Life Cycle Assessment of Material Recovery from Pyrolysis Process of End-of-Life Tires in Thailand

Tarinee Buadit, Cheerawit Rattanapan, Achara Ussawarujikulchai, Krisda Suchiva, Seksan Papong, and Hwong-Wen Ma

***Abstract*—It is estimated that around 600,000 tons of end-of-life tires are generated annually in Thailand. These waste tires will cause danger to the environment and human health if handled improperly. On the other hand, if managed with the proper technology, it will be transformed into valuable products. This research aims to evaluate the potential environmental impacts of a waste tire pyrolysis plant in Thailand by using the Life Cycle Assessment (LCA) method. The functional unit is defined as 1 ton of products from the pyrolysis process of waste tires. The system boundary consists of a pre-treatment and pyrolysis process (gate-to-gate). The LCA calculations were carried out using licensed SimaPro 9.0 software. At the impact assessment step, the ReCiPe2016 method both Midpoint (problem-oriented) and Endpoint (damage-oriented) were applied, and 7 impact categories were selected (global warming, fine particulate matter formation, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, and fossil resource scarcity). If the avoided products from the pyrolysis process, including pyrolysis oil, steel wire, and carbon black were taken into account, the characterization results show that 3 impacts: global warming, terrestrial ecotoxicity, and fossil resource scarcity have a negative value. While the other impacts still have a positive value resulted mainly from electricity consumption. When considering weighting end-point results, it found that human health impact was a major contribution with a totally negative value of -0.947 Pt. As a summary, the outcomes confirm that the utilization of pyrolysis avoided products and the optimization of electricity consumption in the process has the potential to drives pyrolysis to become an environmentally effective technology for end-of-tires management.**

***Index Terms*—Life cycle assessment, material recovery, pyrolysis, end-of-life tires.**

I. INTRODUCTION

Asia is an important source of natural rubber production, which estimated at 90 % of the world. Thailand is the world's number one of rubber production, with an approximate value of 4.56 million tons or 35.9% of the world output in 2017 [1]. In 2018, Thailand is the No.1 exporter of natural rubber with an export volume of 4.15 million tons, followed by Indonesia, Vietnam, and Malaysia [2], representing value of exports equal to 221,412 million baht [3]. In addition, the amount of rubber used in the country tends to increase slightly as well. The domestic rubber consumption was 0.61 0.65 and 0.80 million tons in 2016-2018, respectively [4]. The automobile tire industry has the highest demand for natural rubber, within the year 2018, tire factories used 484,256 tons from 800,000 tons of the total rubber [2]. An investigation of passenger car tire manufacturers in the country found that there was a total of 56 million productions of tires in 2018 [5].

After use until the end of life, these tires will become enormous amounts of waste tires. Quantity of end-of-life tires in Thailand are more than 18 million pieces or around 600,000 tonnes per year, but only 5-6 million pieces were introduced into the treatment process that reuse and recovery material or energy, while the remaining were treated by the useless practice or open burned that lead to environmental problems consequently [6]. There are many problems correlated with waste tires such as open-air fires that can threaten the environment from release pollutants into the atmosphere and tire piles can form an ideal breeding ground for rodents and mosquitoes, the vectors of encephalitis and dengue fever, particularly in tropical climates like Thailand [7].

The proportion of recycling of used tires in Thailand is less than 29%, while in the successful waste tire management countries are more than 50% [6]. A former study stated that several viable waste tire management technologies could be used at higher rates in Thailand. And pyrolysis can also be highly effective approaches for employing waste tires as a valuable resource [7]. The existing production capacity of pyrolysis plants in Thailand can remove 44,497 tons of end-of-life passenger car tires, accounting for 58% by material recovery [8]. Although pyrolysis creates useful products, in that process uses intensive energy and also releases pollutants as well. Hence, there is a need to examine the potential environmental impact and the compensatory effect from the pyrolysis process of waste tires. Currently, only one study in Thailand evaluates the mid-point environmental impacts of pyrolysis but does not consider the benefits of the product obtained [6].

