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Life cycle assessment and circularity of polyethylene terephthalate bottles via closed and open loop recycling

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A R T I C L E I N F O

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A B S T R A C T

Polyethylene terephthalate (PET) recycling is considered as one of the key approaches to achieving the circular economy (CE) of plastic waste. Bottle-to-Bottle and Bottle-to-Fiber recycling were assessed using Life Cycle Assessment (LCA) and Material Circularity Indicator (MCI). Three allocation methods (i.e., substitution, recycled content, and economic allocation) were used to deal with the recycling system. Producing bottle-grade PET resin and polyester fiber from PET bottle waste can reduce environmental impacts for most midpoint impact categories (e.g., 60% greenhouse gas emissions reduction and 85% fossil resource scarcity reduction). At the endpoint level, the damages to resources, ecosystem quality, and human health of the recycled PET bottles derived from Bottle-to-Bottle recycling were less than virgin PET bottles when using the substitution and recycled content methods. When using the economic allocation method, the final LCA findings highly depended on the recycled content used to produce the PET bottles. On the other hand, regardless of the allocation method used, recycled polyester fiber derived from Bottle-to-Fiber recycling caused less environmental damages than virgin polyester fiber. The MCI scores of Bottle-to-Bottle recycling in the baseline scenarios range between 0.20 and 0.31, whereas the MCI scores of the expected scenario in the future show a higher level of material circularity (0.55–0.60) as a result of 100% collection rate for recycling of PET bottles and the use of recycled PET as a feedstock. Therefore, higher collection rates and recycled content support Bottle-to-Bottle recycling. On the other hand, the MCI score of Bottle-to-Fiber recycling in the baseline scenario is 0.52. This high score resulted from the use of 100% recycled PET as a feedstock of polyester fiber. Recycling polyester fiber at the end-of-life could further increase the MCI to almost 0.7. However, to keep the materials at their highest quality and value, Bottle-to-Bottle recycling should be the preferred option.

1. Introduction

As the economy grows, we need more raw materials for the production of goods while resources like fossil fuels, food, and water are increasingly hard to get. The conventional economy of "take-make-use-dispose", called the linear economy which, is not sustainable for production and consumption. This linear system uses the resources intensively and waste is not circulated or reused at the end-of-life. As a result, the circular economy (CE) model is now gaining attention as a potential solution to deal with unsustainable production and consumption issues (Kristensen and Mosgaard, 2020). The CE is an economic model, also referring to business and industrial models, which aims to limit the extraction of raw materials and stop the generation of waste. To move away from "take-make-use-dispose", materials, products, and services need to be redesigned to consume less resources, and waste needs to be circulated and used as a raw material to create new products (EPA, 2022). The CE normally consists of three main principles, namely (1) designs out of waste and pollution, (2) keeps products and materials at the highest quality, and (3) regenerates natural systems (Ellen MacArthur Foundation and Granta Design, 2015). In addition, this circular system can be achieved by the 9 R framework; Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover (Okorie et al., 2018; Hirsch and Schempp, 2020). In the CE context, Material Circularity Indicator (MCI) is one of the assessment tools that can quantify the degree of material circularity; measuring how well the product's materials circulate in the economy. It is one of the few

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indicators that considers the lifetime or intensity of use of the products. The comprehensive approach of MCI can be used to identify opportunities for further improvement (e.g., increasing recycled content and extending the product's lifetime). In addition, MCI can be used to compare the circularity of various products (Ellen MacArthur Foundation and Granta Design, 2015; Rocchi et al., 2021).

Nowadays, plastics play an important role in human daily life and we can see plastic in the form of many different products (e.g., packaging, textiles, building and construction). The majority of plastic (>99%) which is often called virgin plastic is made from fossil fuels (e.g., crude oil, natural gas) (Tamoor et al., 2022). Packaging is the largest end-use industry worldwide for plastic usage; in addition, almost half of the plastic waste is generated by packaging (47%) (World Bank Group, 2021). Therefore, plastic packaging needs to be focused on, especially polyethylene terephthalate (PET) which is one of the most used plastic packaging materials in the world; it is mostly used in food and beverage packaging (e.g., PET bottles). Being durable, low cost, and lightweight makes PET advantageous when compared to other packaging materials such as glass bottles and aluminum cans. Moreover, this type of plastic is 100% recyclable and can be recycled many times (World Bank Group, 2021). Therefore, the usage of PET plastic should be optimized by recycling rather than ending up in a landfill or the environment. Moreover, recycling processes are considered as the most effective way to economically reduce PET waste (Sarioğlu and Kaynak, 2017).

Currently, there are two main technologies for PET recycling, namely, (1) mechanical recycling and (2) chemical recycling. Mechanical recycling is the most widely used for recycling PET. It is conducted by cleaning the PET bottles before grinding them into flakes. However, this washing process only effectively removes impurities from the PET's surface; it is unable to get rid of organic compounds that the polymer has absorbed. PET flakes that have been washed are insufficiently pure to be used for food packaging (e.g., PET bottles), hence it is primarily used for non-food applications, mostly as fibers and sheets (Shen et al., 2010; Valentino, 2017). In the PET industries, intrinsic viscosity (IV) is used to control the quality of PET. This indicator is related to molecular weight and reflects the material melting point, crystallinity, and tensile strength of PET. Each use of PET has a certain IV value that must be met; for instance, the IV value of bottle grade ranges between 0.70 and 0.78 dL/g, and the IV value of fiber grade ranges between 0.40 and 0.70 dL/g. Thus, to produce recycled bottle-grade PET, solid-state polycondensation (SSP) is the main process used to decontaminate and increase the IV of recycled PET (Valentino, 2017; Elamri et al., 2017).

Recycled PET (rPET), which is derived from the recycling process, can be used to produce many different types of new products. In 2020, the application of rPET was dominated by fibers which accounted for 44%, followed by food and beverage containers and bottles, sheet and film, non-food containers and bottles, strapping, and other, respectively (Grand View Research, 2021). In addition, most recycled PET flakes are globally used in the textile sector for staple fiber applications (Sarioğlu and Kaynak, 2017). However, nowadays, the use of rPET in PET bottles has been growing. Especially, in European countries, the laws and policies governing PET circularity and recycled content in beverage bottles have been established. The Single-Use Plastics (SUP) Directive of the EU, for instance, sets goals for recycled content in PET beverage bottles of 25% by 2025 and 30% by 2030 (Directive, 2019/904; Lonca et al., 2020).

The previous life cycle assessment (LCA) studies related to the PET recycling revealed that using recycled PET has environmental benefits over using virgin PET and for every kilogram of recycled PET flake used, greenhouse gas emissions and energy consumption can be reduced by 71% and 84%, respectively (Bataineh, 2020; Zhang and Wen, 2014). Furthermore, the environmental impacts of recycled PET are lower than fossil-based and bio-based PET for all impact categories (Rybaczewska-Błażejowska and Mena-Nieto, 2020). Additionally, as compared to thermal recovery (e.g., burning plastic with power recovery), recycling PET is the more environmentally friendly option (Chilton et al., 2010).

LCA studies of Bottle-to-Bottle and Bottle-to-Fiber recycling showed that recycling has a better environmental performance than virgin PET products (Shen et al., 2010; Gileno and Turci, 2021). Although the LCA studies on Bottle-to-Bottle and Bottle-to-Fiber recycling have been previously investigated, there are some limitations of the studies; for example, lack of consideration of air emissions (from the recycling process), chemical use (in the recycling process), and the system boundary of Bottle-to-Bottle being limited to the recycled bottle-grade PET resin not including PET bottle manufacture.

