A review of eco-efficiency feasibility in rubber glove manufacturing in Thailand

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Graphical Abstract

Abstract

Commodity rubber-based products are essential goods in the present-day market. Rubber gloves industry, based on a renewable raw material with exceptional properties, presents an important example of making rubber products. Most of the rubber glove manufacturing in Thailand is located in the southern and eastern regions. Various environmental problems and cost inefficiencies pose a challenge to processing, which is likely to consume a lot of energy and material. In this study, it was proposed to improve rubber glove processing with a novel methodology to become more cost efficient and environmentally friendly. This methodology consisted of three phases. In the first, material flow analysis (MFA), material flow cost accounting (MFCA) and life cycle assessment (LCA) are used to evaluate the economic losses and greenhouse gas emissions. Next, there is development of proposed improvements. Finally, there is benefit validation of the proposed improvement options for implementation. The research methodology reported here is used extensively in the implementation of a feasibility model for the rubber glove manufacturing industry, and can be applied to other similar manufacturing industries in developing countries.

Keywords: Life cycle assessment, Glove production, Biomass fuel, Economic impact, Environmental impact

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1. Introduction

Market of the nitrile butadiene rubber (NBR) latex-based gloves will reach US$ 66.8 billion by 2027, owing to the spread of coronaviruses. Medical gloves are required to protect against Covid-19 with over 80 million gloves needed for healthcare teams (Anon n.d.). The demand for rubber gloves in several industries, particularly in the health services, has been continuously growing in the recent past due to the increased use of health and hygienic products among consumers with the COVID-19 pandemic. Nitrile powder-free glove product is important for manufacturing in Thailand regarding both employment and exports (Sein et al. 2010). If considered in the energy aspects, glove manufacturing is a high level energy consumer and tends to increase its consumption with economic growth (Anon n.d.). The biomass boilers can utilize renewable fuel sources such as palm kernels, wood chips, or wood pellets, thus avoiding greenhouse gas emissions from fossil fuel combustion (Anon n.d.). There is Material Flow Analysis (MFA) reported for rubber glove products available in the literature (Dunuwila, Rodrigo, and Goto 2018b). MFA is a widespread and standardized methodology for accounting for a system's input and output material flows (Rattanapan, Suksaroj, and Ounsaneha 2012).

The Thai Rubber Glove Manufacturers Association (TRGMA) has set a target to increase the share of rubber gloves in the global market by 5 percent (from 15 to 20 percent) by 2026. They are pushing to improve competitiveness of and increase the investments in the rubber glove industry. The long-term goal is to achieve a 40 percent share of the global market. Due to the Covid 19 pandemic, 3.6 million rubber gloves will be produced in Thailand, leading to a 20 percent increase in demand. Moreover, the demand is expected to increase by 20 percent in 2022. Therefore, the government should urgently provide more financial support to help glove manufacturers expand their investments. It should also make it easier for new factories to start up by streamlining regulations. Nineteen glove manufacturers in Thailand produce 46 million gloves a year, 90 percent of which are exported. This makes us, Thailand, the second largest exporter of rubber gloves in the world, 88 percent of which are medical rubber gloves (Phoonphongphiphat A 2021).

The Covid 19 pandemic is impacting global demand for rubber gloves, which saw exports rise 16 percent year-on-year in the first quarter of 2020. Thailand has free trade agreements (FTAs) in force with 18 territories and countries. Only India maintains a 10 percent import tariff on Thai rubber gloves, while 17 countries no longer impose import tariffs on Thai rubber gloves. Besides the Association of Southeast Asian Nations (ASEAN), these include Japan, China, Australia, South Korea, Chile, New Zealand, Hong Kong and Peru (Arunmas Phusadee 2021).

