of condoms are manufactured from natural rubber latex (NR condom), a synthetic non-latex condom has been developed as an alternative for people who are allergic to the protein content in natural latex. In Thailand, synthetic condoms are mainly produced from polyisoprene (PI) elastomers, which are stereoregular polymers that closely resemble natural rubber in molecular structure as well as in properties (strength, elasticity, and softness). Although the share of PI condoms is currently small, the PI condom production is anticipated to grow by~8% from 2019 to 2025 due to the limited supply of natural rubber latex (GMI 2019).

Besides ensuring the quality of condoms, information regarding sustainable production is required in the international market. To maintain the leadership position among condom producing countries, it is inevitable for Thai rubber entrepreneurs to seek cleaner measures for producing environment-friendly rubber products. This is because the production of natural rubber products causes ecological and environmental problems due to rubber plantation, transportation, processing, and waste disposal (Musikavong and Gheewala 2017; Pyay et al. 2019).In addition, the Thai government has proposed the direction of sustainable production and consumption in its 20-years national strategy (MOAC 2019).

Some studies on the environmental impacts of the production of primary and intermediate rubber products in Thailand are available. For example, Musikavong and Gheewala (2017) assessed the ecological footprint (EF) of ribbed smoked sheet rubber, concentrated latex, and blocked rubber. Their results indicated that the EF of the production of primary products (fresh latex, cup lump, and unsmoked sheet) accounted for more than 92% of the total EF. Pyay et al. (2019) evaluated the environmental footprint of intermediate products (ribbed smoked sheets (RSS), ribbed smoked sheet bales (RSSB), block rubber (Standard Thai Rubber, STR 20), and concentrated latex). It was found that eutrophication is an important environmental impact caused by concentrated latex production. Our previous studies included the analysis of greenhouse gas emissions from smoked sheet rubber, concentrated latex, and blocked rubber (Jawjit et al. 2010), as well as an environmental performance assessment of concentrated latex production (Jawjit et al. 2015).The most important sources of emissions of greenhouse gases were the energy use in the mills and the use of synthetic fertilizers in rubber plantations (Jawjit et al. 2010). In the study of concentrated latex production, it was found that electricity use in centrifugation process was a large contributor to global warming, acidification, and photochemical oxidation, whereas use of ammonia and DAP (Diammonium phosphate) had a large share in human toxicity and eutrophication, respectively (Jawjit et al. 2015).

Studies on the environmental impact of the production of some final rubber products are available, such as for vehicle tires (Sun et al. 2016) and guayule automobile tires (Eranki and Landis 2019). However, studies on the environmental impacts of the production of final rubber dipping products, such as condoms, gloves, and balloons, are still limited. The only study published on this subject is by Birnbach et al. (2020), who reported on the footprint of a natural rubber condom obtained from Einhorn products GmbH, to identify environmental hotspots. They conclude that the production process and the disposal phase had the largest share in the overall environmental impact of condoms. They contributed by 37–52% and 10–39% to the overall emissions, respectively. This indicates that most of the environmental impact (90%) is from the production and the downstream phases. Moreover, electricity consumption was among the activities with the largest contribution to the environmental impact (10–37%), as well as the ingredients in the condoms (10–56%). Some options to reduce the environmental impact of the life cycle of the natural rubber condom were recommended. However, their study did not include the environmental impact of the synthetic condom production process. Moreover, the effect of the options to reduce the impact was not quantitatively reported. This study aims to fill this knowledge gap.

The three objectives of this study were, therefore, 1) to analyse the potential environmental impact of the production of natural rubber (NR) condoms over its entire life cycle, and to explore the important causes of the environmental impact in each life cycle stage; 2) to compare the environmental performances of natural rubber (NR) condom and synthetic polyisoprene (PI) condom production process; and 3) to propose and evaluate options to reduce the environmental impact of the production of NR condoms.

2. Methodology

Life cycle assessment (LCA), based on ISO 14,040/ISO 14,044, was used to analyse the potential environmental impacts of condom production. The LCA consists of four steps: (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment, and (4) interpretation (Guinee 2002).

2.1 Goal and scope definition

The goals of this study were to analyse the potential environmental impact of the life cycle of NR condoms, to compare the environmental performances of natural rubber (NR) condom and synthetic polyisoprene (PI) condom production process, and to investigate options to reduce the environmental impact. According to the objectives, there are two scopes of study. First, “cradle-to-grave” refers to analysing the potential environmental impact over the complete life cycle of NR condoms. Second, “gate-to-gate” refers to the comparison between the production processes of NR and PI condoms. The scope of the comparative study is limited to the gate-to-gate approach, because the cradle or sources of PI latex and a few raw materials are unknown due to business confidentiality.

The study of the whole life cycle of NR condom considers six phases: 1) fresh latex production, 2) concentrated latex production, 3) condom production, 4) condom transportation, 5) condom use, and 6) condom disposal (Figure 1).Corporate activities (such as energy use in the office works, staff transportation) were not included because this study focused on the environmental performance of the product rather than the corporate. The resource use, waste generation, emission inventory, and potential environmental impact were quantified relative to the functional unit used for commercial purposes, which is one gross of condoms. One gross sample contained 144 condoms with a weight of 238 g.

The allocation of the environmental burden of rubber products in the life cycle was based on economic aspects. In fresh latex production, economic allocation factors (based on

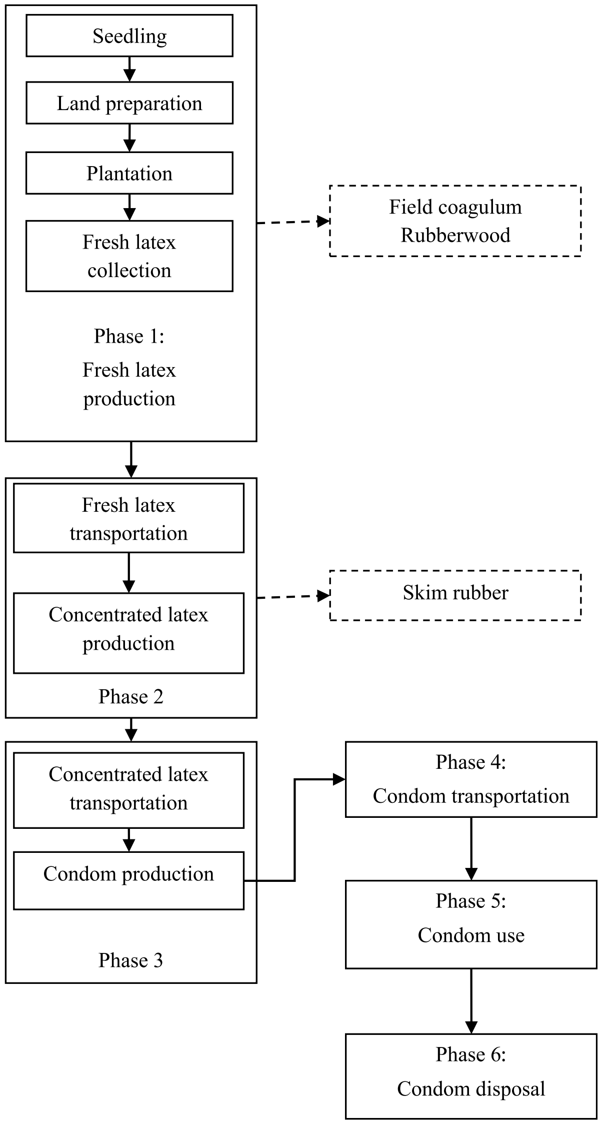

Figure 1. Scope of the study of the life cycle of NR condom (activities in dotted boxes are excluded from the study).

product price in Thailand) for fresh latex, rubberwood, and field coagulum are 0.6, 0.3, and 0.1, respectively. In concentrated latex production, the factors for concentrated latex and skim rubber are 0.95 and 0.05, respectively. Skim rubber, a by-product of concentrated latex production, was excluded from the scope because it is not related to condom production.