Therefore, this study aims to determine the environmental impact of end-of-life tire pyrolysis with real plant data in Thailand using the life cycle assessment (LCA) method both

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problem-oriented and damage-oriented impacts, as well as analysis of their benefits from material recovery. The outcome will help decision-makers and promote the environmentally waste tire management program in Thailand.

II. MATERIALS AND METHODS

A. Goal and Scope Definition

The objective of this study was to evaluate the potential environmental impacts, identify major environmental effects and key contributory elements of worn-out tires pyrolysis in Thailand using actual plant data, as well as analyze their benefits from material recovery of avoided products and explore development opportunities to improve pyrolysis to be a suitable technology for waste tire management. The functional unit is defined as 1 ton of total products from the pyrolysis process.

B. System Description

A gate-to-gate LCA was performed for the pyrolysis process of end-of-life tires. The system is based on a representative of the waste tires pyrolysis plant in Samut Prakan province, Thailand. The process includes pre-treatment (dust removal and shredding) and pyrolysis processes. In the pre-treatment process, the contaminants attached to the tires are eliminated by blowing air, and then the whole tires are fed into the shredder for cut into large pieces approximately 5-15 cm. Next, the tire chips enter a grinder to obtain rubber granules of a proper size for pyrolysis and dumped to a silo for storage. In the pyrolysis process, rubber granulates are fed to a pyrolysis reactor by a conveyer belt. Pyrolysis is achieved by a horizontal batch reactor at the temperature of 400 °C around 11 h per one batch. The output consists of 3 fractions: gaseous fraction (pyrolysis gas), a liquid fraction (water and fuel oils), and a solid phase (carbon black and scrap wire). The average yield (weight %) of products as measured in the plant was as follows: pyrolysis oil = 42%, carbon black = 36%, steel = 11%, and pyrolysis gas = 11%. The pyrolytic gas produced is compressed and stored. Then fed back into the pyrolysis process for heating purposes. At the startup, diesel oil is used for heating, but after the process starts the pyrolytic gas can provide enough energy needed. However, the pyrolysis oil cannot be directly used as diesel and need more purification steps, but it can use as a fuel oil for another purpose. For the solid residue, steel wire and carbon black are separated by using a magnetic separator, then packed for distribution.

C. Systems Boundaries

The system boundaries that were considered in this LCA analysis are presented in Fig. 1. Based on the system description and the assumptions as follows:

- Production and use phase of tires and collection of end-of-life tire were not considered in this study, since the purpose was to assess only the pyrolysis process.
- It is out of the scope to consider the transportation of materials to the pyrolysis facility due to its difficulty to calculate the distribution of materials from multiple sites and it is also the responsibility of the suppliers.
- In the pyrolysis process, the impacts from resources and fuels required during the processes such as water, electricity heating oil consumption were considered.
- Negative environmental effects were considered for the recycled materials from valuable products.
- Impacts from utilization of valuable products will not be taken into this consideration for avoiding complexity and confusion.
- The manufacturing impacts of plant machinery, supplemental equipment, and infrastructure were not considered.

In summary, the total environmental impacts associated with the pyrolysis of waste tires in this study consist of 3 categories: indirect impacts caused by material and energy used, direct impacts caused by pyrolysis process (air emission), and avoided impacts caused by valuable products (material recovery).