Therefore, this study aims to assess the eco-efficiency feasibility by using LCA and MFA to determine the environmental and economic impacts of rubber glove manufacturing. These should be evaluated to improve the process by reducing the environmental impact while increasing the value added.
Table 1: Thailand's top 10 rubber glove export markets (Arunmas Phusadee 2021)

<table>
<thead>
<tr>
<th>Market</th>
<th>Value: US$ million</th>
<th>% Change</th>
<th>Share of total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2018</td>
<td>2019</td>
<td>2020 (Jan-Apr)</td>
</tr>
<tr>
<td>US</td>
<td>551.70</td>
<td>568.80</td>
<td>193.90</td>
</tr>
<tr>
<td>EU</td>
<td>258.90</td>
<td>249.10</td>
<td>82.90</td>
</tr>
<tr>
<td>China</td>
<td>39.40</td>
<td>49.80</td>
<td>31.00</td>
</tr>
<tr>
<td>Japan</td>
<td>74.00</td>
<td>69.40</td>
<td>22.60</td>
</tr>
<tr>
<td>Asean</td>
<td>36.00</td>
<td>38.10</td>
<td>18.30</td>
</tr>
<tr>
<td>Brazil</td>
<td>17.80</td>
<td>27.30</td>
<td>11.60</td>
</tr>
<tr>
<td>Australia</td>
<td>25.90</td>
<td>18.70</td>
<td>9.60</td>
</tr>
<tr>
<td>Israel</td>
<td>23.20</td>
<td>22.50</td>
<td>9.40</td>
</tr>
<tr>
<td>India</td>
<td>15.50</td>
<td>17.00</td>
<td>8.30</td>
</tr>
<tr>
<td>South Korea</td>
<td>19.70</td>
<td>17.50</td>
<td>7.90</td>
</tr>
<tr>
<td>World</td>
<td>1,188.50</td>
<td>1,203.10</td>
<td>449.20</td>
</tr>
</tbody>
</table>

Source: Commerce Ministry

2. The technology of glove manufacturers

2.1 Resources of glove manufacturing (energy and materials)

The manufacture of rubber gloves is labor-, energy-, and material-intensive process. The several stages of rubber glove manufacturing process need to consume a huge amount of resources such as freshwater, chemicals, firewood, thermal energy and electricity. Freshwater is a major factor in material consumption. Water is often used to dilute field latex and chemicals, wash equipment, clean the factory and even cool the machines. The chemicals and gloves are dried by using thermal energy generated by burning firewood. Electricity is used mainly for lighting the factory, pumping water, heavy machinery, and wastewater treatment (Jawjit, Kroeze, and Rattanapan 2010) and (Jawjit, Pavasant, and Kroeze 2015). Saidur and Mekhilef analyzed the energy consumption and energy conversion in Malaysian rubber production through energy audit, energy audit data, estimation of energy consumption, energy savings, payback period and emission reduction, assessing for example annual energy used by electric motors, energy savings by using high-efficiency engines, mathematical formulations to estimate energy savings using high efficient motors (HEMs), and variable speed drives (VSD), estimation of boiler energy savings, compressed air energy savings, chiller energy
savings, mathematical formulations of the payback period, and estimates of emission reduction (Saidur and Mekhilef 2010).

Rubber-based goods include various types of commodities mainly manufactured by small, medium and large-scale industries. Size of production line in a generic rubber glove plant is 800–1200 m in length and such lines are usually spread out in various buildings. The main processing steps for rubber products are grinding, mixing and vulcanizing. All processing steps of rubber glove products require energy, which is the highest cost for some equipment, such as compressors. Therefore, they have a relatively high-power consumption, accounting for more than 50% of the total consumption.

In comparison, the vulcanizing process uses up 80% of the total energy consumption (Christoffersen, Larsen, and Togeby 2006). Energy consumption and its negative impact on the environment are on the rise. Most developing countries have shifted from agriculture to industrialization in recent decades. While promising a healthy expansion of the gross domestic product (GDP), the development of the industrial sector has severely affected the countries' ability to maintain fuel supply or reserves. The introduction of the concept of rational use of energy aims to reduce energy use and targets the optimum use of all energy forms. One way to achieve high efficiency consumption of the end point in an industry is to determine the energy consumption and the energy losses. Different types of plants and equipment would have different energy efficiencies depending on their characteristics, but adoption is limited by economic resources (Kelly Kissock and Eger 2008) and by the conditions for manufacturing.