2.2 Activity data collection and inventory analysis

Activities data related to resources, energy use, and waste generation in the life cycle of condoms were collected from ten plantation sites, four concentrated latex mills, and one condom mill in Thailand. Information on fresh latex transportation was acquired by interviewing 30 farmers who were responsible for latex transportation. The activity data collected per one ton of fresh latex and concentrated latex were later converted relative to a functional unit (one gross of condom). Approximately 2.5 tons of fresh latex are used to produce 1 ton of concentrated latex (and 0.07 tons of skimmed crepe rubber). One gross of condoms (238 g) was obtained from ~470 g of concentrated latex (~1,180 g of fresh latex). Information on NR and PI condom production as well as concentrated latex transportation was collected from a condom mill that produced both types of condoms. The locations and names of the concentrated latex and condom manufacturing mills cannot be disclosed because of business confidentiality. For the transportation of condoms, the products are delivered worldwide by both airplane and cargo ship. In this study, transportation by a cargo ship to China, the largest importer, was used for calculation with the distance from Bangkok to Beijing (3,300 km). Since the distance to retail shops in Beijing highly varies, an assumption based on estimations of the company was made. Condoms were transported by trucks over a distance of 100 km from the port to retail shops. The only activity taken into account during condom use was the use of toilet paper. We assumed that toilet paper was used to wrap the condom after usage. For the condom disposal phase, we assumed that used condoms wrapped with toilet paper and their packages were discarded with household waste. Based on a study on municipal waste management in China by Zhang et al. (2010), the used condoms were assumed to be mixed with organic household/ municipal waste and then brought to the landfill site. The emission of pollutants relative to the functional units was calculated by Simapro (version 7.3) with Ecoinvent version 2.2 database (Ecoinvent 2018). All emissions factors were from Ecoinvent, except for the emission factors for greenhouse gas emissions from the use of nitrogen fertilizers and electricity production in Thailand, which were taken from IPCC (2006) and TGO (2019), respectively.

2.3 Impact assessment

Five environmental impacts were analysed in this study based on the geographical scale of the impact. Global warming represents a global scale impact, whereas acidification and eutrophication represent regional-scale impacts. The local-scale impact is represented by human toxicity and photochemical oxidation. The results from the emission inventory are multiplied with the characterization factor to calculate the potential environmental impact. The characterization factors developed by the Center of Environmental Science of Leiden University (CML) embedded in Simapro (version 7.3) were used to quantify the potential environmental impact (CML 2018). The CML method is based on a “problem-oriented” or “mid-point” approach (Guinee 2002). A sensitivity analysis was also conducted to determine the influence of the selection of the life cycle impact assessment method on the results. The method “Eco-indicator 99”, which is based on a “damage-oriented” approach, was also used for quantifying the environmental impact; the impacts were categorized into three damage categories: human health, ecosystem quality, and resource consumption (Goedkoop and Spriensma 2001).

2.4 Option for reducing environmental impact

Results from the potential impact assessment were used to identify the activities that have the largest shares or the hot spot of the environmental impacts in each phase of the life cycle of condoms. Options to reduce environmental impact were discussed and their consequences were evaluated relative to the current case in which options were not applied.

3. Results and discussion

3.1 Activity data and inventory analysis

Tables 1 and 2 present important activity data in each phase of the life cycle of condoms (fresh latex production, concentrated latex production, and condom production). The emission inventory of fresh latex production, concentrated latex production, NR condom production are presented in the supplementary tables (Tables S1–S3), whereas Table 3 presents an emission inventory of life cycle of one gross of NR condom. Emissions from condom transportation and disposal phase were also presented in Table 3 (Only emissions of pollutants that are responsible for 90% or more of the total contribution to each environmental impact were presented). Important findings from activity data are summarized and discussed in the following sections.

3.1.1 Fresh latex production

Data from ten rubber plantation sites revealed that~440 rubber trees were planted per hectare with a plantation cycle of 25–30 years. The first to seventh year is the pre-tapping period and from the eighth year onward, it is the tapping period for collecting fresh latex. The rubber clone preferred by farmers in the south of Thailand was RRIM 600, having an average yield of ~1.8 ton/ha/year. The percentage of dry rubber content (DRC) in the fresh latex is about 30–40% (Kerdtongmee et al. 2014). Land preparation was normally carried out using a tillage tractor after collecting rubberwood residues from the previous plantation. The diesel used in a tractor was about 18.8 liters/ha. As rubberwood residues can be sold as fuel, open burning of the wood was not favourable for farmers in the last decade. Thus, in this study, we did not include emissions from open burning. Rock phosphate was used in the early growth stage of the plantation; inorganic fertilizer was applied through the plantation cycle. The amount of fertilizer applied varied according to the financial status of farmers. The average amount of fertilizer applied was 203 kg/ha/year during the pre-tapping period (1–7 years) and 312 kg/ha/year during the tapping period (8–30 years). These rates are lower than those recommended by the Thailand Rubber Institute (TRI) and, hence, affected the yield. For the calculation of emissions and environmental impacts of the inorganic fertilizers, values of N fertilizer, P_2O_5 fertilizer, and K_2O fertilizer in the inorganic fertilizer were used (Table 1). Most farmers did not apply organic fertilizer despite the TRI recommendations. Glyphosate was used as a herbicide, especially during the pre-tapping period. Human labour was preferable during the tapping period.

Table 1. Activity data for the production of 1 ton of fresh latex (annual average for 30 years plantation cycle) and concentrated latex.

Fresh latex production		
Activity	Average value	Unit (per 1 ton of fresh latex)
Diesel use in land preparation	11.4	kg
Rock phosphate	1.3	kg
N-fertilizer	34.2	kg
P_2O_5-fertilizer	13.7	kg
K_2O fertilizer	34.2	kg
Glyphosate	3	kg
Concentrated latex production		
Activity	Average value	Unit (per 1 ton of concentrated latex)
Fresh latex transportation	75	tkm
Fresh latex	2.5	ton
Water	5	m^3
Electricity	100	kWh
Diammonium phosphate (DAP)	2.5	kg
Tetramethyl thiruam disulphide (TMTD)	0.5	kg
ZnO	0.5	kg
Lauric acid	0.5	kg
Ammonia	18	kg
Wastewater	7	m^3

3.1.2 Concentrated latex production

According to the visit of four concentrated latex mills, it was observed that all mills used similar production technologies and management. Approximately 2.5–2.7 tons of fresh latex were used to produce 1 ton of concentrated latex. The distance between fresh latex plantations and concentrated latex mills ranged from 3 to 60 km. Based on interviewing 30 farmers, 30 km was used for the calculation. The preferred vehicle was pick-up trucks with a 2.5-ton capacity for fresh latex. Since the unit for calculation of transportation is tkm (ton kilometre), value of fresh latex transportation was converted to 75 tkm (2.5 ton of fresh latex multiplied with 30 km). After fresh latex was delivered to the concentrated latex mill, it was transferred through a sieve into the reception tank. Chemicals including ammonia, lauric acid, TMTD (tetramethyl thiuram disulphide)/ZnO, and DAP (Diammonium phosphate) were added to preserve the latex quality. The latex was, then, diluted and centrifuged to separate the rubber content and water. After centrifugation, the concentrated latex (with %dry rubber content (DRC) of~60%–70%) was ammoniated to produce HA (high ammonia) latex or LA (low ammonia) latex; it was then moved to storage tanks and, finally, transported. Water use is an important resource in production because it is primarily used for cleaning fresh latex storage tanks and centrifugation machines, and diluting concentrated latex. Aerobic wastewater treatment systems were operated in every visited mill. It should be noted that an emission factor of TMTD is not available in any database. Therefore, it was not used for calculating the emissions and environmental impact.