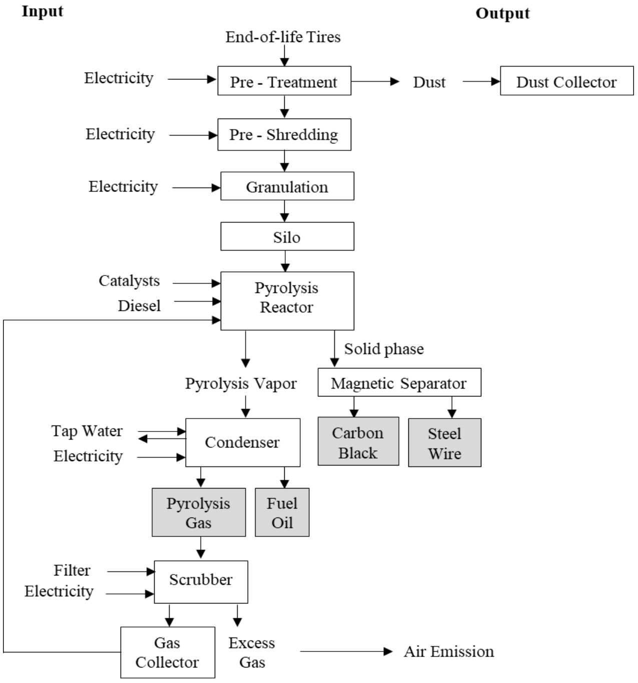

Fig. 1. System boundaries.

D. Life Cycle Inventory

Primary data on the inputs and outputs were obtained from actual production process of the Thailand representative pyrolysis plant in the form of the 3 years average values (2015-2017) as summarized in Table I, expressed per functional unit of 1 kg of total products from pyrolysis of end-of-life tires. The inventory is divided into six categories: raw materials, energy, resources, emission to air, final waste, and avoided products. Air emission data (CO_2, NO_x, SO_2 and dust) from used pyrolysis gas as a fuel to feed back into the pyrolysis process were obtained from literature reviews, the total CO_2 emission was 68.06 (kg/ton waste tire pyrolysis) reported by Banar M. (2015) [9]. While SO_2, NO_x and dust emission data (3.55 kg SO_2, 1.40 kg NO_x and 0.58 kg dust per 1 ton of waste tire pyrolysis) were obtained from Li *et al.* (2010) [10]. These data inventory has been recalculated concerning the functional unit considered for this study. Due to avoided products cannot be accepted as a full substitution of the same volume of original materials because of the decline in its properties and market rate, the substitution factor should be assumed. Substitution factors for carbon black and pyrolysis oil in this study were both quantified as 1:0.5, while the factor for steel wire was quantified as 1:1 [9].

TABLE I: INPUTS AND OUTPUTS OF PYROLYSIS ACCORDING TO THE FUNCTIONAL UNIT (1 KG OF TOTAL PRODUCT)

Category	**Sub-Category**	**Value**	**Unit**	**Data Sources**
Raw material	End-of-life tire	1.0526	Kg	Primary data
Energy	Electricity	0.8576	Kwh	Primary data
	Diesel (Start-up)	0.0017	L	Primary data
Resource	Tap water	0.0025	m^3	Primary data
	Rain water	0.00003	m^3	Primary data
Emission to air	Carbon dioxide	0.06806	Kg	Banar M. (2015)
	Sulphur dioxide	0.00355	Kg	Li et al. (2010)
	Nitrogen oxides	0.0014	Kg	Li et al. (2010)
	Particulates	0.00058	Kg	Li et al. (2010)
Final waste flow	Plastic waste	0.0008	Kg	Primary data
Avoided products	Pyrolysis oil	0.21	Kg	Primary data
	Carbon black	0.185	Kg	Primary data
	Steel wire	0.105	Kg	Primary data

E. Life Cycle Impact Assessment

The LCA calculations were carried out using licensed SimaPro (Faculty version 9.0.0.35) software with the Ecoinvent 3.2 database. In the impact assessment step, the ReCiPe2016 (V1.03) both problem-oriented (midpoint) and damage-oriented (endpoint) impact categories was applied. The ReCiPe2016 method is an update of the ReCiPe2008, the characterization factors are representative for the global scale, instead of the European scale as it was done in previous version [11]. Normalization results were calculated using the World (2010) H calculation. The ReCiPe2016 available for three different perspectives (individualist (I), hierarchist (H), and egalitarian (E)). It based on a different assumption regarding the cultural perspectives and impact timeframe, hierarchist valuation approach was selected for the reason of holding a balance between short- and long-term effects of emissions. At the midpoint level, 18 impact categories are taken into account. This study selected 7 impact categories from this approach that are easy to communicate, worldwide interest, and related to the pyrolysis process. These impact categories are the global warming potential, fine particulate matter formation, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, and fossil resource scarcity. For the endpoint, 18 midpoint environmental impact categories are then classified into three damage categories: 1) human health, 2) ecosystem quality, and 3) resources. Results of the ReCiPe endpoint were expressed in ecopoints (Pt), one aggregated environmental indicator.