In Thailand, PET bottle was the most recycled plastic with a collection rate for recycling (CRR) of 31–62%. PET bottles were mostly recycled as nonfood-grade recycled PET (rPET), especially for fiber production. On the other hand, only 3% of PET bottles were recycled as food-grade rPET, all of which were exported (Appendix A Fig. A1) (World Bank Group, 2021). This is because, in the past, Thailand prohibited the use of recycled plastic (e.g., rPET) in food and beverage packaging (e.g., PET beverage bottles). Hence, PET bottles in Thailand were made from 100% virgin PET, leading to fossil fuel scarcity and

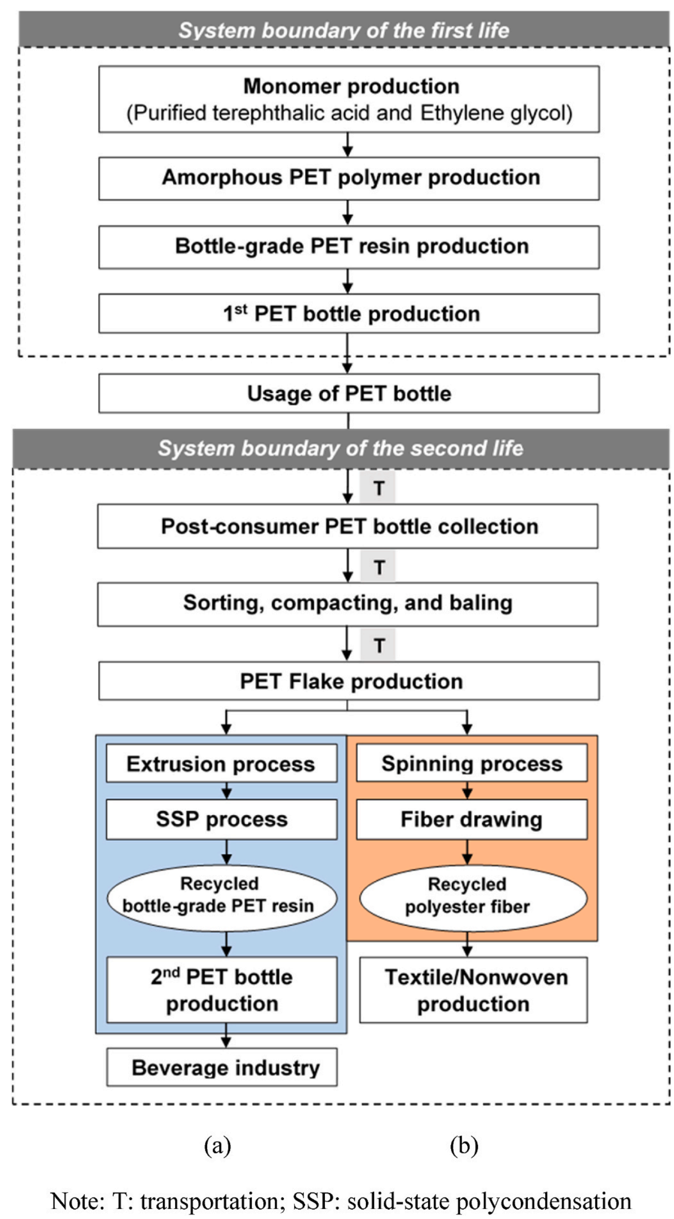


Fig. 1. System boundary of (a) Bottle-to-Bottle and (b) Bottle-to-Fiber recycling Note: T: transportation; SSP: solid-state polycondensation.

plastic waste problems. Fortunately, to drive the CE of plastic, rPET is now allowed to be used in food and beverage packaging in Thailand, but only after it has been tested for safety and shown that contaminants have been reduced or eliminated. (Ministry of Public Health, 2005; Ministry of Public Health, 2022).

Even though most PET bottles are currently recycled into polyester fiber, however, the use of rPET in beverage bottles has been increasing extensively. Therefore, the study aims to (i) assess the environmental impacts of two different recycling pathways: (1) Bottle-to-Bottle (closed-loop recycling) and (2) Bottle-to-Fiber (open-loop recycling) and (ii) assess the degree of material circularity of two different recycling pathways. Furthermore, the products produced from rPET (i.e., recycled PET bottle and polyester fiber) need to be evaluated vis-à-vis their environmental performance as compared to those produced from virgin PET. The results of the study can be used for strategic planning and provide information to support the implementation of a circular economy policy on PET bottle waste, for example, Thailand's Roadmap on Plastic Waste Management 2018–2030. To better understand the environmental performance and material circularity of these two recycling pathways, Life Cycle Assessment (LCA) and Material Circularity Indicator (MCI) have been used as the evaluation tools.

2. Methodology

To understand the environmental performance of Bottle-to-Bottle and Bottle-to-Fiber recycling pathways, life cycle assessment (LCA) was used. The study follows the principles and framework of ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) which are the standards for conducting the life cycle assessment. Furthermore, the Material Circularity Indicator (MCI) was used in this study to show how well a product's material (i.e., PET) circulates in the economy for each recycling pathway.

2.1. *Life cycle assessment (LCA)*

2.1.1. *Goal and scope definition*

The purpose of the study is to assess the environmental impacts of polyethylene terephthalate (PET) bottle recycling via two different recycling pathways, namely, (1) Bottle-to-Bottle (closed-loop recycling) and (2) Bottle-to-Fiber (open-loop recycling), compared to the virgin products. The results can be used for strategic planning and provide information to support the implementation of a circular economy policy on PET bottle waste. The results could not be used for chemical recycling of PET since only mechanical recycling has been considered in this study. The government and other stakeholders such as the recycling business can use these study results for their decision-making and process development. The results are valid for approximately 10 years within which it is anticipated that the recycling technologies and electricity grid mix, etc. would not change substantially.

The recycling process serves two functions, namely, waste management and secondary material production. Since the study focuses on end-of-life management of used PET bottle, therefore, the functional unit (FU) is 1 tonne of sorted PET bottle waste recycling. The sorted PET bottle waste refers to the PET bottles after being sorted and baled at the material recovery facility (MRF). The system boundary of this study is divided into two phases; the first life and the second life. The first life starts from resource extraction to virgin PET bottle production. The second life, on the other hand, starts from PET bottle waste collection to secondary PET bottle production for closed-loop recycling (Fig. 1 (a)) and secondary polyester staple fiber production for open-loop recycling (Fig. 1 (b)). The reference products in this study were (1) 0.5 L, 14.8 g (body, cap, and label) (1 unit) of PET beverage bottle and (2) polyester staple fiber. Related transportation services between the life cycle stages were also taken into account. Substitution, recycled content, and economic allocation methods were used to deal with the recycling systems. Thailand's data and database were used as a case study. The assumptions are provided in section 2.1.2.4.

In addition, the results of the study could be influenced by the source of electricity use, recycling efficiency, quality of inventory data, and so on. Therefore, the sensitivity and uncertainty analysis were conducted to show the variation and robustness of the results (section 3.2 and section 3.3).

2.1.2. *Data collection and inventory analysis*

The data specific to Thailand such as electricity, natural gas, diesel, LPG, and road transportation were from the Thai National LCI Database (MTEC, 2014). Background data on chemicals production, production of PET resin, etc. were sourced from ecoinvent version 3 (Wernet et al., 2016). Bottle-to-Bottle and Bottle-to-Fiber recycling inventory data were from Gileno and Turci (2021). PET bottle production data were from Calrecycle (2011). Furthermore, the study also validated the inventory data with some industrial experts in Thailand to ensure that the data used were reasonably aligned with real practice. Since the study is related to both the first life and second life of PET bottles, the data requirement is quite substantial. The sources of data used in this study are shown in Appendix B Table B1.

This study focused on two different recycling pathways (i.e., Bottle-to-Bottle and Bottle-to-Fiber) in which non-renewable energy use and production efficiency could affect the final results. Therefore, the

Table 1
Assumptions of the study.

Issue	Assumption
Chemical use in recycling process (washing line)	Assumption based on Franklin Associates, A Division of Eastern Research Group (ERG) (2018); • 8.1 kg NaOH per tonne PET bottle • 2.6 kg defoamer per tonne PET bottle • 2.3 kg washing agent per tonne PET bottle Note: considered only the three chemicals that are typically used in the washing line of the recycling process.
Water consumption in Bottle-to-Bottle and Bottle-to-Fiber recycling	Assumption: water consumption refers to make-up water which is assumed to be a 20% loss of water use. Note: make-up water is the water added to compensate for losses
PET bottle production	Adjusted the inventory data from Calrecycle (2011); assumed that • recycled PET resin can replace virgin PET resin in 1:1 ratio by weight • the amount of energy and fuel use are the same between a preform that is 100% virgin and that which has some recycled content Note: this assumption was cross-checked by PET recycling expert.
Virgin polyester production	Assumption based on Shen et al. (2010); 0.64 kWh electricity and 5 MJ heat (from fossil fuels) per kg fiber.
Air emission from fossil fuel combustion	This study calculated the greenhouse gas (GHG) emissions and non-GHG emissions from fossil fuel combustion using emission factors from the Intergovernmental Panel on Climate Change (IPCC) and European Environment Agency (EEA), respectively.
Allocation of recycling impacts to by-products	Economic allocation would be a reasonable way to share the environmental burdens between the main product of recycling and the by-products. However, there were limitations to access such information from the recycling company due to confidentiality issues. An estimate based on selling prices from public sources revealed that less than 3% of the total economic value from recycling was contributed by the by-products. Hence, cutting out the by-products from the system boundary would not significantly influence the study results.

comparative data on non-renewable energy use and recycling efficiency used in this study and previous studies are provided in Appendix B Table B2. Furthermore, in the case of recycled bottle-grade PET, the recycling company revealed that "The efficiency of recycled bottle-grade PET production is around 75–79% yield on average. However, this depends on the type of raw material, quality of raw material, impurities, and so on. Sometimes the recycling efficiency could go as low as 65–70%" (personal communication, January 24, 2023). As can be seen from Appendix B Table B2, the data used in this study are relatively consistent with other studies and can thus be considered reasonable.