3.1.3 Condom production

Activity data of condom production was collected from a condom production mill with a production capacity of ~600,000 gross/month (93% NR condom and 7% PI condom).

Most of the products were exported to China, the USA, Europe, and Brazil. Approximately 0.47 kg of concentrated latex was used to produce one gross NR condom. The distance from the concentrated latex mill to the condom production mill varies between 30 and 120 km. A distance of 60 km was used for the calculations, which is equivalent to 0.028 tkm (0.47E-03 ton of concentrated latex multiplied with 60 km).

The production process of the natural rubber condom consists of nine major steps: 1) compounding, 2) dipping, 3) drying, 4) beading, 5) curing or post-vulcanization, 6) stripping, 7) washing, 8) physical property testing, and 9) packing. The first step is the compounding process in which the latex, chemicals, water, and colour are mixed to achieve the required specification. The chemicals used in the compounding process are mainly alkaline salts, stabilizers, vulcanizing agents, activators, accelerators, and antioxidants (Blackley 1997). The names of some chemicals are unknown because of business confidentiality. Therefore, they were not included in the calculations. The latex and chemicals were mixed and stirred at 60°C for 14 h, followed by maturation at ambient temperature for 6–10 days (Lucas et al. 2020). The next step was the dipping process. The compound latex was delivered to a dipping continuous chain line. Clean glass formers were dipped in a compound latex tank having a typical temperature of 20°C (Attrill et al. 2015; Potter et al., 2015). Afterwards, the glass formers were moved into the oven for drying at 70–100°C before the second dipping and drying processes. Then, the open-end dried condoms were beaded to strengthen the edges and for ease-of-use. Subsequently, the dried beaded condoms were moved to the last oven maintained at a temperature of 110–130°C (Lucas et al. 2020) to achieve complete vulcanization. The next step is the leaching process, in which condoms are leached to remove excess chemicals and residues, including proteins; then, they are stripped off from the glass former by jet alkaline water. Next, the condoms were moved to a washing machine, where they were coated with silicone emulsion, magnesium carbonate, and corn powder to prevent the rubber from sticking to itself. All condoms were, then, tested for their length, strength, thickness, and leak using electronic testing machines. Lubricants and other additives, such as odour, flavour, and/or spermicides, are added to the foiling process. Information on the condom packaging was derived from Birnbach et al. (2020). The values of packaging materials presented in Table 2 were calculated relative to one gross of condom (144 condoms, 238 g).

The production of the PI condom also follows the same process. However, owing to the different properties of natural rubber latex and polyisoprene latex, different conditions in compounding, dipping, and leaching processes are applied. The details of these conditions are discussed in the comparative study in Section 3.3.

3.1.4 Condom transportation

There are two transportations of condoms taken into account in this study. As mentioned in section 2.2, the condoms were transported to Beijing by a cargo ship with a distance of 3,300 km, which is equivalent to 0.7854 tkm for one gross of condoms. Transportation to a retail shop was carried out by a truck. Distance at 100 km was assumed to be used for calculation, which is equivalent to 0.0238 tkm for one gross of condoms. The values of 0.7854 tkm and 0.0238 tkm were used for calculation of emission inventory and the environmental impact of transportation. It should be noted that there is an inevitable uncertainty in the calculation of transportation of condoms to the retail shop in Beijing,

Table 2. Activity data of the production of 1 gross NR and PI condom.

Activity	NR condom	PI condom	Unit
Concentrated latex	0.4696	-	kg
Concentrated latex transportation	0.028	-	tkm
Polyisoprene latex	-	0.69	kg
Diesel	0.075	-	litre
Electricity use in the production line			
-Compounding Process	0.04238	0.4113	kWh
-Dipping Process	2.45047	7.2382	kWh
-Electronic Testing Process	0.20839	0.1911	kWh
-Foiling Process	0.09790	0.1885	kWh
-Packing Process	0.03426	0.0343	kWh
Electricity use in wastewater treatment	0.105	0.1050	kWh
Chemicals in production process			
Chemicals in compounding process*	14.9	29.6	g
Ammonia	2.18	8.69	g
Corn starch	32.9	140	g
Silicone emulsion	3.4	16.3	g
Foiling silicone	-	80	g
Magnesium carbonate	2.88	-	g
Trisodium phosphate	2.44	-	g
Sodium hydroxide	12.8	20.0	g
Soap	-	2.75	g
Antibacteria	-	3.75	g
Packaging			
Primary package			
Paper	56.4	56.4	g
Polyethylene	49.98	49.98	g
Aluminium	21.79	21.79	g
Secondary package			
Paper	92.7	92.7	g
Polyethylene	43.62	43.62	g

aChemicals consist of vulcanizing agents, surfactants, stabilizers, activators, dispersing agents, accelerators, and curing agents. Information on these substances is confidential, and their chemical formula/ingredient is, thus, unknown. Hence, these substances were not included in the calculation of the emission inventory and potential environmental impact.

because the distance to the shop varies considerably. We considered an estimation of the company as the best data available. This issue should be fulfilled in the future assessment.

3.1.5 Condom use

Toilet paper was assumed to be used for wrapping the used condoms. Weight of toilet paper weight was based on Birnbach et al. (2020). The weight of the paper used for calculation was 3.46 g per one gross of condom. The environmental impact of toilet paper was calculated from its production.

3.1.6 Condom disposal

The used condoms wrapped with toilet paper and their package (149 g of paper, 93.6 g of polyethylene, 21.8 g of aluminium per one gross of condom) were discarded with household waste and then brought to the landfill site. The emissions and potential environmental impact from landfilling were modelled base on type of materials and calculated by Simapro with an ecoinvent database.

Table 3. Emission inventory of life cycle of one gross of natural rubber condom.

Impact/ pollutant	Unit	Total emission	Phases of life cycle: Fresh latex production	Concentrated latex production	Condom production	Condom transportation	Condom use	Disposal
Global warming								
CO_2	g	4,038	31	61	2,695	93	1.67	1156
CH_4	g	22	0.08	0.23	14	0.01	0.001	8
N_2O	mg	69	0.67	1	59	0.02	0.001	8
Acidification								
SO_2	g	28	0.14	0.41	22	1	0.01	4
NO_x	g	14	0.06	0.14	10	2	0.005	2
NH_3	mg	327	19	0.77	131	0.01	1	175
Eutrophication								
N	mg	99	1	16	41	0	<0.0001	40
P	mg	2	0.08	0.05	2	0	<0.0001	0
NO_3^-	g	6	0	0.01	1	0	<0.0001	5
PO_4^{3-}	mg	496	114	62	232	0.07	0.001	88
NO_x	g	14	0.06	0.14	10	2	0.005	2
COD*	g	154	0.08	0.06	4	0	0.0003	149
Human toxicity								
SO_2	g	28	0.14	0.41	22	1	0.01	4
CO	g	4	0.05	0.05	2	0.27	0.003	2
NO_x	g	14	0.06	0.14	10	2	0.005	2
PM*	mg	792	20	8	722	3	0.78	38
Photochemical oxidation								
CO	g	4	0.05	0.05	2	0.27	0.003	2
NMVOC*	g	2	0.01	0.02	2	0	0.0004	0.11
NO_x	g	14	0.06	0.14	10	2	0.005	2
PM	mg	792	20	8	722	3	0.78	38

*COD = Chemical Oxygen Demand, PM = Particulate Matter, NMVOC = Non-Methane Volatile Organic Carbon

Table 3 presents the emissions during each phase of the condom life cycle relative to one gross of the NR condom. Emissions of greenhouse gases and acidifying substances primarily arise from the condom production and disposal phase. The emissions of substances contributing to human toxicity and photochemical oxidation are mainly from the condom production phase, which is associated with energy consumption. Emissions of eutrophying substances, such as nitrogen, nitrate and COD, were mainly from condom disposal by landfilling.