III. RESULTS AND DISCUSSION

A. Problem-Oriented (Midpoint) Impacts

The results of the characterization and normalization of all impact categories are presented in Table II. It can be seen that 3 impacts including global warming, terrestrial ecotoxicity, and fossil resource scarcity have negative values as a result of avoided production from valuable products. Beneficial products obtained from pyrolysis of waste tires, including pyrolysis gas, fuel oil, carbon black, and steel wire. The gas produced most often used as fuel in the pyrolysis process. For oil obtained, it can be used directly as fuel oil and as a raw material in petrochemical processes. The low-grade carbon black derived can be further treated to obtain high-grade carbon black, activated carbon, or other valuable chemicals. Normalization values represent the real or potential magnitude of impact categories that solves the discrepancy of units. It is useful to compare the impact of the different categories. According to the normalization results, it can be concluded that the most significant impact on environmental contribution to freshwater ecotoxicity which is equal to 4.5943, while all of the other impacts are less than 1.

TABLE II: CHARACTERIZATION AND NORMALIZATION RESULTS OF MIDPOINT IMPACTS

Impact category	**Characterization**		**Normalization**
	Unit	**Value**	
Global warming	kg CO_2 eq	-37.6659	-0.0047
Fine particulate matter formation	kg PM2.5 eq	0.0848	0.0033
Terrestrial acidification	kg SO_2 eq	2.1235	0.0518
Freshwater eutrophication	kg P eq	0.2373	0.3654
Terrestrial ecotoxicity	kg 1,4-DCB	-134.0857	-0.1293
Freshwater ecotoxicity	kg 1,4-DCB	5.6372	4.5943
Fossil resource scarcity	kg oil eq	-457.8500	-0.4670

Freshwater ecotoxicity refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to water. Ecotoxicity impact is related to heavy metals and aromatic hydrocarbons such as benzene, toluene and styrene emission [10]. From Fig. 2, power consumption attributed predominantly to freshwater ecotoxicity, estimating for 97.2%. Because the pyrolysis process uses intensive energy and in the electricity generation process, there may be heavy metal and other pollutants contamination into the water source. Comparison with the previous study, the results of this study are consistent with Raja [12] which compared LCA between the traditional pyrolysis process and CFC (newly developed process) in Sweden. They stated that ecotoxicity effects mainly caused by power generation. The second environmental impact contributor is freshwater eutrophication. The largest share is from electricity applied similar to freshwater ecotoxicity. Müfide Banar [9] using LCA to evaluate the potential environmental impact of waste tire pyrolysis in Turkey. On the contrary, their result shows that eutrophication impact is mainly due to NO_x emissions in the combustion flue gases. Besides, the impact is a noticeable negative impact of avoided steel wire production sustained by the avoided NO_x and phosphate emissions, the dominant contributing pollutants of the eutrophication effect. Avoided diesel and carbon black production also results in negative eutrophication values because of the avoided pollutants which cause a COD. Although the fuel oil obtained from the pyrolysis process in this study can compensate for the impact of diesel substitution 37.1 % (Fig. 2), but not sufficient to create negative values. When considering negative values in 3 impact categories, fossil resource scarcity contributes the most, followed by terrestrial ecotoxicity and global warming. Avoided carbon black presented the highest value of savings in fossil resources. Also, in the former study [9] and [10], non-renewable energy resources like crude oil, natural gas and coal are saved from avoided diesel, carbon black, and steel wire production which has been substituted from valuable products from the pyrolysis process. In Thailand, only one research was conducted LCA of pyrolysis of end-of-life tires. Prasert Pavasant *el al.* [6] studies the comparative LCA of 4 waste tire management technology, including reclaimed rubber, crumb rubber production, pyrolysis and replacing fuels in the cement kiln. But their evaluation does not state the method or program used, they define only impact categories, life cycle inventory, and functional unit. There are 9 midpoint impact categories included such as acidification, eutrophication, global warming, ozone layer depletion, and human toxicity. The results indicate that the use of the waste tire as a substitute fuel in cement kilns most reduces the environmental impact in 7 impact groups, followed by reclaimed rubber. While the pyrolysis process has the most positive environmental effects. Their results were in contrast to this study because of the avoided products were not included.