2.1.2.1. Bottle-to-bottle recycling. Normally, to produce recycled PET flakes, PET bottles are first sorted and compressed into bales which are then transported to the recycling plant. At the recycling plant, the bales are opened, and the green and blue bottles and undesired materials (e.g., paper, wires, and tapes) are sorted by hand or machine. Some recycling plants use thermal processing (hot water) to remove the labels from the bottles before the sorting process. After any impurities are cleaned out, the bottles are crushed into small flakes. After that, PET is separated from other plastics (e.g., HDPE or PP caps) using the float separation step. The separated PET flakes are washed in a cleaning solution and dried. Theses dried PET flakes are finally ready to be used for the further production process (Shen et al., 2010). However, to produce recycled bottle-grade PET, a decontamination process is used to remove the contaminants (e.g., acetaldehyde). Then, a solid-state polycondensation (SSP) reaction is required to increase the intrinsic viscosity (IV) and meet the required IV value for bottle-grade PET (e.g., 0.70–0.78 dL/g for water bottles) (Elamri et al., 2017; Gomes et al., 2017). The recycled bottle-grade PET goes through a stretch blow molding process to produce PET bottles. The reference flow of Bottle-to-Bottle recycling in this study is shown in Fig. 2. The inventory data of recycled PET bottle grade and PET bottle production are provided in Appendix B Table B3 and Appendix B Table B4, respectively.

2.1.2.2. Bottle-to-fiber recycling. To produce recycled PET flakes used for polyester fiber production, the steps are the same as above which include bale opening, label removing, sorting, chopping, float separation, washing and drying the PET flakes. After recycled PET flakes are produced, they can go directly to the polyester fiber production process. To produce polyester fiber, PET flakes are dried until the moisture content is lower than 0.02% by mass. After that, PET flakes are sent to the melt extrusion unit. The extruded polymer is filtered before it passes through small holes called spinnerets to form long threads (filament spinning). After passing through a denier setter, the filaments go to the finishing stage, where they are drawn, dried, and cut into the staple fiber (Shen et al., 2010; Gomes et al., 2017). The reference flow of Bottle-to-Fiber recycling is provided in Fig. 3. The inventory data of recycled polyester fiber production is provided in Appendix B Table B.5.

2.1.2.3. Transportation. For transportation, PET bottle waste collection and PET bale transportation were taken into account. In 2016, 76% of what was recycled in Thailand came from saleng and recycle traders (Sutthichaya, 2021). Therefore, this study assumed that the PET bottle waste is first transported from source (e.g., curbside bin, household) to the small recycle trader by tricycle (saleng) which is driven manually and thus, has no fuel consumption or emissions. After that, a 4-wheel pick up (1.5-tonne capacity) is used to transport PET bottle waste from a small recycle trader to a big recycle trader (e.g., Wongpanit) located 50 km away. After PET bottle waste is sorted at the big recycle trader, sorted PET bottles will then be transported 100 km from the big recycle trader to the recycling plant by a 6-wheel truck (8.5-tonne capacity). The transportation distance from the recycling plant to the PET bottle manufacture and polyester fiber plant is assumed to be zero as they are located in the same area. In addition, solid waste, other types of plastic waste, and sludge obtained from each plant will be sent to the landfill by a 10-wheel truck (16-tonne capacity) over a distance of 100 km. All the average distances were assumed based on the current locations of some facilities in Thailand.

2.1.2.4. Assumptions in this study. This section aims to clarify the assumptions of the study, some of them already crossed-checked with the recycling expert. The assumptions in this study are shown in Table 1.

2.1.3. Life cycle impact assessment

The ReCiPe2016 method was used as for life cycle impact assessment as it is a relatively recently updated and widely used method (Huijbregts et al., 2017). Impact assessment was conducted at the midpoint and endpoint (damage) levels. The midpoint impact categories considered included Global warming (GW), Stratospheric ozone depletion (OD), Ionizing radiation (IR), Ozone formation, Human health (OF-HH), Fine particulate matter formation (PMF), Ozone formation, Terrestrial ecosystems (OF-TE), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Terrestrial ecotoxicity (TET), Freshwater ecotoxicity (FET), Marine ecotoxicity (MET), Human carcinogenic toxicity (HCT), Human non-carcinogenic toxicity (HNCT), Land use (LU), Mineral resource scarcity (MRS), Fossil resource scarcity (FRS), Water consumption (WC). The endpoint impact categories included damage to human health, ecosystems, and resources. The SimaPro 9.2.0.2 software was used for conducting the life cycle impact assessment.

2.1.4. Allocation methods

As the recycling process involves two product systems (the producer and the user of recycled materials) therefore, the environmental impacts of the recycling process and the environmental benefits of the recycled material should be allocated between two product systems. According to ISO 14044 allocation procedure, there is no agreement on which allocation method is the most suitable one for the recycling system; in addition, each method has its conditions and limitations. As different allocation methods can result in different LCA results (Shen et al., 2010; Valentino, 2017), thus, three different allocation methods were used to show the variation of the results in this study, namely, (1) Substitution method, (2) Recycled content method, and (3) Economic allocation method.

2.1.4.1. Substitution method (credit for end-of-life recycling). In this method, the studied product system will get the environmental impacts of the end-of-life recycling process and also get the credits from the

Table 2
Environmental impacts of Bottle-to-Bottle recycling (endpoint level) per functional unit.

Impact category	Unit	Allocation method				
		Substitution	Recycled content		Economic allocation	
			25%RC	35%RC	25%RC	35%RC
Resources	USD2013	253.98	1592.31	1037.62	2218.16	1425.05
Ecosystem quality	species.yr	1.12×10^{-05}	5.06×10^{-05}	3.43×10^{-05}	6.59×10^{-05}	4.37×10^{-05}
Human health	DALY	4.26×10^{-03}	2.08×10^{-02}	1.40×10^{-02}	2.77×10^{-02}	1.82×10^{-02}

Note: RC: recycled content.