3.2 Impact assessment

This section presents the results of a potential environmental impact assessment. First, the contribution of different activities in each phase was determined (potential environmental impact value for fresh latex production and concentrated latex production are presented inTables S4 and S5). Subsequently, the contribution of each phase in the life cycle of condoms is presented and discussed.

3.2.1 Impact assessment of different phases in condom life cycle

(a) Fresh latex production phase

Application of inorganic fertilizer is the most important activity, contributing the largest share (70%–95%) to every environmental impact (Figure 2). The impact of inorganic fertilizer

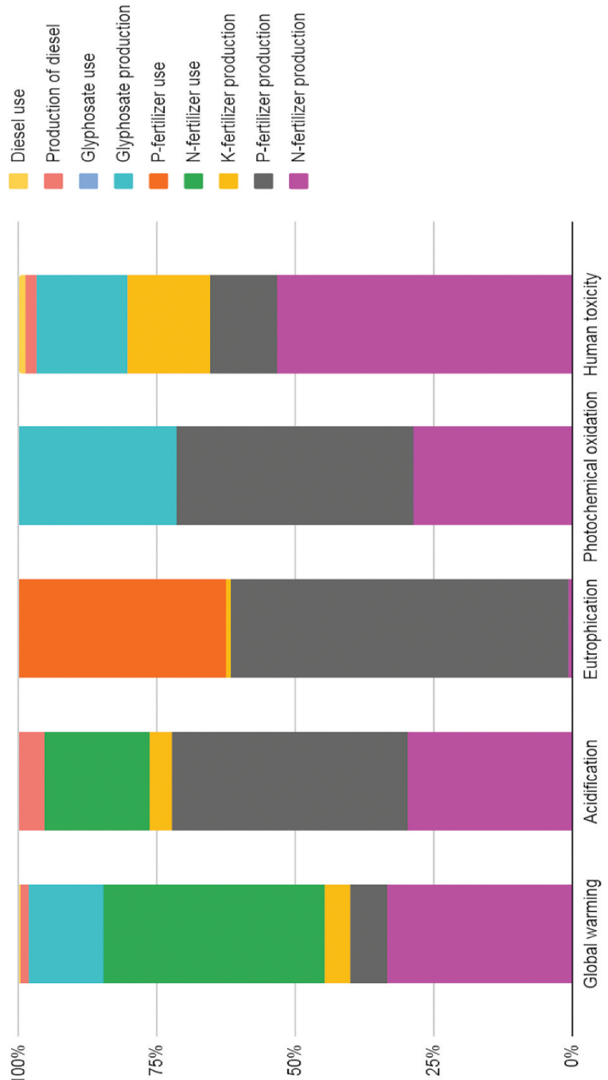

Figure 2. Contribution of activities in fresh latex production to environmental impact.

arises from upstream production, transportation, and application (Hasler et al. 2015).It was found that the production of inorganic fertilizer contributed the most to all environmental impacts except global warming. Nitrous oxide emissions from the use of nitrogen fertilizers play an important role in global warming. Nitrous oxide is emitted from soils due to nitrification and denitrification (Mosier et al. 1998). Rubber plantations may increase these natural emissions by, for example, enhanced N mineralization as a result of land use (Jawjit et al. 2010). Use of nitrogen fertilizer contributed to global warming by ~40%, whereas the production and use of phosphate fertilizer largely contributed to eutrophication by ~61% and 37%, respectively. The production of potassium fertilizer has share on the environmental impact in the range of 1%-15%. Since Potassium is taken up by plant roots very rapidly and is leached in the small amount, its use is considered to represent little environmental impact (PDA 2019; DPI, 2020). Birnbach et al. (2020) also reported that the production and application of inorganic fertilizers largely contributed to the environmental impact (45%–90%) by rubber plantations. Several mitigation options such as a combination of organic and inorganic fertilizer, improving the timing and frequency of fertilization, avoiding spilling of fertilizer, increasing the efficiency of fertilizer use, and growing high-yielding rubber trees, are proposed to reduce the environmental impacts of rubber cultivation (Jawjit et al. 2010; Musikavong and Gheewala 2016).

(b) Concentrated latex production phase

Electricity use plays an important role in global warming, acidification, and photochemical oxidation with a contribution of ~50–70% (Figure 3). Electricity is mainly used in the centrifugation process, which is the main process for separating the dry rubber content from the water. This result is in line with Birnbach et al. (2020). Ammonia used for latex preservation was found to be an important contributor (~45%) to human toxicity. DAP, used for removing magnesium from latex, has the largest share (~70%) in eutrophication. Reducing the use of electricity, ammonia, and DAP is, therefore, a key strategy for enhancing the environmental performance of concentrated latex production. An inverter installed for the centrifugation process to prevent energy loss during machine start-up resulted in a 10% reduction in electricity use in concentrated latex production. A reduction in ammonia use (~5%) can be achieved by installing chillers to prevent ammonia loss (Jawjit et al. 2015). An optimum concentration of DAP is recommended to both reduce environmental impact and produce stability of concentrated latex (Karunanayake et al. 2006). Reducing DAP use can also be achieved by extending the sedimentation time from 12 to 24 h (PCD, 2005).

(c) Condom production phase

This section presents the environmental impacts of the production process of NR condoms. For comparative purposes, the impact of the PI condom production process is assessed and presented separately in Section 3.3.

In the condom production phase, electricity use is the main contributor to global warming, acidification, and photochemical oxidation, accounting for approximately 80%, 81%, and 34%, respectively. The packaging largely contributes to eutrophication and human toxicity by approximately 60% whereas diesel used for heating during the maturation process contributes to photochemical oxidation by approximately 60% (Figure 4).