B. Identification of Key Contributory Elements

As seen in Fig. 2, it is evident that the key contributory element of environmental impact is electricity consumption (yellow color block), followed by the pyrolysis manufacturing process (green block). The use of electricity in the pyrolysis of waste tires is the primary contributor to fossil resource scarcity, terrestrial ecotoxicity, global warming, freshwater ecotoxicity, and freshwater eutrophication. It accounts for 27.3–97.4 % of the total to each impact category, respectively. The analysis results show the need for a sustainable green energy source to eliminate the environmental impacts from using the intensive electricity and also need for improvement in the pyrolysis process to reduce pollutant emission to the atmosphere.

Regarding the negative values, fuel oils as a substitution for diesel can avoid environmental impacts in all categories as seen in the dark blue block. It can reduce the terrestrial ecotoxic impact most of 56.3%.

Apart from diesel, carbon black and steel wire also substitute the virgin material to lessen environmental impact in several categories. Around 49 % of fossil resource scarcity can decrease by carbon black replacement, followed by 46 % the global warming, and 34% of fine particulate matter formation. As steel wire, a large proportion of impact mitigation is from terrestrial ecotoxic and global warming.

C. Damage-Oriented (Endpoint) Impacts

At the endpoint level, all of the midpoint impact categories are multiplied by damage factors and aggregated into three endpoint categories: human health, ecosystems, and resource scarcity [11]. The damage pathway of 18 midpoint impacts to 3 endpoint categories as depicted in Fig. 3. This study chose only 7 midpoint impacts that most related to the pyrolysis process. For example, fine particulate matter formation increasing in respiratory disease and climate change (or global warming) increasing in malnutrition. Both of them can damage human health. From the database manual of Sima Pro software [11], human health expressed as the number of years life lost and the number of years lived disabled. These are combined as Disability Adjusted Life Years (DALYs), an index that is also used by the World Bank and WHO. Ecosystems meant as the loss of species over a certain area during a certain time.