An energy audit is a quantitative assessment of energy consumption in a production plant. Energy audit and energy analysis have been published for numerous industries (Tam, Leung, and Probert 1989) (Tekasakul and Promtong 2008). Industrial energy consumption and efficiency have also been studied by various surveys in different countries (Saidur and Mekhilef 2010). However, there are few studies on energy consumption with breakdown by machine for Asian rubber glove industry. This method was used in this case study to evaluate actual energy consumption. Although this method attempts to extract as much savings information as possible from readily available utility billing, production, and temperature data, the extractable information is limited by the dataset, which is sparse in both the system and time domains. The most critical limitation is in the system domain, where the method attempts to determine savings from individual subsystems based on the energy consumption of the entire system. (Kelly Kissock and Eger 2008). The trigeneration method is presented in the reference as an alternative way to improve energy use in CHP systems. The savings result from the reduction of fuel supplied to the turbo-generator units. Thermodynamic methods of (energy and exergy) analysis have been used to evaluate energy use in industry and it has been found that poor thermodynamic performance is mainly due to exergy losses in combustion and heat transfer processes (Bayindir, Sagiroglu, and Colak 2009).

Heat supply in a boiler system is lost for 10-30 percent due to flue gases at high temperatures, as shown in Fig. 1. Thus, boiler systems can achieve significant energy savings from utilizing the waste heat in high temperature flue gas. In addition, optimizing the excess air ratio to minimize heat loss using a variable speed drive (VSD) for the blower motor, to change the excess air ratio, can improve boiler efficiency. The energy lost as heat in rubber products industry is shown in Fig. 2 (Barma et al. 2017).
Biomass is the most popular alternative energy source due to being a clean, inexpensive, and widely available renewable resource. There are different types of biomasses, such as energy crops, wood, agricultural residues, municipal wastes, industrial wastes, etc., and there are different ways to convert biomass into energy. By the way, biomass is the only trustworthy resource that can be converted into all forms of energy for use, and densification of biomass is the essential technique to get better properties in pellet form. Several studies have focused on biomass pellets in recent years, for example on wood residues and pellets from wood, pellets from municipal solid waste, pellets from agricultural residues, from sewage sludge, and pellets from industrial wastes (Wattana et al. 2017).
The palm oil industry generates significant amounts of solid waste. Solid wastes, also referred to as oil palm biomass, include the trunk (OPT) and fronds (OPF) from the plantation, as well as empty fruit bunches (EFB), mesocarp fibers (MF), and palm kernel shells (PKS) from the processing plants (see Fig. 3) (Ahmad et al. 2019). Tables 2 and 3 summarize the contents of lignocellulose in oil palm biomass and the proportions of cellulose, hemicellulose, lignin and ash in oil palm biomass.

**Table 2:** Lignocellulosic biomasses from palm oil mill (Onoja et al. 2019).

<table>
<thead>
<tr>
<th>Biomass type</th>
<th>Moisture content (%)</th>
<th>Volatile matter (%)</th>
<th>Ash (%)</th>
<th>Fixed carbon (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palm kernel shell (PKS)</td>
<td>11.00</td>
<td>67.20</td>
<td>2.10</td>
<td>19.70</td>
</tr>
<tr>
<td>Empty fruit bunch (EFB)</td>
<td>6.36</td>
<td>78.20</td>
<td>4.53</td>
<td>16.46</td>
</tr>
<tr>
<td>Mesocarp fiber (MF)</td>
<td>-</td>
<td>73.03</td>
<td>10.83</td>
<td>16.13</td>
</tr>
</tbody>
</table>

**Table 3:** The compositions of oil palm biomass (Ahmad et al. 2019).

<table>
<thead>
<tr>
<th>Biomass type</th>
<th>Cellulose</th>
<th>Hemicellulose</th>
<th>Lignin</th>
<th>Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palm kernel shell (PKS)</td>
<td>28.8-27.2</td>
<td>21.6-22.7</td>
<td>44.0-50.7</td>
<td>8.6-16.3</td>
</tr>
<tr>
<td>Empty fruit bunch (EFB)</td>
<td>34.0-40.4</td>
<td>17.2-22.4</td>
<td>23.1-29.6</td>
<td>5.0-6.5</td>
</tr>
<tr>
<td>Mesocarp fiber (MF)</td>
<td>23.0-28.8</td>
<td>25.3-30.5</td>
<td>25.5-28.97</td>
<td>2.6-5.8</td>
</tr>
</tbody>
</table>
Fig. 3: Biomass fuels for thermal hot oil (TOH): empty fruit bunches (EFB), palm fiber, wood chips, and palm kernel shells (PKS).