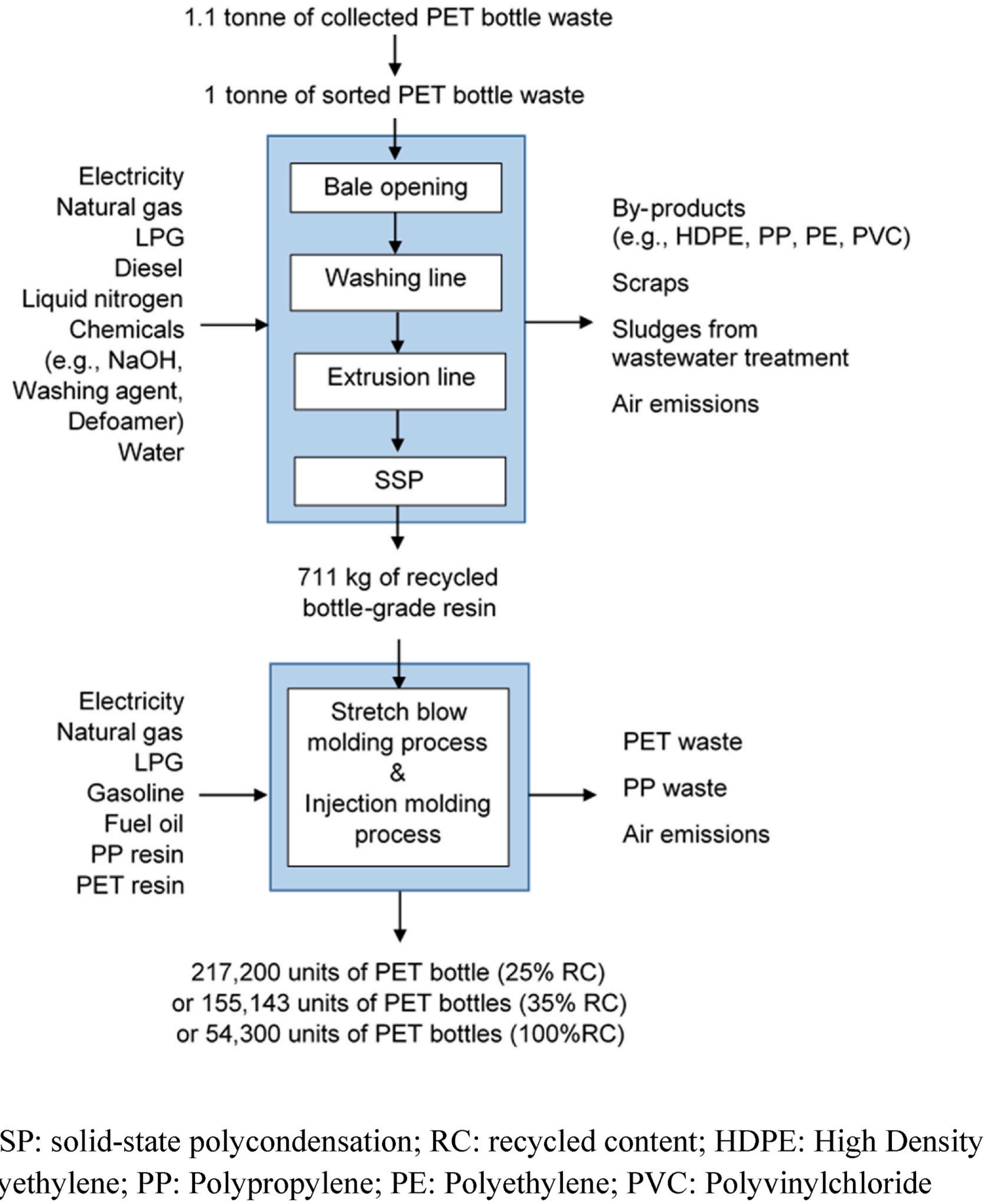


Fig. 2. Reference flow of Bottle-to-Bottle recycling
Note: SSP: solid-state polycondensation; RC: recycled content; HDPE: High Density Polyethylene; PP: Polypropylene; PE: Polyethylene; PVC: Polyvinylchloride.

Table 3
Environmental impacts of Bottle-to-Fiber recycling (endpoint level) per functional unit.

Impact category	Unit	Allocation method		
		Substitution	Recycled content	Economic allocation
Resources	USD2013	198.67	76.02	301.98
Ecosystem quality	species.yr	9.80×10^{-06}	3.99×10^{-06}	9.52×10^{-06}
Human health	DALY	3.76×10^{-03}	1.44×10^{-03}	3.92×10^{-03}

amount of the recycled material recovered from the recycling process of the studied product (assumed to be equivalent to virgin material) (van der Harst et al., 2016). Fig. 4 (a) shows the overview of substitution method of Bottle-to-Bottle recycling; PET bottle production (first life) will get the environmental burdens from the recycling process and also get the credits from avoiding the conventional production of virgin bottle-grade PET material (substitution of virgin bottle-grade PET).

2.1.4.2. Recycled content method. The recycled content method (also known as cut-off method) separates the virgin product (first life) and the recycled product (second life) as two distinct systems. This means that the recycled material used in the studied product system does not bear any environmental impacts from the first life; it bears the environmental burdens only from the collection, transportation, sorting, and recycling of PET bottles. Virgin material used in the studied product system bears

Table 4
Environmental impacts of virgin PET bottles and polyester fiber.

Impact category	Unit	Virgin PET bottle			Virgin polyester fiber
		67,568 units [(a)]	217,200 units [(b)]	155,143 units [(c)]	770 kg produced [(d)]
Resources	USD2013	605.62	1946.79	1390.56	482.87
Ecosystem quality	species.yr	1.78×10^{-05}	5.73×10^{-05}	4.09×10^{-05}	1.20×10^{-05}
Human health	DALY	7.49×10^{-03}	2.41×10^{-02}	1.72×10^{-02}	5.16×10^{-03}

Note: (a) used to compare with the recycled PET bottles and polyester fiber for substitution method; (b) used to compare with the recycled PET bottles with 25% RC for both recycled content and economic allocation methods; (c) used to compare with the recycled PET bottles with 35% RC for both recycled content and economic allocation methods; (d) used to compare with the recycled polyester fiber for the recycled content and economic allocation methods.

the complete environmental impacts of its production. Thus, information on virgin material and recycled material used in the studied product system is required (Shen et al., 2010; van der Harst et al., 2016). Fig. 4 (b) illustrates the overview of the recycled content method applied for bottle-to-bottle recycling.

2.1.4.3. Economic allocation. As post-consumer PET bottle is a valuable resource, thus, the environmental impacts of producing virgin PET resin should be allocated between the first life and second life. Based on Shen et al. (2010), the environmental burdens of virgin PET resin production are allocated between first life and second life by using equation (1). This study used Thailand's market price of recycled PET flake (rPET flake) from https://www.recyclenow.in.th/(25.00 baht/kg) (Recyclenow, 2022) and virgin PET resin from Plastic Intelligence Unit (PIU) (48.23 baht/kg), using the average price in 2022. The allocation factor (AF) in this study is 0.52 which used to allocate the environmental burdens from the first life (i.e., virgin PET resin production) to second life (i.e., recycled PET bottles and polyester fiber production). The AF calculation can be done by using equation (2).

$$\text{Environmental impact of recycled product} = E_{cut-off} + [AF \times E_{vPET}\ resin] \tag{1}$$

where $E_{cut\text{-}off}$ is the environmental impact of recycled product based on the cut-off method; $E_{vPET\ resin}$ is the environmental impact of virgin PET bottle rade resin; and AF is allocation factor.

$$AF = \frac{\text{the market price of rPET flake}}{\text{the market price of virgin PET bottle grade resin}} \tag{2}$$

2.2. Material Circularity Indicator (MCI)

The Material Circularity Indicator (MCI), developed by the Ellen MacArthur Foundation and Granta Design, enables us to determine how successfully are a products' materials circulated in the economy. Furthermore, it may be used to improve the material circularity of the products. In addition, MCI is similar to LCA in terms of considering a holistic view of a product, but it is primarily focused on the material flow. As a result, it can be considered as complementary to LCA. MCI is used to assess the material circularity by considering three main characteristics of the product, namely, (1) the mass of virgin feedstock, (2) the mass of unrecoverable waste, and (3) the utility factor that accounts for the lifetime or intensity of use. The parameters needed for Bottle-to-Bottle and Bottle-to-Fiber recycling are as follows: (1) recycled feedstock or recycled content (RC), (2) collection rate for recycling (CRR), (3) efficiency of the recycling process, and (4) utility during the use phase. The calculation of MCI involves multiple steps, beginning with the calculation of the virgin feedstock material, followed by the calculation of unrecoverable waste, utility conversion factor, linear flow index, and MCI, respectively. The scores range from 0 to 1; higher scores imply greater circularity (Ellen MacArthur Foundation and Granta Design, 2015; Niero and Kalbar, 2019). The full methodology of MCI calculation can be seen in Appendix C Equation C.1 – C.8.

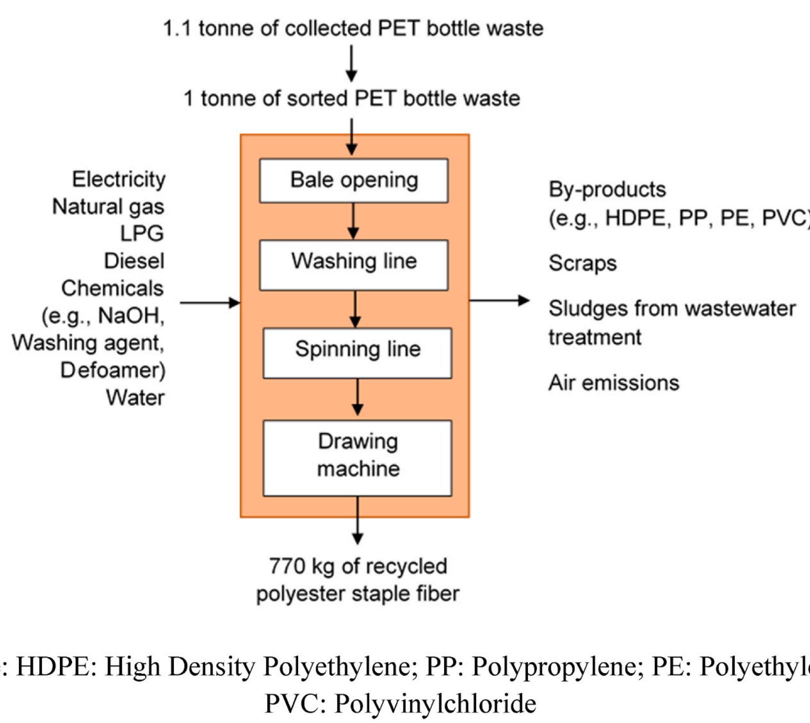


Fig. 3. Reference flow of Bottle-to-Fiber recycling
Note: HDPE: High Density Polyethylene; PP: Polypropylene; PE: Polyethylene; PVC: Polyvinylchloride.