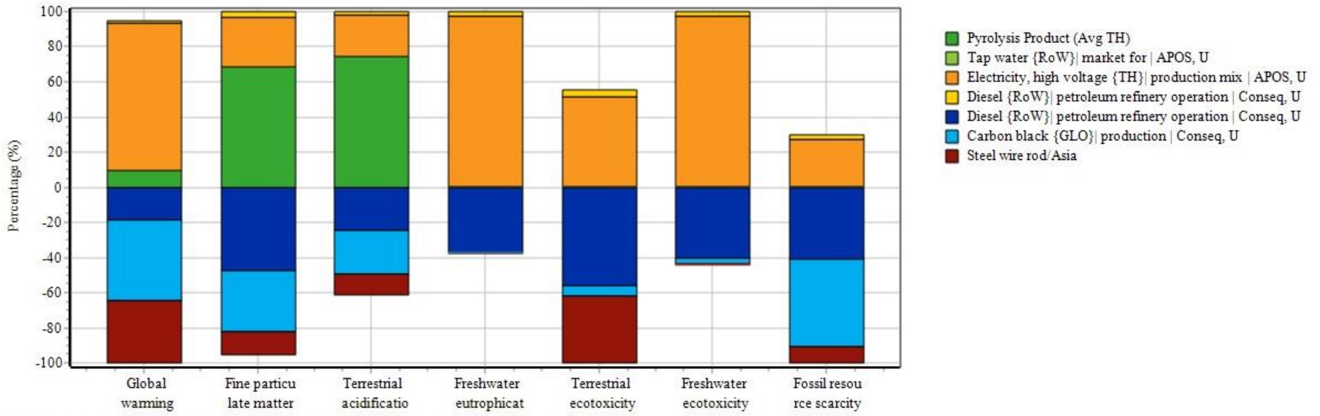

Fig. 2. Characterization results of 8 midpoint impact categories from pyrolysis process.

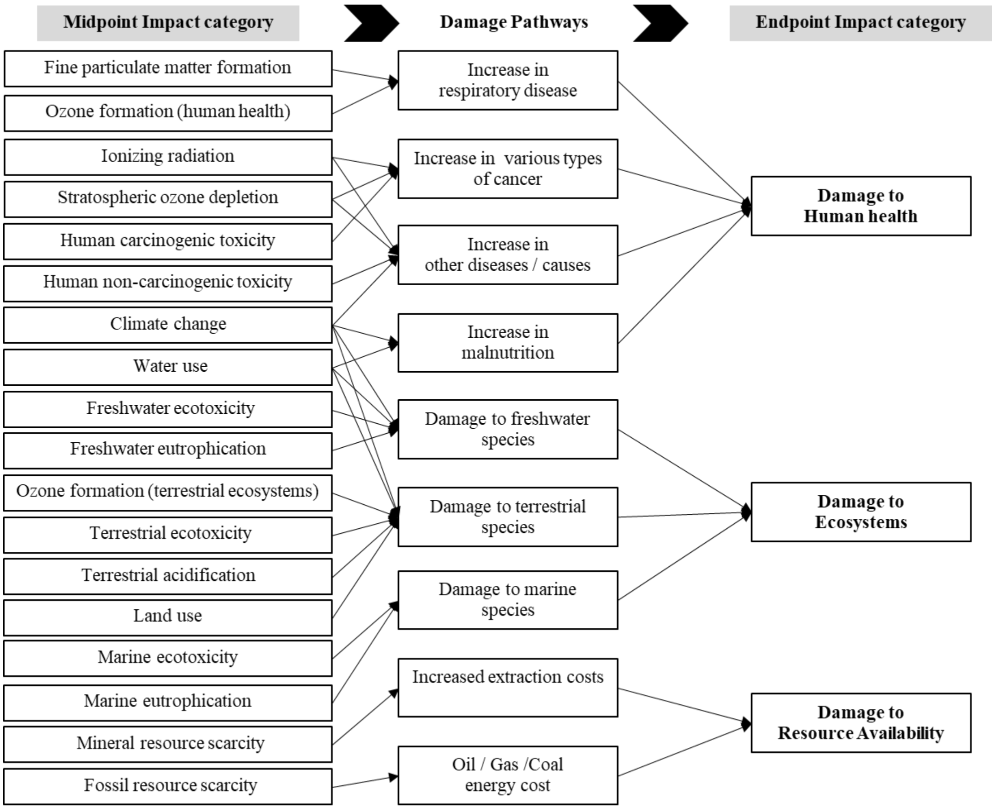

Fig. 3. Relation between the impact categories midpoint and endpoint (modified from SimaPro Database Manual, 2019) [11].