2.2 Alternative manufacturing methods

The process flow diagram of NBR glove production is shown in Fig. 4. Firstly, the previous batch of glove production is reused, the hand shaped mold is cleaned and then dipped in coagulant to improve adhesion. Then, the mold is dipped in NBR latex that is gelled to form a latex film, and it goes through leaching, beading, drying and vulcanizing to improve the mechanical and physical properties of the NBR gloves, followed by cooling, chlorination, post leaching, drying, stripping, product quality testing, and finally packaging for distribution to end users.
2.2.1 NBR powder-free glove dipping process with polymer coating

Primary stage includes three processes, namely the acid cleaning, the alkaline cleaning, and the water rinsing. The mold must be cleaned after the previous batch of glove production. First the molds are immersed in the acid solution tank to convert the stricture into stearic acid, then they are neutralized by water washing. After the molds pass through the water wash tank, they are transferred to the caustic tank by a conveyor chain to remove the stearic acid from the molds. The stream is then transferred to the water rinse tank, which is the last operation before this phase is completed. The cleaned molds are sent to the secondary phase with nine different process types: coagulant dipping, compounded latex dipping, latex film drying, pre-leaching, beading, polymer dipping, vulcanizing, post-leaching, and drying. The product is then sent via the conveyor chain to the third stage, the online packaging process.

2.2.2 NBR powder-free glove dipping process with online chlorination.

The first stage, the earlier described cleaning process, is similar to that used in the manufacture of polymer-coated gloves. After the water rinsing, the cleaned molds are sent to the second stage with ten different processes: coagulant dipping, compounded latex dipping, latex film drying, pre-leaching, beading, vulcanizing, cooling, chlorinating, post-leaching and drying. The product is then fed to the packaging process.

**Fig. 4:** Glove dipping processes with online chlorination and with polymer coating.
3. Life cycle assessment (sustainability recycling)

Life cycle thinking is one of the most important ways to reduce emissions to the environment by reducing resource use and improving socio-economic performance over the life cycle (The UNEP Working Group for Cleaner Production in the Food Industry 2004). The life cycle perspective helps to ensure that activities are environmentally sustainable, have a competitive advantage with reduced costs, and help develop a better product. LCA is both a concept and a tool for environmental assessment, which determines the extent of exposure of the environment to human activities. The best approach to determine the potential environmental impacts is by using LCA, as referred to by the European Commission (EC), according to its design function which analyzes and evaluates the entire life cycles of products. For its function, the product cycle can be qualitatively and quantitatively analyzed (encompassing the raw materials, manufacturing process, products, and disposal) in terms of energy consumption and waste considerations. As an advantage, the principles of LCA can assist the decision makers to select a set of activities with minimal negative impact on the environment. In addition, LCA can support the eco-efficiency approach and provide a quantitative value of the impact. For ISO 14040, LCA is currently governed by the technical requirements that describe the principles and framework and guidelines. LCA is used as a tool to quantify the energy and materials consumed and the waste released into the environment (as shown in Fig. 5) (Dunuwila et al. 2018b).

Maulina et al. had enhanced eco-efficiency in crumb rubber processing in Indonesia through life cycle assessment (LCA) (Maulina, Sulaiman, and Mahmood 2015). Crumb rubber factories consume a large amount of energy and water to be more efficient, which leads to environmental problems. This study proposed to analyze the environmental impact and implement environmental improvements for crumb rubber processing through LCA. They have also suggested ways to remedy the effects of current crumb rubber processing practices through changes towards eco-efficiency.

According to the case study of a crepe rubber factory in Sri Lanka, they have three phases of learning. At the beginning, they qualify the raw material used in the factory, greenhouse gas emissions and economic losses by using MFA, MFCA and LCA. Then they develop the proposal to improve viable options. Finally, they validated the benefits of the proposed improvement options for safe implementation. Several studies have also used LCA approach to mitigate and quantify the environmental impacts (i.e., emissions) associated with the overall natural rubber production process. For example, Jawjit et al. conducted studies using concentrated latex (CL), block rubber, and ribbed smoked sheet (RSS) in Thailand to qualify greenhouse gas (GHG) emissions. This highlighted the energy and fertilizer use in the Thai agriculture industry as primary sources of GHG emissions (Jawjit et al. 2010). Efficiency improvements in fertilizer and energy were achieved by replacing the synthetic fertilizer with animal manure and applying renewable energy instead of fossil fuels (Jawjit et al. 2015). They proposed practically and technically feasible clean technology options to improve energy consumption (of fossil fuels and electricity), and reduce use of diammonium phosphate and ammonia. GHG emissions from crepe rubber processing were also assessed, emphasizing the importance of using renewable energy sources (Kumara et al. 2016).
Synthetic glove manufacturing will have negative impacts on the environment, including carbon footprint, water use footprint, global warming, acidification, eutrophication, photochemical ozone formation, and toxicity risks to humans. An ecological management tool is used to assess the environmental impacts, minimize energy consumption and greenhouse gas emissions by performing life cycle optimization and proposing five alternative process improvement scenarios. The many synthetic glove processes show that the electricity from biodiesel has the least impact on the environment among the practical alternatives (Dunuwila et al. 2018b).