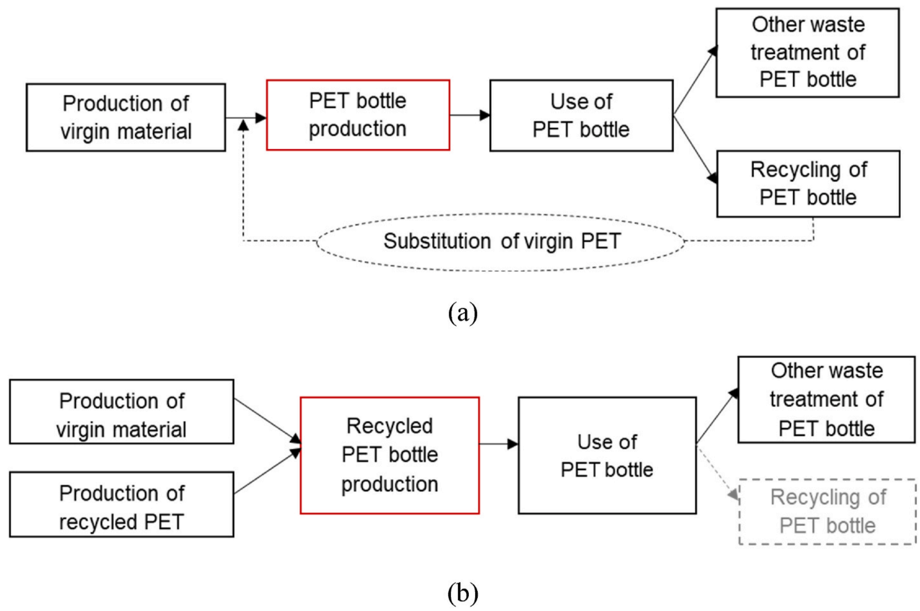


Fig. 4. Illustration of (a) substitution method and (b) recycled content method Source: adapted from van der Harst et al. (2016).

2.2.1. *Data used for bottle-to-bottle recycling*

The degree of circularity of PET bottles was assessed by including four scenarios, using Thailand as a case study. For MCI-Baseline (BL) scenarios, the collection rate for recycling of both the worst case (31%) and the best case (62%) referred to the material flow analysis of PET packaging resin in Thailand (Appendix A; Fig. A.1). The collection rate for recycling of MCI-Circular economy (CE) 1 and MCI-CE 2 scenarios referred to the policy framework in which 100% of target plastic waste will be recycled. The study used 71% efficiency for Bottle-to-Bottle recycling; based on the studies of Shen et al. (2010) (75% efficiency for rPET flake production) and Gomes et al. (2017) (94% efficiency for recycled bottle-grade PET). This 71% of Bottle-to-Bottle recycling efficiency lies between the ranges of 65–70% and 75–79% provided by the industrial experts in Thailand. The recycled content (RC) was based on EU legislation where all new PET bottles must include 25% recycled content by 2025 and 30% by 2030 (Packaging Europe, 2022). Therefore, this study used 25% RC for MCI-CE1 and 35% RC for MCI-CE2. Appendix B Table B.6 shows the data used to analyze the material circularity of PET bottles from Bottle-to-Bottle recycling.

2.2.2. *Data used for bottle-to-fiber recycling*

The degree of circularity of polyester fiber in Thailand was assessed by using the current scenario (MCI-BL) in which polyester fiber can be produced from 100% of recycled PET. However, polyester used in textiles and fiber applications is recycled in a very small amount (0%–5%) as Thailand lacks the technologies to recycle mixed polyester products (World Bank Group, 2021). Therefore, this study assumed that the collection rate for recycling of polyester fiber is 0%. As can be seen in Appendix B Table B.7, the yield of PET flakes during the recycling process ranges from 75% to 80%. Thus, the study used 75% for the efficiency of the recycling process used to produce the recycled content. The data used to analyze the material circularity of polyester fiber from Bottle-to-Fiber recycling are shown in Appendix B Table B.8.

3. Results and discussion

3.1. *Life cycle assessment results*

The reference flow of the two different recycling pathways in this study is shown in Figs. 2 and 3. In the case of Bottle-to-Bottle recycling, the system boundary of this study was expanded to the PET bottle manufacture. The reference product is 0.5 L and 14.8 g (body, cap, and label) (per 1 unit) of PET beverage bottle. As can be observed that the less recycled content, the more PET bottle will be produced (Fig. 2). It should be noted that these two recycling pathways have the different outputs (i.e., recycled PET bottles and polyester fiber), making them unable to compare. However, the study aims to assess the environmental impacts of each recycling pathway and compare it to the virgin products rather than compare these two recycling pathways. As the recycling process is related to two product systems (the producer and the user of recycled material), therefore the environmental burdens and benefits of the recycling process should be shared between these two product systems. To deal with this complexity, three allocation methods were used to demonstrate the variation in the results (section 3.1.3).

3.1.1. *Life cycle assessment results for recycled bottle-grade PET and polyester fiber production*

As seen in Appendix B Table B.9, the environmental impacts of recycled products bottle-grade PET resin and polyester fiber are lower than virgin products in all impact categories except for stratospheric ozone depletion. The latter resulted from the defoamer (or anti-foaming agent) usage in mechanical recycling (washing process). When compared to virgin products, producing bottle-grade PET resin and polyester fiber from PET bottle waste can reduce greenhouse gas emissions by about 60% and fossil resource scarcity by about 85%. As sorting and recycling processes are frequently powered by electricity and fossil fuels, the main contributors to the environmental impacts of both recycled bottle-grade PET and polyester fiber production are electricity, fossil fuels (e.g., natural gas, liquefied petroleum gas), and chemicals (e.g., defoamer, sodium hydroxide) use (as shown in Appendix A Fig. A2). It should be noted that the results of the recycled products in section 3.1.1 and section 3.1.2 refer to the total impacts of PET bottle waste collection, transportation, sorting, and recycling and do not include the burdens from the first life of PET bottles (virgin PET resin production). All environmental impacts at the midpoint level are shown in Appendix B Table B9.

The impacts at the endpoint level or final damage to resources, ecosystem quality, and human health are presented in Appendix B Table B.10. The recycled products have lower impacts on the resources, ecosystem quality, and human health when compared to their virgin counterparts. When compared to virgin products, recycled bottle-grade PET and polyester fiber can reduce the impact on the resources, ecosystem quality, and human health by about 85%, 67%, and 73%, respectively. The main contributors of each endpoint impact category at the midpoint level can be seen in Appendix A Fig. A3. Global warming is the major environmental issue contributing to impacts on ecosystem quality and human health for both recycled bottle-grade PET and polyester fiber. In addition, other than global warming, terrestrial acidification and ozone formation have a great impact on ecosystem quality and fine particulate matter formation has a great impact on human health. The damage to resources is from fossil resource scarcity which results mainly from the use of natural gas and defoamer.

3.1.2. Life cycle assessment results per unit of PET bottle produced

For PET bottle production, the amount of energy and fuels used in the stretch blow molding process is not different between a preform that is 100% virgin and that which has some recycled content (RC) (i.e., 25% and 35% RC). Therefore, the different environmental impact results are due only to the different amounts of virgin and recycled bottle-grade PET resin used to produce the PET bottles. The findings show that all environmental impacts (except for stratospheric ozone depletion) of PET bottles decrease when more recycled material is used. The key contributor for all environmental impact categories is virgin polyethylene terephthalate (PET) resin used in the stretch blow molding process. Thus, if virgin PET is replaced resin with recycled PET resin (with lower impact), the environmental impacts can be reduced for most environmental impact categories. All environmental impacts at the midpoint level are shown in Appendix B Table B.11 and contribution analysis results of virgin PET bottle production are shown in Appendix A Fig. A4.