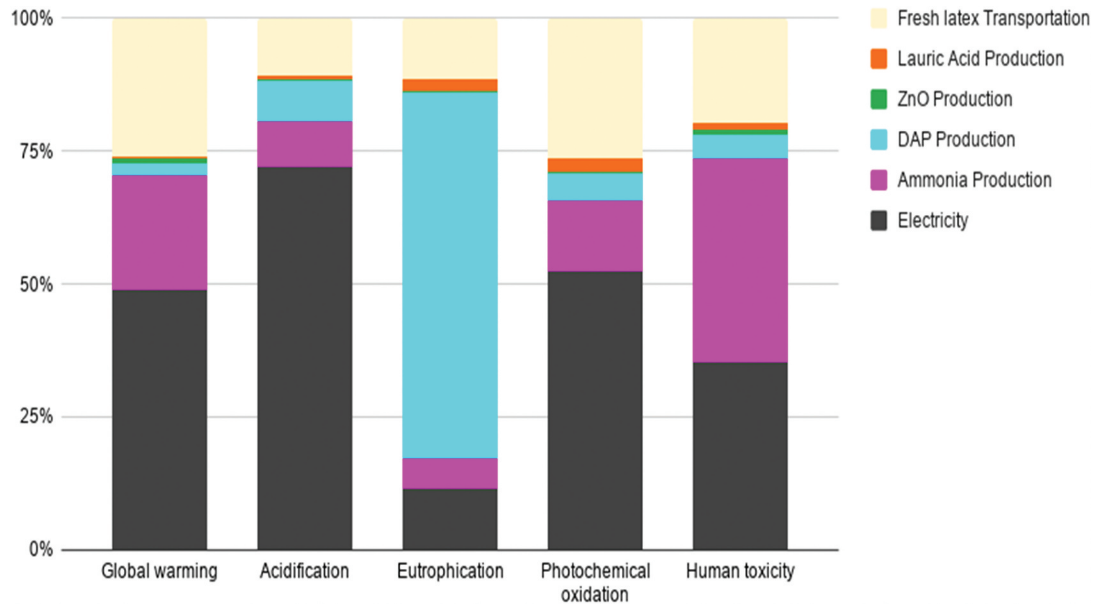

Figure 3. Contribution of activities in concentrated latex production to environmental impact.

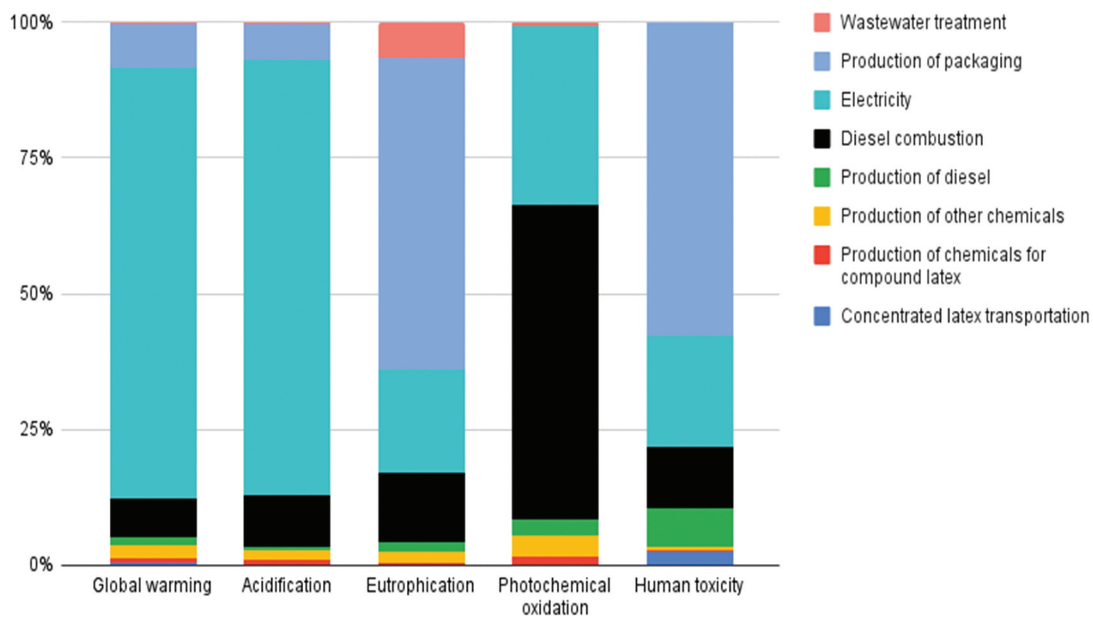

Figure 4. Contribution of activities in natural rubber condom production to environmental impact.

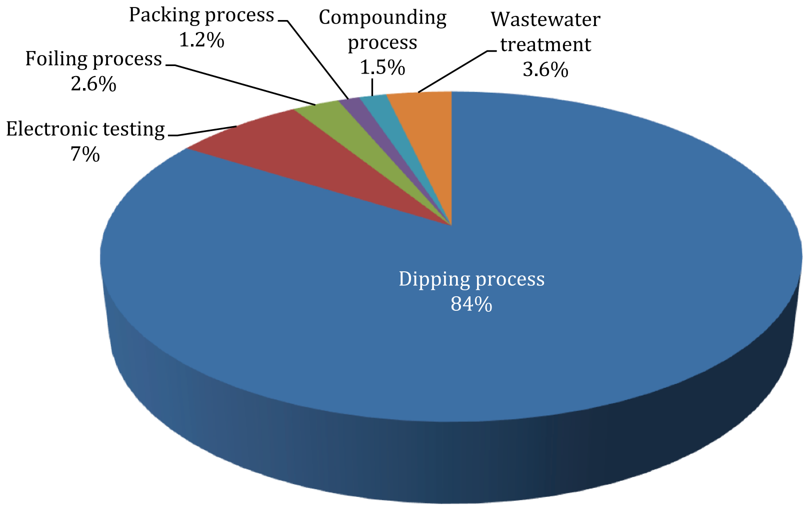

Figure 5. Electricity use in the NR condom production process.

Birnbach et al. (2020) moreover indicate that electricity consumption and the packaging materials are also important contributors in the NR condom production process, but they did not mention the effect of diesel use or other activities on photochemical oxidation. Electricity consumption is an important activity, because the dipping process requires a large amount of electricity owing to the heating (for vulcanization) of the oven after each dipping, as described in section 3.1.3. It is responsible for ~84% of the total electricity use (Figure 5). It should be noted that the value of electricity consumption in the dipping process included electricity consumption in beading and leaching the condoms. The potential impact of the packaging materials was from the upstream activities. The primary packaging contributed the highest share of emissions compared to other packaging. Aluminium in the packaging was found to be an important contributor (Birnbach et al. 2020). In case of chemicals used in the production process, it contributed less than 5% in all impacts. However, it should be noted that the impact of chemicals may be higher because not all chemicals are included in the calculation because of the unavailability of data. Transportation of concentrated latex contributed less than 1% in all impacts, and it was not presented in Figure 4.

(d) Condom transportation phase

The results of the potential environmental impacts of condom transportation were presented in Table 4. As expected, the impact from international transportation from Bangkok to Beijing dominated (95–98%) the transportation to a retail shop due to much further distance. The impact of international transport is supposed to be much higher, if the condoms were transported by plane. Birnbach et al. (2020) reported that although only 3% of the condoms have been transported by plane in their study, the associated emissions contribute by about 60% to the total greenhouse gas emissions. In spite of a small contribution in the environmental impact in this study, the emissions of transportation to retail shops can be reduced by adopting green supply chain management approach. For instance, Chanchaichujit et al. (2016)

Table 4. Environmental impacts of different phases of the life cycle of one gross of condoms.

			Phase of the life cycle					
Impact	Unit	Total	Fresh latex production	Concentrated latex production	Condom production	Condom transportation	Condom use	Condom Disposal
Global warming	g CO_2-eq	5,584	33	67	2,946	97	0.6	2440
Acidification	g SO_2 -eq	41	0.2	0.6	30	2	0.03	8
Eutrophication	g PO_4^{3-} eq	10	0.1	0.08	4	0	0.01	6
Human Toxicity	g 1,4-DB* eq	114	14	15	39	3	3	40
Photochemical oxidation	g C_2H_4- eq	2	0.01	0.03	1	0.1	0.001	0.6

*DB = Dichloro Benzene

developed an optimization model to optimize greenhouse gases emissions along the rubber supply chain by restructuring transportation and distribution methods. They found that the restructure of transportation to increase rail freight service capacity show a positive result in reducing greenhouse gases emissions as well as cost reduction.