4. Material flow analysis (MFA)

The visualization of overall material balance, inputs and outputs from a systematic assessment of material flows and inventories within the manufacturing system, is done in material flow analysis (MFA). The MFA calculations in the current study are performed by using the software STAN 2.5. MFA is a tool to assist in the improvement of eco-efficiency (environmental performance) and cost effectiveness by reducing material consumption (Christ and Burritt 2016). Referring to ISO 14051: 2011, four categories of cost information are considered by MFA as input data at each quantity center (QC): material cost, system cost, energy cost and disposal cost (Huang et al. 2019).

In addition, output costs associated with energy, material, and system costs are divided into positive and negative product costs by multiplying them by the percentage of raw material loss by weight at each QC. Notwithstanding the above, only waste management costs are charged. In addition to natural materials, MFCA includes two other materials: auxiliary and operating materials (Christine M. Jasch 2009). Auxiliary materials are the materials that are needed to produce the final product and are always included in the final product itself. At the same time, the materials that are needed to produce the final product but always end up as non-product outputs (NPOs), i.e. emissions and effluents, are operating materials.

5. Economic impact

The natural rubber (NR) production industry plays a crucial role in the economy of many developing countries, especially in Asia. Among the various NR types, crepe rubber occupies a significant position as it is used in the manufacture of pharmaceutical, surgical and food contact rubber articles. Currently, the production of crepe rubber is hampered by low productivity, increasing production costs, and environmental problems. Dunuwila et al. in their study investigated the feasibility of adopting sustainable manufacturing practices in crepe rubber production in Sri Lanka. They found per 1 metric ton of rubber input the underlying economic losses and GWP impacts in the current manufacturing process were identified as LKR 19,585 (USD 98.16) and 279.3 kg CO2e with the values of 7% and 13% for relative standard deviation, respectively; and ways to reduce water, chemical and electricity use were proposed as improvement options. It was found that by adopting these reduction options, 32,064 kg of water per metric ton of rubber input and 30.1 kWh per metric ton of rubber inputs of electricity could be reduced, resulting in a cost saving of 5.3% and a global warming
potential (GWP) reduction of 4.3%. Other impacts related to the improvement options and their limitations are also discussed in (Dunuwila, Rodrigo, and Goto 2018a).

Fig. 5: A flow chart outlining the procedures and tools used in the examination (Dunuwila et al. 2018b)
According to Amadeo (AMADEO 2020), financial capital is any economic resource of financing that forms the assets of a company. It also refers to the credibility of a company for its business investments. Typically, many industries usually use the financial capital to invest in their fixed assets such as buildings, materials, and equipment. They also create their profits through research and development projects (Sharafeddine 2016).

Based on the research of Wu et al., the Top Glove company mainly used biomass fuel, renewable energy, to run their boiler. However, this technology is high in investment cost and has only been adopted in six factories so far. Therefore, the Top Glove company needs to raise sufficient capital for all its factories to apply renewable energy in their production lines. A large capital investment would allow the Top Glove company to use heat exchangers, which are advanced technology. Heat consumption can be reduced by recovering the heat from hot air emissions and hot wastewater. In addition, Top Glove could purchase 5-star energy saving devices to replace all old refrigerators and air conditioners, in order to increase energy efficiency with the fiscal capital allocation. Simultaneously, using fewer air conditioners and refrigerators will reduce global warming impacts. The purpose of capital investments in Top Glove is to use green power and replace fossil fuels used in production, because Top Glove wants to reduce environmental problems from fossil fuel use, carbon dioxide (CO₂) emissions, and reduce climate change. If Top Glove wants to make this project a reality and use renewable energy in every factory, they will need significant financial capital. Green energy services from these studies show that green power can be more dependable than regular energy services. However, the occurrence of sizable outages is less probably with green energy systems. Except in the UK, South Australia, Texas, and California, where the outages have been caused by windfarms and solar farms replacing conventional electric power plants that were shut down. (Wu et al. 2020).