Similar to the environmental impacts at the midpoint level, PET bottles made from recycled PET resin have lower impacts than PET bottles made from virgin PET resin for all endpoint impact categories (Appendix B; Table B.12). Furthermore, when looking at the contribution analysis (Appendix A; Fig. A.5), global warming is the main contributor that causes damage to ecosystem quality and human health. Whereas, damage to resources is mainly contributed by fossil resource scarcity from virgin PET resin and virgin polypropylene (PP) resin production.

3.1.3. Life cycle assessment results based on three allocation methods

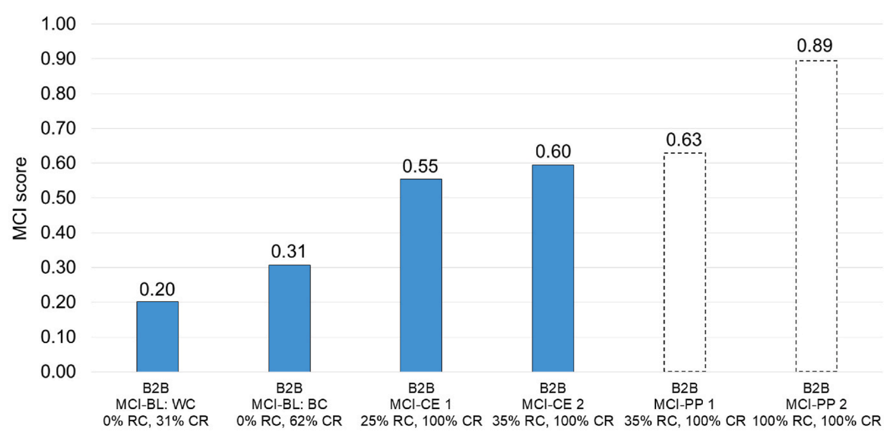
This section aims to show the LCA results per functional unit (i.e., 1 tonne of sorted PET bottle waste recycling) for the two different recycling pathways based on three allocation methods (i.e., substitution, recycled content, and economic allocation methods). The reference flows for the two recycling pathways according to the functional unit can be seen in Figs. 2 and 3. Tables 2 and 3 show the environmental impacts at the endpoint level of Bottle-to-Bottle and Bottle-to-Fiber recycling, respectively. The environmental impacts of virgin PET bottles and polyester fiber used to compare to the recycled products are provided in Table 4. In the case of Bottle-to-Bottle recycling, recycled PET bottles have lower environmental impacts than virgin PET bottles

Fig. 5. Comparative impacts on resource, ecosystem quality, and human health of the recycled PET bottle and recycled Polyester fiber using different allocation methods
Note: SST: substitution method; RC: recycled content method; EA: economic allocation method.

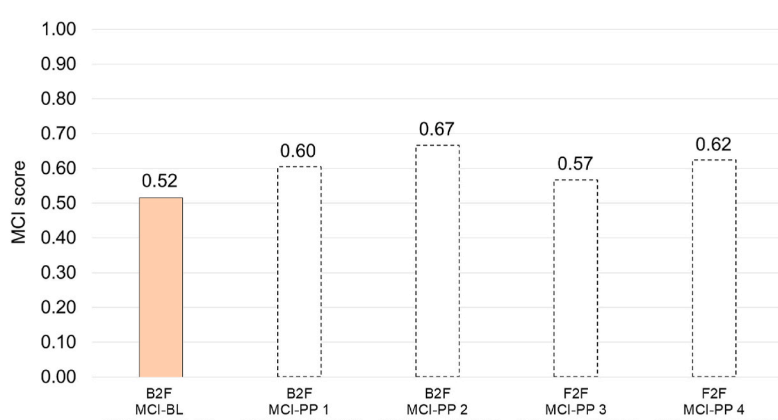
for all endpoint impact categories when using the substitution and recycled content methods. On the other hand, when using the economic allocation method, the impacts of recycled PET bottles are higher than virgin PET bottles (Fig. 5). This is because the benefits of using recycled material are not big enough when compared to the burdens allocated from the virgin PET resin from the first life. On the other hand, in the case of Bottle-to-Fiber recycling, regardless of the allocation method used, recycled polyester fiber has lower environmental impacts than virgin polyester fiber for all endpoint impact categories.

Fig. 5 illustrates the variation of the results at the endpoint level, using three different allocation methods. Based on the substitution method, when compared to virgin products (red bar), the impact reductions of Bottle-to-Fiber are higher than Bottle-to-Bottle for all endpoint impact categories. This is because the production of virgin polyester fiber needs more energy and fossil fuels (more impacts), as well as the higher amount of substitution of virgin polyester fiber when compared to the production and substitution of virgin bottle-grade PET resin, and therefore receive more credits (more reductions). For example, the credits for avoided 711 kg of virgin bottle-grade PET production (−402.63 USD2013) are lower than the credits for avoided 770 kg of virgin polyester fiber production (−482.98 USD2013) (Appendix A Fig. A6). In terms of recycled content and economic allocation methods, the impact reductions of Bottle-to-Fiber recycling are still higher than Bottle-to-Bottle recycling. This is because recycled polyester uses 100% of recycled PET as a feedstock (get more benefits from using recycled material) while recycled PET bottles in this study contain a smaller percentage of recycled PET (i.e., 25% and 35% recycled content) (get smaller benefits).

As can be observed from Fig. 5, the LCA results highly depend on the allocation method. However, each method has its conditions and limitations. For example, the substitution method should be applied when the recycled content of the product is unknown, the demand for recycled material exceeds the supply, and the lifetime of the product is short. The disadvantage of this allocation method is that it already takes credit for the supposed future use of recycled materials, leading to weak sustainability. While the recycled content method rewards the actual use of recycled material in the products, resulting in strong sustainability; however, the recycled content of the product is required (van der Harst et al., 2016). In the case of economic allocation, it may have a high variability in results because of the fluctuation price of recycled PET flake and virgin PET resin. Therefore, the most appropriate allocation method in this study should be the recycled content allocation method.



(a)



(b)

Note: BL: baseline scenario; CE: circular economy scenario; WC: worst case; BC: best case; PP: proposed scenario; RC: recycled content; CR: collection rate for recycling

Fig. 6. Material Circularity Indicator (MCI) results of (a) PET bottle and (b) polyester fiber for various scenarios
Note: BL: baseline scenario; CE: circular economy scenario; WC: worst case; BC: best case; PP: proposed scenario; RC: recycled content; CR: collection rate for recycling.

3.2. Uncertainty analysis

As the quality of the inventory data can influence the LCA study, uncertainty analysis was performed to demonstrate the robustness of the results by considering data quality, using SimaPro software. Reliability, completeness, temporal correlation, geographical correlation, further technological correlation, and sample size of the inventory data were the aspects of data quality taken into account. Appendix A Fig. A.7 illustrates the uncertainty results of the sorting process, recycled bottle-grade PET, recycled polyester fiber, and PET bottle production. The findings show that the LCA results of the Bottle-to-Bottle and Bottle-to-Fiber recycling can be considered relatively robust as there is reasonably low variation for most impact categories, except for water consumption (Appendix A Fig. A7(b) and (c)) which has high variation due to the background database used. The uncertainty analysis results also imply that the inventory data and assumptions used in this study seem to be reasonable; this is because they were based on reliable and consistent sources (e.g., the data from processes under study (identical technology), the time period of the data is less than 10 years) and cross-checked with some industry experts.

3.3. Sensitivity analysis

3.3.1. Energy and fuel dataset

To generalize the results rather than base them on one specific country, this sensitivity analysis was performed by using the GLO (global) dataset from the ecoinvent database instead of the Thai national LCI database for all electricity and fuels consumption. The data show that the environmental impacts of the GLO database are higher than the Thailand database mostly due to the electricity (Appendix B; Table B.13 –; Appendix B; Table B.14). However, the comparative results are similar to the results based on the Thai national LCI database. In the case of Bottle-to-Bottle, the environmental impacts of recycled PET bottles are less than virgin PET bottles for all endpoint impact categories when using the substitution and recycled content methods. In the case of Bottle-to-Fiber, the environmental impacts of recycled polyester fiber are lower than virgin polyester fiber for all impact categories whichever allocation method is used.