(e) Condom use

The potential environmental impact of toilet paper was from its production and was presented in Table 4. Compared with other phases, the contribution of the use phase was relatively small (less than 1% in all impacts but human toxicity (2%)).The impact in this phase will be different or zero if different practices, such as knotting the used condom and throwing away without any wrapping or flushing down the toilet, are used. In this study, wrapping with toilet paper was assumed because it was regarded as a correct way to dispose of used condoms.

(f) Condom disposal phase

The potential environmental impact of the disposal phase was from activities at the landfill sites. Results from Table 4 and Figure 6 indicated that the disposal phase played an important role in global warming and eutrophication. It contributed approximately 44% and 58%, respectively. The leachate containing eutrophying agents (phosphate, nitrogen, and COD) and greenhouse gases emissions from landfills were important sources contributing to the impacts. Differences in condom disposal methods also yielded different impacts. Birnbach et al. (2020) used incineration as a disposal method that significantly contributed to human toxicity, whereas in our study landfill primarily contributed to eutrophication.

3.2.2 Impact assessment of the whole NR condom life cycle

The results of the potential environmental impact assessment and contribution of each phase in the life cycle of condoms are shown in Table 4 and Figure 6. It is noticeable that the condom production phase and the disposal phase are important phases in the life cycle of condoms. The condom production phase has the largest share in global warming, acidification and photochemical oxidation with contributions of 52%, 73%, and 58%, respectively. Energy consumption and the packaging are the important contributors in

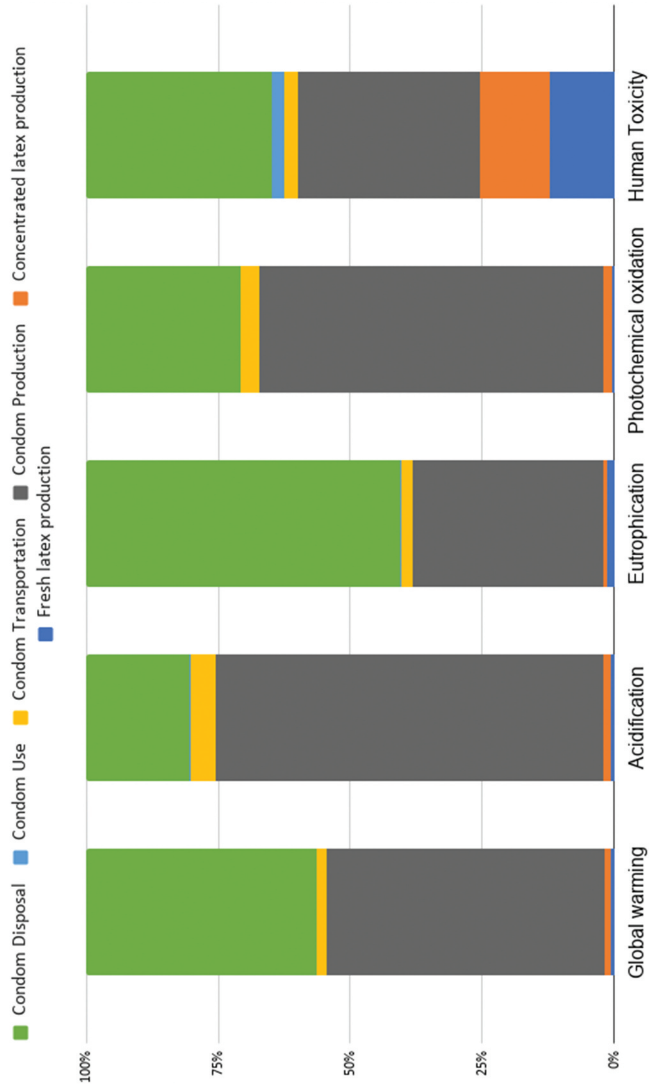

Figure 6. Contributions of each phase in the life cycle of an NR condom (CML method) to the environmental impact.

the production phase. The disposal phase was found to be the second-highest contributor to the environmental impacts (20–58%), especially in eutrophication (58%).

Condom transportation by container ships (international transportation) and trucks (domestic transportation) has a small share in environmental impact within a range of 2%-5%. As mentioned before, the environmental burden will be different with the choice of transportation methods (such as airplanes) employed. The condom use phase is the least contributor in the life cycle of NR condom. It contributed ~2% in human toxicity and less than 1% in other impacts. Fresh latex production and concentrated latex production also have small shares (less than 2%) in all environmental impacts except human toxicity, which they contributed to ~13% and 14%, respectively. It should also be noted that the large contribution of the condom production phase to the environmental impact is related to the rubber content in condom, which is derived from the fresh latex and concentrated latex. This is because ~2.5–2.7 tons of fresh latex were used to produce one ton of concentrated latex; and only 0.47 kg of concentrated latex was used to produce one gross of condoms. The hotspots in the life cycle of natural rubber products differ according to product functions. In this study, the production and disposal phase contributed the most to environmental impacts in the case of condoms, whereas in the studies of Eranki and Landis (2019) and Sun et al. (2016) the use phase contributed the most for vehicle tires.

When we compare our results with the study of Birnbach et al. (2020), we find that the production phase and disposal phase are the most important phases in both studies. Birnbach et al. (2020) reported that the condom production phase contributes most to the environmental impact (37–53%), whereas in this study the production phase contributes by 33–73%. The share of the condom production phase in our study was higher because corporate activities (e.g. business travel and electricity demand) are outside the scope of this study. Similar results for the small shares of the phase of fresh latex production, concentrated latex production and transportation were reported in both studies.

For a sensitivity analysis, the Eco-indicators 99 method was applied for impact assessment. The results in Figure 7 show that the condom production phase and the disposal phase also contribute most to all three impacts. The production phase has the largest contribution in human health (~50%) and resources consumption (~86%), whereas the disposal phase largely contributed (~72%) to ecosystem quality (Figure 7).

3.3 Comparison of the environmental impacts of the production process of natural rubber condom (NR) and synthetic polyisoprene condom (PI)

The emission inventory of NR and PI condom production process (1 gross) is presented in Table S6, whereas the potential impact assessment of the NR and PI condom production process is presented in Table 5. The contribution of activities to each environmental impact of NR and PI during the production process is presented in Table S7 and S8, respectively. The electricity use in PI condom production process contributes the most to all environmental impacts. It contributed approximately 90%, 94%, 43%, 78%, and 49% to global warming, acidification, eutrophication, photochemical oxidation, and human toxicity, respectively (Figure 8). Chemicals used in PI production process contributed ~20% to photochemical oxidation and only about ~5% to other environmental impacts. Other activities (chemical use in the compounding process and wastewater treatment) contributed very less to the environmental impact. The dipping process in the PI condom