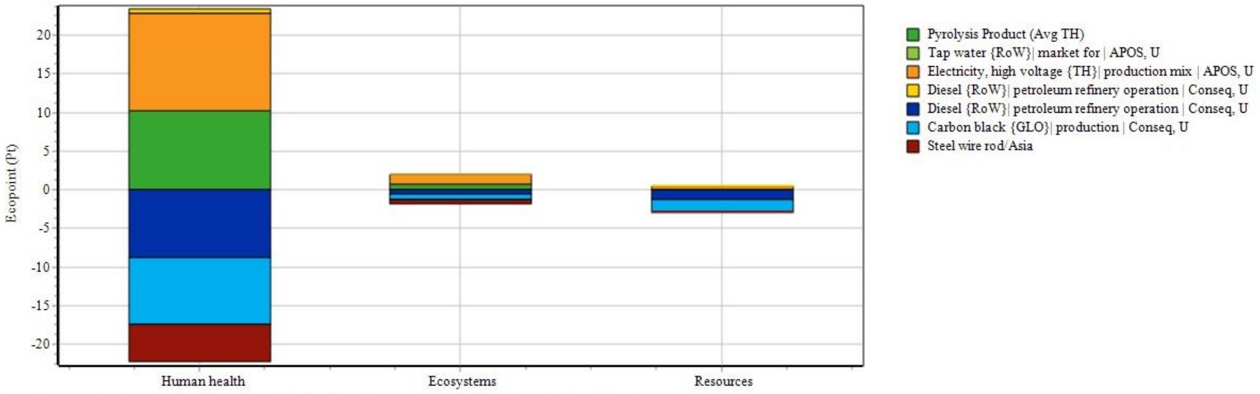

Fig. 4. Weighting results of 3 endpoint impact categories from pyrolysis process.

And the last, resource scarcity, represented as the surplus costs of future resource production over an infinitive timeframe (assuming constant annual production), considering a 3% discount rate. The results of the characterization and normalization of all impact categories are displayed in Table III. According to the normalization results, the largest damage burden is human health impact with the value 0.0038, meanwhile, the resource scarcity contributes the least with negative value -0.0077.

TABLE III: ENDPOINT RESULTS

Impact category	Damage assessment		Normalization
	Unit	Value	
Human health	DALY	0.000092479	0.0038
Ecosystems	species.yr	0.000000357	0.0004
Resources	USD2013	-216.2195764	-0.0077

Weighting endpoint results were expressed in eco points (Pt), one aggregated environmental indicator. Pyrolysis of waste tires in Thailand generated a negative value which equals -0.948. As shown in Fig. 4, the primary contributor to human health also from the usage of electricity 12.6 Pt, followed by the air emission from process 10.2 Pt. Concerning the negative values, the contribution from the avoided impact of diesel and carbon black are similar.

IV. CONCLUSION

Economic growth motivated the number of vehicles use domestically in Thailand, resulting in a dramatic increase in end-of-life tire creation. Approximately 600,000 tonnes of these waste tires are produced annually. If improperly disposed of, it has the potential to harm local environments and negatively affect human health. This study not only evaluates the potential environmental impacts of a waste tire pyrolysis plant in Thailand by using the Life Cycle Assessment (LCA) method but also estimates material recovery from avoided products produced. At the problem-oriented level, 3 impacts: global warming, terrestrial ecotoxicity, and fossil resource scarcity have negative values as a result of avoided products from pyrolysis of the waste tires, including pyrolysis gas, fuel oil, carbon black, and steel wire. The other 4 categories still have an impact on the environment. At damage level, human health is the dominant category from fine particulate matter formation global warming impact. The major contributors to most impacts are the electricity used and air emission during the process, so energy optimization is necessary to be done together with the utilization of gas treatment systems to enhance power consumption efficiency and diminish the environmental impacts. Further investigations should be implementing a comparative LCA of existing waste tire management to find the best suitable technology for dealing with waste tire problems more environmentally practice.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Tarinee Buadit analyzed the data and wrote the manuscript; Cheerawit Rattanapan reviewed the overview of the paper and provided suggestions; Krisda Suchiva facilitated factory data collection and suggested on tire supply chain; Achara Ussawarujikulchai guided about the environmental impact; Seksan Papong and Hwong-wen Ma advised on life cycle assessment and Sima Pro program; all authors had approved the final version.

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