Emitted from combustion of fossil fuels, water and air pollution can cause serious health problems such as respiratory problems, cancer, heart attacks, and other diseases. Green energy sources to replace fossil fuels can help reduce harmful emissions and improve water and air quality. Green energy will eventually have a positive impact on improving public health and reduce overall health care costs. According to (Owusu and Asumadu-Sarkodie 2016), renewable energy sources will bring benefits to human health and well-being and reduce climate change, which will benefit the environment. By using green energy sources, Top Glove can release less or no harmful emissions.

However, non-renewable forms of energy release emissions associated with heat and the rise in average temperatures around the globe, leading to global warming. The continuously released emissions from non-renewable energy sources will lead to more harmful climate change impacting human health and the environment. One of the specific factors that Top Glove should emphasize is cost. The cost of current non-renewable energy resources is in a constant state of flux, causing uncertainty and confusion around the globe. Green energy, however, leads to more price stability.
The cost of maintaining and operating this source is consistent and often very low compared to fossil fuels (Ren, Zhao, and Shi 2016). Non-renewable energy sources can cause severe health problems as they further pollute the air, water, and soil. These pollutants can harm children. As a social and environmentally friendly company, Top Glove could use these green energy sources to avoid spewing out the current amounts of pollutants. In fact, several of them would not spew any pollutants at all. The better overall health among the citizens of the world can come from these improvements. In some places, people will take renewable energy sources more seriously due to them being vital. So, Top Glove understands the wide benefits that green energy sources have to propose for the environment in general and for the company in particular. After all, they only have one planet to reside on, and keeping that planet healthy is a compelling part of keeping us healthy as well. Green power is one of the various very useful ways to preserve and improve the environment. In conclusion, they need more financial capital to apply this green power as it will aid Top Glove to make profit in the long run as they know that the focus on green power that will bring benefits to their life. Therefore, it is worthwhile for Top Glove to invest in renewable energy in every subsidiary operation.

6. Environmental impact

In 2016, the production of gloves in the global market generated a retail revenue of $5 billion. With the compounding of annual growth rate (CAGR) of 8.6% this may reach nine billion dollars by 2024, based on glove manufacturing. Workers from various sectors, commodity, manufacturing, beverage, food, and others got the best hand protection from glove manufacturing, and this has led to a robust demand growth. Still, the many environmental problems impacted by glove manufacturing include GWP, carbon footprint (CF) (Birnbach et al. 2020), water footprint (WF), human toxicity (HTP), eutrophication (EP), photochemical ozone formation (POFP), and acidification (AP). Consequently, these environmental aspects need to be identified, evaluated, and interpreted to reduce harmful waste from raw materials, operating units, processes, and products. LCA is adopted to help producers evaluate ecological burdens and service sectors to remain competitive. Referring to ISO 14040, LCA is an environmental management tool (Thai Industrial Standard 2006). It provides an approach to environmental impact analysis based on a cradle-to-grave consideration of products or services from raw materials through production to final disposal, reuse or recycling in their life cycle (Poh, Chew, and Tan 2019).

The environmental impact of latex concentrate production is examined using gate-to-gate life cycle activities. Data collection begins with the receipt of cup lumps and skims latex as a by-product from production. The Eco-Indicator 99 method is used to calculate the environmental impact for this study. Fossil fuels are very prominent in the impact category and have the highest percentage, followed by inorganic substances in the air we breathe and climate change (Maulina et al. 2015).

In addition, there are studies on the environmental impacts of coal and biomass in China. A case study in Jiangsu, China. They have studied speciation profiles of anthropogenic non-methane volatile organic compounds (NMVOCs) and improvement of the provincial emission inventory. It was found that the emission factors for coal and biomass for heating and
industrial boilers were 0.18 and 1.10 g/kg, respectively. These studies found non-methane volatile organic compounds from open combustion of biomass, including alkanes, alkenes, alkynes, aromatics, and oxygen volatile organic compounds at 14.83, 17.24, 2.20, 10.98, 52.58, and 2.16 %w/w, respectively. (Zhao et al. 2017). Another study investigated the thermal effects and functional group differentiation of low-grade coal sourced from China. Concurrent thermal analysis included heat fluxes and thermal mass evaluation.