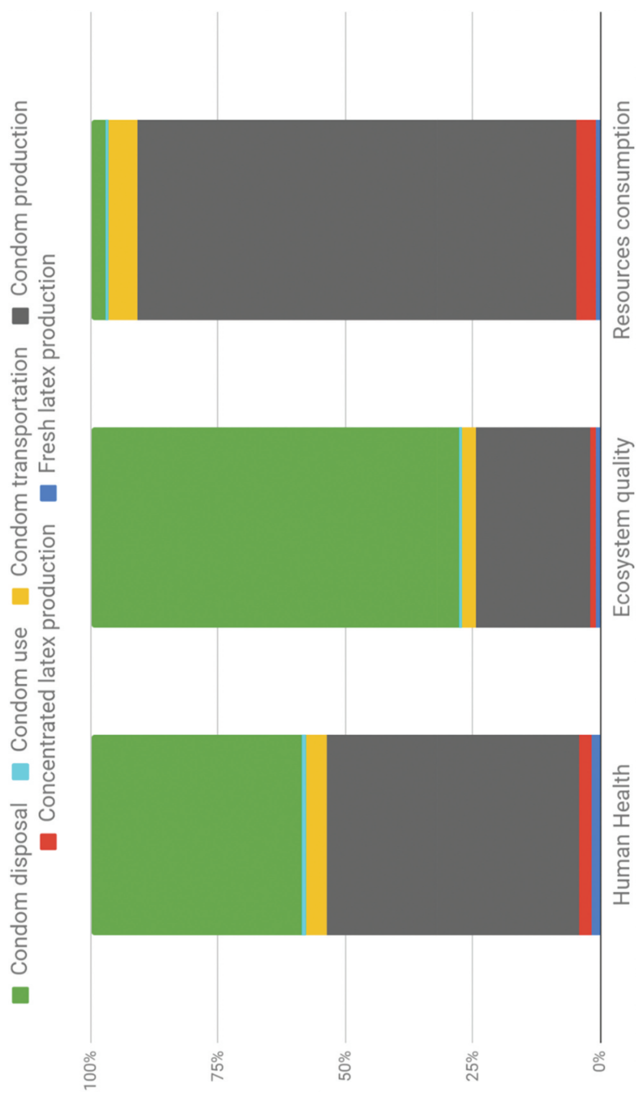

Figure 7. Contribution of each phase in the life cycle of NR condom (Eco-indicator 99 method) to the environmental impact.

Table 5. Environmental impacts of the production process of one gross of NR and PI condom.

Impact category	Unit	NR condom	PI condom
Global warming	g CO_2-eq	2,946	7,250
Acidification	g SO_2-eq	30	72
Eutrophication	gPO_4^{3-} eq	4	5
Photochemical oxidation	g C_2H_4-eq	1	2
Human toxicity	g 1,4 DB-eq	39	47

production process also consumed the largest share (86%) of electricity. It is noticeable that the electricity use in the compounding process of the PI condom has a larger share (5%) than that of the NR condom (1%). This is because more electricity is consumed to maintain a low temperature during the compounding process.

Compared with that of NR condom production process, the environmental impact of PI production process is ~2–2.5 times higher in the cases of global warming, acidification, and photochemical oxidation, and ~1.2–1.3 times higher in the cases of eutrophication and human toxicity (Table 5). As mentioned above, electricity use is a key activity that contributes to the environmental impact of both NR and PI condom production. The electricity consumption in PI condom production process (8.19 kWh/gross) is ~3 times higher than that in NR condom production process (2.92 kWh/gross), thereby causing a larger environmental impact. The processes that consume the major share of electricity in PI condom production include compounding, dipping, and leaching processes.

Compared to that of the compounding process in NR condom production, the electricity consumption of the PI compounding process is relatively larger because of the lower cooling temperature required for compounding, storage, and dipping tanks (~15°C; Potter et al., 2015 and Attrill et al. 2015). The low temperature in the PI compounding process prevents pre-vulcanization, which adversely affects PI condom quality. These include flocking of the latex compound, unevenness of the surface of the condom, and weak tensile strength of the condom (Attrill et al. 2015). Hence, more energy must be supplied to generate a higher temperature for subsequent drying and curing (post-vulcanization) in the oven to ensure complete vulcanization (Potter et al., 2015; Lucas et al. 2020). In addition, the thickness of the PI condom film was thicker than that of the NR condom. This results in more time and energy consumption for drying and vulcanization. Further, for PI condom films, it is more difficult to leach residues out and to strip off (Keddie and Routh 2010; Blackley 2012). Therefore, increasing the temperature of the leaching water is necessary to separate the dried vulcanized condom film from the glass surface. These different conditions in the production process of PI condoms directly cause higher energy consumption and, consequently, result in a higher environmental impact.

3.4 Options to reduce environmental impact

The environmental impact assessment indicated that electricity use in NR and PI condom production processes is the important contributor (hotspot) to environmental impact. Therefore, options to reduce electricity consumption in condom production must be devised. Based on the data collected during a visit to a condom mill, several options

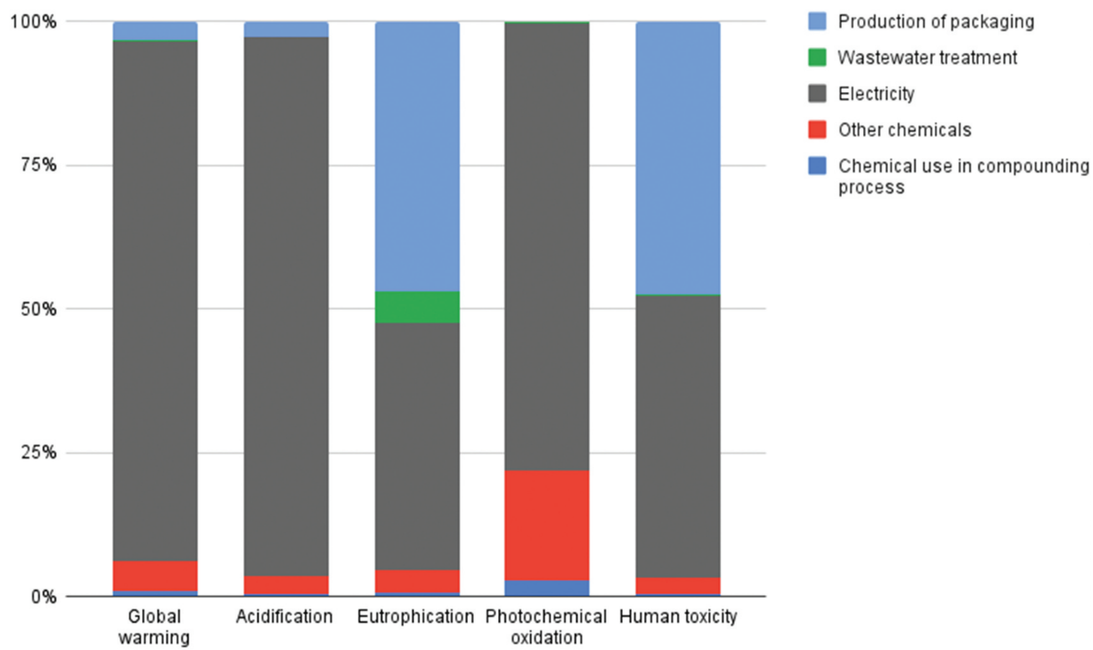

Figure 8. Contribution of activities in synthetic rubber (PI) condom production to environmental impact.

have been applied to reduce electricity consumption in the production line, including temperature control during the condom dipping process, reducing air leakage by improving the air distribution system, improving the efficiency of the chiller, and recovering waste heat from the exhaust gas. Other options that were not directly related to the production line were also applied. These included changing the light bulb from T8 type to LED, controlling aeration time at the wastewater treatment plant, and replacing few air conditioners with steam fans. According to the data collected by an interview with a technician, these measures resulted in ~10% reduction in electricity consumption, and consequently reduced the impact of global warming, acidification, eutrophication, photochemical oxidation, and human toxicity by approximately 8%, 13%, 2%, 10%, and 7%, respectively. In addition to these strategies, the Department of Alternative Energy Development and Efficiency (DEDE) (2017) suggested some potential options to reduce electricity use for producing dipping products. These include controlling the water flow rate in the leaching process, controlling the compressed air flow rate and pressure during the stripping process, improving the mould design and curing method, and applying the double former in the dipping process.