3.3.2. Efficiency of recycled bottle-grade PET production analysis

As mentioned before, the final LCA findings could be influenced by the production efficiency of recycled bottle-grade PET and polyester fiber, particularly when using the substitution method. As a consequence, an efficiency-related sensitivity analysis was carried out. This analysis was conducted by increasing the efficiency of recycled bottle-grade PET production to 79% (the maximum efficiency given by the industrial experts in Thailand). The results show that (Appendix B; Table B.15) although the efficiency of recycled bottle-grade PET production is higher than recycled polyester fiber production, the final LCA findings do not change; the impact reductions of Bottle-to-Fiber are still higher than Bottle-to-Bottle (gets more benefits when PET bottle is recycled into fiber). This is because the environmental impacts of virgin polyester fiber production are much higher than virgin bottle-grade PET production, therefore Bottle-to-Fiber recycling still receives more credits (lower impacts).

3.3.3. Recycled content of PET bottle analysis

The recycled content in products could highly affect the LCA results, especially when using the recycled content and economic allocation methods. Therefore, a sensitivity analysis was conducted by assessing the environmental impacts of recycled PET bottles with 100% recycled content (RC) based on these two allocation methods. The findings showed that even though recycled PET bottles contain 100% recycled PET, the impact reductions of Bottle-to-Fiber are still higher than Bottle-to-Bottle. The important point is that when using economic allocation, the environmental impacts of recycled PET bottle containing 100% recycled material are lower than virgin PET bottle (Appendix B Table B.16 and Appendix B Table B.17); the benefits of using recycled material are big enough when compared to the environmental burdens allocated from virgin PET resin production from the first life. Therefore, the amount of recycled material used in PET bottles can change the final LCA findings, particularly when using the economic allocation method.

3.4. Material Circularity Indicator results

In the case of Bottle-to-Bottle recycling, the MCI scores of the baseline scenario (MCI-BL: WC and MCI-BL: BC) range between 0.20 and 0.31, whereas the MCI scores of the expected scenario in the future (MCI-CE 1 and MCI-CE 2) show a higher level of material circularity (0.55–0.60) as a result of 100% collection rate for recycling of PET bottles and the use of recycled PET (i.e., 25% and 35% recycled content) as a feedstock. Therefore, increasing the recycled content and collection rate for recycling of PET bottles is needed. For further development from MCI-CE2, the circularity of Bottle-to-Bottle recycling can be enhanced by improving the efficiency of the recycling process (e.g., 79% recycling efficiency) and increasing the recycled content (e.g., 100% recycled content) in the PET bottles; the results of the proposed scenarios (i.e., MCI-PP 1 and MCI-PP 2) can be seen in Fig. 6 (a) as dotted bars. The details of MCI scores or the material circularity degree of Bottle-to-Bottle recycling are provided in Appendix B Table B.18.

In the case of Bottle-to-Fiber recycling, the MCI score of the baseline scenario is equal to 0.52 and this high score resulted from the use of 100% recycled PET as a feedstock. However, if this recycled polyester fiber (from Bottle-to-Fiber recycling) can be further recycled at the end-of-life, the MCI score can be increased even further. Thus, to demonstrate the potential for polyester fiber recycling to be enhanced, this study employed 60% textile recycling efficiency based on Spathas (2017) and assumed that the collection rate for recycling is between 30% (MCI-PP 1) and 50% (MCI-PP 2). The results are shown Fig. 6 (b).

Furthermore, European countries have especially promoted the Fiber-to-Fiber recycling to address the textile waste problems (McKinsey, 2022; European Commission, 2022). Therefore, this study also estimated the MCI scores of closed-loop polyester fiber recycling (Fiber-to-Fiber) using a 30% (MCI-PP 3) - 50% (MCI-PP 4) collection rate and 60% textile recycling efficiency. The MCI scores of Fiber-to-Fiber recycling are lower than Bottle-to-Fiber, this is because the efficiency of the recycling process used to produce the recycled feedstock of Bottle-to-Fiber (75%) is higher than Fiber-to-Fiber (60%). However, Fiber-to-Fiber or closed-loop recycling can prevent the downgrade of materials (e.g., a decrease in polyester's IV value). In this sense, materials are kept in the economy at the highest quality and value. On the other hand, when PET bottle is recycled into fiber (open-loop recycling), the IV value of the materials is not as high as when recycled into PET bottle (closed-loop recycling). The MCI results of Fiber-to-Fiber recycling are shown as MCI-PP 3 and MCI-PP 4 in Fig. 6 (b). The details of MCI scores of Bottle-to-Fiber recycling can be seen in Appendix B Table B.19.

It should be noted that PET bottles can be recycled several times, whereas, polyester fiber is now hardly recycled at the end-of-life. In addition, Bottle-to-Bottle has the highest economic value for recycled products (World Bank Group, 2021). Therefore, based on circular economy principles (e.g., keeping materials in the economy at their highest quality and economic value), closed-loop recycling (e.g., Bottle-to-Bottle) seems to be better than open loop recycling (e.g., Bottle-to-Fiber). However, recycling PET again and again can lead to down-cycling which results in a lower quality and economic value. In addition, scientific tests have already proved that PET can be recycled and used for new bottles at least ten times (Goldsberry, 2018; Pinter et al., 2021). As a result, to keep the quality and economic value of the recycled material as long as possible, the Bottle-to-Bottle recycling pathway should be employed until PET is no longer suitable for use in bottles, at which point Bottle-to-Fiber recycling should be encouraged (recycled into lower quality products).

4. Practical applications and future research prospects of this work

The results showed that the main contributors to the environmental impacts of mechanical recycling were electricity, fossil fuel, and chemical consumption. These findings can be used by PET recycling industries to improve the environmental performance of their manufacturing process, for example, using electricity produced from renewable sources and controlling the amount of chemical consumption. Furthermore, the study indicated that increasing the recycled content and collection rate of PET bottles can maximize the benefits of Bottle-to-Bottle recycling in terms of environmental and material circularity aspects. Additionally, a PET bottle recycling hierarchy has been proposed. All of the findings may be used by the government to support and encourage the adoption of a circular economy strategy for PET waste management, for example, Extended Producer Responsibility (EPR) implementation. Lastly, the advantages and disadvantages of each recycling allocation method have been provided. The most suitable recycling allocation method has also been suggested. All of this offers some ideas for choosing the allocation method to be used in further study. However, the final product (e.g., cloth) of Bottle-to-Fiber recycling and the life cycle cost analysis of both recycling pathways may be needed to be further studied.

5. Conclusions

The study assessed the environmental impacts and material circularity of PET bottle recycling to bottles and fiber. When are recycled into PET bottles, the environmental damages were less than virgin PET bottles when using the substitution and recycled content methods, but not for economic allocation. When recycled into fiber, the environmental damages were lower than virgin polyester fiber for all the three allocation methods. The LCA findings can be highly influenced by the recycled content in the products, especially when using economic allocation. For enhanced material circularity, increasing the collection rate and recycled content are necessary for Bottle-to-Bottle recycling, and further recycling at the end-of-life of polyester fiber is needed for Bottle-to-Fiber recycling. However, based on circular economy principles, Bottle-to-Bottle recycling should be preferred at first to maintain the quality of the PET for more cycles and then followed by Bottle-to-Fiber recycling when further recycling to bottles cannot be sustained.