Table 4: Environmental characterization factors adopted from (Poh et al. 2019)

<table>
<thead>
<tr>
<th></th>
<th>GWP (g CO₂ eq.)</th>
<th>AP (g SO₂ eq.)</th>
<th>POFP (g C₂H₄ eq.)</th>
<th>EP (g NO₃⁻ eq.)</th>
<th>HTP (m³ air)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>2</td>
<td>0</td>
<td>0.03</td>
<td>0</td>
<td>830</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0</td>
<td>0.7</td>
<td>0.028</td>
<td>1.35</td>
<td>8600</td>
</tr>
<tr>
<td>PM10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6667</td>
</tr>
<tr>
<td>SO₂</td>
<td>0</td>
<td>1</td>
<td>0.048</td>
<td>0</td>
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<tr>
<td>VOC</td>
<td>3</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>2500</td>
</tr>
<tr>
<td>CO²</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5: The result of LCA inventory in glove manufacturing (Poh et al. 2019)

<table>
<thead>
<tr>
<th></th>
<th>Electric generation</th>
<th>Natural gas generation</th>
<th>Acid synthesis</th>
<th>Alkali synthesis</th>
<th>Coagulant synthesis</th>
<th>Synthetic rubber synthesis</th>
<th>Chlorine synthesis</th>
<th>Ceramic former</th>
<th>Cleaning process</th>
<th>In-process</th>
<th>Packaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0.04</td>
<td>3.68</td>
<td>0.48</td>
<td>0.38</td>
<td>0</td>
<td>0.19</td>
<td>0</td>
<td>0.06</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0.24</td>
<td>0.19</td>
<td>0</td>
<td>5.34</td>
<td>0</td>
<td>0.58</td>
<td>0.59</td>
<td>0.10</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PM10</td>
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<td>SO₂</td>
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<td>9.16</td>
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<td>VOC</td>
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<td>CO²</td>
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<td>0.03</td>
<td>3.84</td>
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<td>0.15</td>
<td>0.15</td>
<td>0.09</td>
<td>0</td>
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In this research, a range of water contents (moisture) was found where water impregnated coal (WIC) burned better than raw coal. The combustion of coal occurred in four stages; mass loss due to water evaporation, mass gain due to oxygen uptake, combustion, and burnout (Wang, Shi, and Guo 2017). The immersion in the water and the drying process has a great influence on the oxidation of low-temperature heat of low-rank coals and the initial exothermic temperature. The low-temperature heat oxidation characteristics of low-rank coals change when water-soaked coal has been dried in air to a certain water content range. The risk of ignition and combustion is increased compared to raw coal. There is a water content that is most prone to ignition. WIC is more combustible than raw coal because the primitive content
of reactive functional groups, aliphatic hydrocarbons and hydroxyl, is significantly increased after immersion in water. The reactive functional groups increase the reaction rates of the active groups during oxidation and accelerate the overall chain reaction when the char ignites spontaneously. This accelerates the low-temperature oxidation of coal (Zhong et al. 2019).

**Fig. 6:** Eco-Efficiency of crumb rubber processing based on Impact Categories (Maulina et al. 2015).

7. **Conclusion**

Rubber glove manufacturing is an essential component among the export products from Thailand. However, the manufacturing process of rubber gloves could be made more environmentally friendly. Life cycle assessment and material flow analysis have proven to be appropriate tools to achieve sustainable development. This article showed that the eco-efficiency of rubber glove products can be divided into ecological performance and economic performance. The ecological aspects of rubber glove production involve material, energy and water consumption, waste and wastewater production, and greenhouse gas emissions. The economic key aspects are the quantity of product and net sales. Therefore, eco-efficiency evaluation would help find more economical and effective ways to increase recyclability, improve production process, or reduce energy and material intensity. Moreover, this eco-efficiency indicator is used to evaluate the eco-efficiency performance of rubber glove products in Thailand, in the next step of our project.
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