In particular, options for reducing electricity consumption by condom dipping and drying processes should be specifically considered because these processes contribute~84%–86% of the total electricity use. The only source of energy and heating for dipping in this study was electricity. In this study, we propose a method that combines the use of electricity and natural gas. As a pilot project, in one condom mill, 80% and 20% of the total energy required by the condom production line were produced by electricity and natural gas, respectively. In this study, we used the ratio of electricity and natural gas to determine the potential environmental impact of NR production process. This option resulted in a reduction in global warming, acidification, eutrophication, photochemical oxidation, and human toxicity by approximately 11%, 17%, 6%, 15%, and 10%, respectively (Figure 9). Therefore, the combination of electricity and natural gas for the condom dipping process is a potential option for reducing both the environmental impacts and operating costs. In addition, renewable energy like solar cells can also be another potential source of energy, since it is now more economically feasible in Thailand.

Disposal of the used condom is also an important contributor to the environmental impact. Since it is not feasible to reduce or recycle the used condom, the end-of-pipe disposal methods like landfill and incineration are still the most favourable. Both methods have their advantages and disadvantages. The use of an incineration facility (with energy recovery) to manage the municipal waste was better environmentally while landfilling all of the waste would be preferred financially (Liamsanguan and Gheewala 2008; Assamoi and Lawryshyn 2012). However, these two disposal methods must be well managed and operated correctly. Otherwise, this may lead to adverse impact and results in higher environmental impact. For example, several landfill sites in Thailand are not operated efficiently, and eventually become open dumping sites, which lead to environmental and health impact (Kaosol 2009). It should be noted that the results from the disposal phase were based on a sanitary landfill, which the wastes were assumed to be well managed. However, in practice, some studies mentioned that the self care products (including condoms) are not sustainably managed in the developing countries, such as open dumping, discarding at the public places, flushing down the toilet (Ehiri and Birley 2002; Pachauri et al. 2019). The environmental impact of waste management

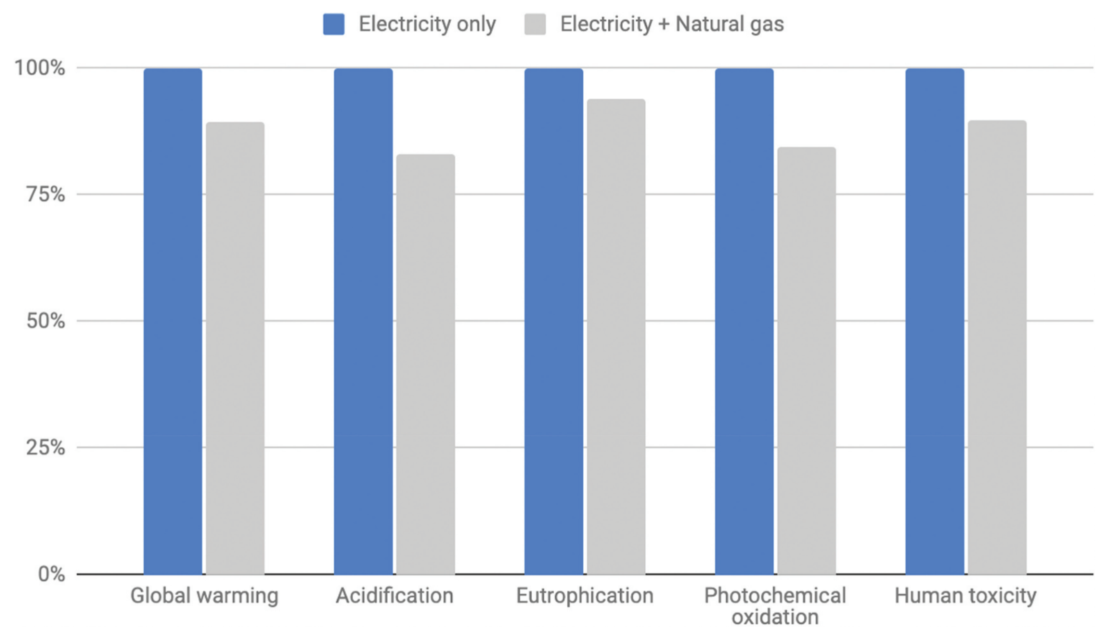

Figure 9. Reduction in potential environmental impact of NR condom production process when a combination of natural gas and electricity was used for heating in condom dipping process.

practices of self care products including condoms is a gap in our knowledge and could be subject of further research.

4. Conclusion

The life cycle assessment of the NR condom along with the CML assessment revealed that the condom production phase contributes most (52–73%) to global warming, acidification and photochemical oxidation. Electricity consumption during the dipping process is the factor contributing the most to the impact. The production of condom packaging is an important activity contributing to the impact during the condom production phase. Condom disposal by landfilling is the second-highest contributor (20–60%), and the largest contributor to eutrophication (60%). When different impact assessment methods are applied (eco-indicator method), the condom production phase is still the hotspot in the life cycle of the NR condom in terms of human health and resource consumption, whereas landfills are an important contributor to ecosystem quality. When analysing the important activities in each phase of the life cycle of the NR condom, it was found that inorganic fertilizer application is the most important activity in the fresh latex production phase. Electricity use for centrifugation and dipping process is the most important activity in concentrated latex production and condom production, respectively. There are some differences between the results of our study and those of Birnbach et al. (2020) as a result of differences in the scope of studies activities included. Nevertheless, both studies identify electricity consumption in the condom production phase as the key activity in the life cycle of the NR condom.

Our study is the first study to compare the potential environmental impacts of NR and PI condom production. Our results indicate that the environmental impact of PI production is ~2–2.5 times higher than that of NR production for global warming, acidification, and photochemical oxidation, and ~1.2–1.3 times higher for eutrophication and human toxicity. The electricity consumption by the PI condom production is more than 3-times that of NR condom production, especially in the compounding, dipping, and leaching processes because of the different properties of NR and PI latex. For the compounding process in PI condom production, more electricity is supplied to keep the temperature of the compound low to prevent pre-vulcanization. In the dipping process, the thickness of the PI condom film is larger than that of the NR condom. This leads to higher energy requirements to maintain higher temperature for subsequent drying and curing (post-vulcanization) in the oven to ensure complete vulcanization. Also, high-temperature leaching water is used to remove the residues and separate the condoms from the formers. These different conditions in the production of PI condom directly resulted in higher environmental impact.

In both NR and PI condom production, reducing electricity consumption is an important measure to reduce environmental impacts. Several energy-saving options can be applied, such as improving the efficiency of chillers, recovering waste heat using heat pipes from the exhaust gas, and applying double former in the dipping process. In this study, a combination of natural gas and electricity was employed, and its effects were analysed; this method resulted in ~6–17% reduction in environmental impact. To follow a national strategy for sustainable production and consumption, it is necessary for Thai entrepreneurs to analyse the comprehensive environmental performance of their products. The results of this study can aid decision-makers in formulating strategies for reducing environmental impacts and manufacturers in producing environmental-friendly condom products.

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