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Credit author statement

Sumonrat Chairat: Conceptualization, Methodology, Software, Validation, Writing – original draft. **Shabbir H. Gheewala**: Supervision, Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

Bataineh, K.M., 2020. Life-cycle Assessment of Recycling Postconsumer High-Density. https://doi.org/10.1155/2020/8905431.
CalRecycle (California's Department of Resources Recycling and Recovery), 2011. Life Cycle Assessment of Polyethylene Terephthalate (PET) Beverage Bottles Consumed in the State of California. Brandon Kuczenski and Roland Geyer, California.
Chilton, T., Burnley, S., Nesaratnam, S., 2010. A life cycle assessment of the closed-loop recycling and thermal recovery of post-consumer PET. Resour. Conserv. Recycl. 54 (12), 1241–1249. https://doi.org/10.1016/j.resconrec.2010.04.002.
Directive, 2019. Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the Reduction of the Impact of Certain Plastic Products on the Environment, 904. https://www.legislation.gov.uk/eudr/2019/904.
EEA (European Environment Agency), 2009. EMEP/EEA Emission Inventory Guidebook 2009: 1.A.2 Manufacturing Industries and Construction.
Elamri, A., Zdiri, K., Harzallah, O., Lallam, A., 2017. Progress in polyethylene terephthalate recycling. In: Polyethylene Terephthalate: Uses, Properties and Degradation. Nova Science Publishers.
Ellen MacArthur Foundation and Granta Design, 2015. Circularity Indicators: an Approach to Measuring Circularity. Methodology. Ellen MacArthur Foundation, Cowes, UK.
EPA (Environmental Protection Agency), 2022. What is a circular economy? Available online: https://www.epa.gov/recyclingstrategy/what-circular-economy#what. (Accessed 12 January 2023).
Europe, Packaging, 2022. Funding secured for project to increase recycled content and quality of PET bottles. Available online: https://packagingeurope.com/news/funding-secured-for-project-to-increase-recycled-content-and-quality-of-pet-bottles/7894.article. (Accessed 18 August 2022).
European Commission, 2022. EU strategy for sustainable and circular textiles. Available at: https://environment.ec.europa.eu/strategy/textiles-strategy_en. (Accessed 11 March 2023).
Franklin Associates, A Division of Eastern Research Group (ERG), 2018. Life cycle impacts for postconsumer recycled resins: PET, HDPE, AND PP. Available at: https://plasticsrecycling.org/images/library/2018-APR-LCI-report.pdf. (Accessed 21 February 2022).
Gileno, L.A., Turci, L.F.R., 2021. Life cycle assessment for PET-bottle recycling in Brazil: B2B and B2F routes. Clean. Environ. Syst. 3, 100057 https://doi.org/10.1016/j.cesys.2021.100057.
Goldsberry, C., 2018. Scientific tests prove HDPE can be recycled at least 10 times. Available at: https://www.plasticstoday.com/packaging/scientific-tests-prove-hdpe-can-be-recycled-least-10-times. (Accessed 16 June 2023).
Gomes, T.S., Visconte, L.L.Y., Pacheco, E.B.A.V., 2017. Comparative Assessment of Two Different PET Recycling Systems in Brazil from a Life Cycle Perspective. Sixteenth International Waste Management and Landfill Symposium, Sardinia.
Grand View Research, 2021. Recycled Polyethylene Terephthalate Market Size, Share & Trends Analysis Report by Product (Clear, Colored), by End Use (Fiber, Food & Beverage Containers & Bottles). By Region, And Segment Forecasts, 2021 – 2028. Available online: http://www.grandviewresearch.com/industry-analysis/recycled-polyethylene-terephthalate-pet-market. (Accessed 12 May 2022).
Hirsch, P., Schempp, C., 2020. Categorisation system for the circular economy. Eur. Comm. 408, 123–134.
Huijbregts, M.A., Steinmann, Z.J., Elshout, P.M., Stam, G., Verones, F., Vieira, M., et al., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.
IPCC (Intergovernmental Panel on Climate Change), 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, vol. 2 (Chapter 2) Stationary Combustion.
ISO, 2006a. Environmental Assessment – Life Cycle Assessment – *Principles And Framework*, 14040. International Organisation for Standardisation, 2006.
ISO, 2006b. Environmental Management – Life Cycle Assessment – *Requirements And Guidelines*, 14044. International Organisation for Standardisation, 2006.
Kristensen, H.S., Mosgaard, M.A., 2020. A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? J. Clean. Prod. 243, 118531 https://doi.org/10.1016/j.jclepro.2019.118531.
Lonca, G., Lesage, P., Majeau-Bettez, G., Bernard, S., Margni, M., 2020. Assessing scaling effects of circular economy strategies: a case study on plastic bottle closed-loop

recycling in the USA PET market. Resour. Conserv. Recycl. 162, 105013 https://doi.org/10.1016/j.resconrec.2020.105013.

McKinsey, 2022. Scaling textile recycling in Europe–turning waste into value. Available online: https://www.nweurope.eu/media/19019/2207-scaling-textile-recycling-in-europe-turning-waste-into-value.pdf. (Accessed 11 March 2023).

MOPH (Ministry of Public Health), 2005. Notification of the Ministry of Public Health (No. 295) B.E. 2548, 2005. Available online: http://food.fda.moph.go.th/law/data/announ_moph/V.English/No.295-48%20Qualities%20or%20standard%20for%20container%20made%20from%20plastic.pdf. (Accessed 2 February 2023).

MOPH (Ministry of Public Health), 2022. Notification of the Ministry of Public Health (No. 435) B.E. 2022 Re: Determination of Quality or Standards of Plastic Containers. Available online: https://ratchakitcha.soc.go.th/pdfdownload/?id=139D139S0000000001100. (Accessed 2 February 2023).

MTEC, 2014. Thai National LCI Database, National Metal and Materials Technology Centre. National Science and Technology Development Agency.

Niero, M., Kalbar, P.P., 2019. Coupling material circularity indicators and life cycle based indicators: a proposal to advance the assessment of circular economy strategies at the product level. Resour. Conserv. Recycl. 140, 305–312. https://doi.org/10.1016/j.resconrec.2018.10.002.

Okorie, O., Salonitis, K., Charnley, F., Moreno, M., Turner, C., Tiwari, A., 2018. Digitisation and the circular economy: a review of current research and future trends. Energies 11 (11), 3009. https://doi.org/10.3390/en11113009.

Pinter, E., Welle, F., Mayrhofer, E., Pechhacker, A., Motloch, L., Lahme, V., et al., 2021. Circularity study on PET bottle-to-bottle recycling. Sustainability 13 (13), 7370. https://doi.org/10.3390/su13137370.

PIU (Plastic Intelligence Unit), 2022. Thailand's PET resin price. Available online: http://plastic.oie.go.th. (Accessed 4 February 2023).

Recyclenow, 2022. Thailand's recycled PET flake price. Available at: https://www.recyclenow.in.th/. (Accessed 4 February 2023).

Rocchi, L., Paolotti, L., Cortina, C., Fagioli, F.F., Boggia, A., 2021. Measuring circularity: an application of modified Material Circularity Indicator to agricultural systems. Agric. Food Econ. 9 (1), 1–13. https://doi.org/10.1186/s40100-021-00182-8.

Rybaczewska-Błażejowska, M., Mena-Nieto, A., 2020. Circular economy: comparative life cycle assessment of fossil polyethylene terephthalate (PET) and its recycled and bio-based counterparts. Manag. Prod. Eng. Rev. 11 https://doi.org/10.24425/mper.2020.136126.

Sarioğlu, E., Kaynak, H.K., 2017. PET Bottle Recycling for Sustainable Textiles. *Polyester-Production, Characterization, and Innovative Applications*, pp. 5–20. https://doi.org/10.5772/intechopen.72589.

Shen, L., Worrell, E., Patel, M.K., 2010. Open-loop recycling: a LCA case study of PET bottle-to-fibre recycling. Resour. Conserv. Recycl. 55 (1), 34–52. https://doi.org/10.1016/j.resconrec.2010.06.014.

Spathas, T., 2017. *The Environmental Performance of High Value Recycling for the Fashion Industry; LCA for Four Case Studies* (Master's Thesis in Industrial Ecology. Chalmers University of Technology.

Sutthichaya, Y., 2021. From Saleng to factories: vulnerabilities & limitations of the recycling business. Available online: https://prachataienglish.com/node/9085. (Accessed 4 February 2023).

Tamoor, M., Samak, N.A., Yang, M., Xing, J., 2022. The cradle-to-cradle life cycle assessment of polyethylene terephthalate: environmental perspective. Molecules 27 (5), 1599. https://doi.org/10.3390/molecules27051599.

Valentino, G., 2017. Life Cycle Assessment of PET bottles: closed and open loop recycling in Denmark and Lombardy region. Available at: https://www.politesi.polimi.it/bitstream/10589/136151/3/2017_10_Valentino.pdf. (Accessed 21 February 2022).

van der Harst, E., Potting, J., Kroeze, C., 2016. Comparison of different methods to include recycling in LCAs of aluminium cans and disposable polystyrene cups. Waste Manag. 48, 565–583. https://doi.org/10.1016/j.wasman.2015.09.027.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

World Bank Group, 2021. Market Study for Thailand: Plastics Circularity Opportunities and Barriers. East Asia and Pacific Region Marine Plastics Series. World Bank, Washington, DC. © World Bank.

Zhang, H., Wen, Z.G., 2014. The consumption and recycling collection system of PET bottles: a case study of Beijing, China. Waste Manag. 34 (6), 987–998. https://doi.org/10.1016/j.wasman.2013.07.015.