Green Chemistry

PAPER

View Article Online
View Journal | View Issue

Cite this: *Green Chem.*, 2026, **28**, 556

Comparative life cycle assessment study of virgin polyethylene and bio-polyethylene, with recycled polyethylene from uncontaminated post-industrial film

Ahdo Kim,†[a] Teuku Naraski Zahari,†[b] Nobuteru Edayoshi,[c] Pin Juo Chou,[c,d] Toshiki Yamamoto,[c] Pin Yen Chou,[c,d] Kei Saito *[a] and Benjamin McLellan *[b]

Received 31st May 2025,
Accepted 24th November 2025

DOI: 10.1039/d5gc02751a

rsc.li/greenchem

Petroleum-derived plastics are widely used but rely on non-renewable resources and contribute to environmental degradation during production. Recycling and the adoption of bio-based plastics offer potential solutions within the framework of green chemistry. However, it is essential to evaluate their relative environmental impacts to avoid burden-shifting within the supply chain. This study conducts a life cycle assessment (LCA) comparing three alternatives for plastic shopping bag production in Japan: virgin polyethylene (PE), bio-based PE, and mechanically recycled PE (Repla™) derived from uncontaminated post-industrial film. The recycled Repla™ material, which would otherwise be incinerated, demonstrated significantly lower CO_2 emissions. While recycled materials often outperform virgin plastics, Repla™ also showed lower impacts than bio-PE. This is largely due to the use of fossil fuels in bio-PE production. Even when substituting fossil energy with alternatives such as bagasse or waste plastic, the recycled option retained its environmental advantage. This study highlights that under realistic technological and policy scenarios, mechanical recycling using clean post-industrial waste can deliver superior environmental benefits, underscoring its value as a green chemistry solution.

Green foundation

1. This study advances green chemistry by providing a more holistic approach to evaluating environmental performance in polymer production and recycling, recognizing that atom economy (AE) alone is insufficient—particularly in recycling contexts.
2. Using life cycle assessment (LCA), we demonstrate that recycled polyethylene from uncontaminated post-industrial film has significantly lower environmental impacts than both virgin and bio-based polyethylene. Specifically, recycled PE outperforms Bio-PE and virgin PE in terms of global warming potential, human carcinogenic toxicity, and fossil resource scarcity.
3. In addition, we identified the major contributors to these impacts and proposed strategies to mitigate them, further supporting the environmental benefits of high-quality plastic recycling.

Introduction

Global warming and other environmental issues are escalating, with human activities identified as the primary cause according to the IPCC's 6th Assessment Report.[1] The mass production, distribution, and consumption of materials, including petroleum-derived plastics, contribute to these problems. Japan, a significant plastic producer and consumer, reported a combined production of 4.4 million tons of polyethylene (PE) and polypropylene (PP) in 2022, with approximately 54% application in the film/sheet sector.[2] However, plastics present risks to the environment, including resource depletion, greenhouse gas emissions, and persistent microplastic pollution.[3] Alternative, and more environmentally acceptable options to produce plastic, are part of the solution to reduce these potential impacts by minimizing the production and utilization of conventional plastic. Alongside this, there is an increasing need to transition from a linear economy which is characterized by the "take-make-dispose" model to a circular economy,

[a]Graduate School of Advanced Integrated Studies in Human Survivability, Kyoto University, Higashi-Ichijo-Kan, Yoshida-nakadachicho 1, Sakyo-ku, Kyoto, 606-8306, Japan. E-mail: saito.kei.1y@kyoto-u.ac.jp
[b]Graduate School of Energy Science, Kyoto University, Yoshida Campus, Yoshida-Honmachi, Sakyo-Ku, Kyoto, 606-8501, Japan. E-mail: mclellan.benjamincraig.7v@kyoto-u.ac.jp
[c]esa Inc., SOC Takanawa Building 8F, 3-19-26 Takanawa, Minato-ku, Tokyo, 108-0074, Japan
[d]Chuang Tieh Machine, No. 6 Chong Shin Road, Tree Valley Park, Tainan, 74148, Taiwan

† These authors contributed equally to this work as first authors.

which emphasizes resource efficiency, recycling, and sustainability.

The adoption of circular economy thought in plastics production is a key strategy to transition this sector. In particular, recycling of plastics presents an opportunity to reduce environmental impacts, which has been an area of research and development (and practical application) for many years.

This research aligns with several principles of green chemistry, defined as the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances, and offers a pathway toward more sustainable industrial practices. Specifically, the twelve principles of green chemistry[4] provided a framework for evaluating the environmental performance of different materials and production processes. Among them, atom economy (AE) has been considered as an important indicator for evaluating environmental performance of a given process, as it quantifies the ratio between input materials and desired output products, measuring how efficiently raw materials are used to produce the intended product.

However, the AE alone is insufficient for evaluating environmental performance. This limitation is particularly evident in the field of polymer production, where only a few studies have conducted more comprehensive assessments, such as combining with life cycle assessment (LCA).[5,6]

Additionally, the AE poses challenges when applied to recycling processes. One core issue lies in the perspective on nominal waste streams (*e.g.* discarded offcuts): whether such waste should be treated as a true waste or as a valuable resource for second-generation products. If considered waste, it should not be counted among desired products (therefore lowering the AE of a process, although not the AE of chemical reactions that are involved); if considered a resource, the AE may be higher, but the utilization of waste in by-products must be included in the calculation of overall process AE. This ambiguity complicates the application of the AE in recycling contexts.

Recycling can be classified into three broad categories or methods: mechanical recycling, chemical recycling, and thermal recycling.[7,8] Mechanical recycling involves changing the form of the material without altering its properties, typically requiring fewer resources and simpler processes than chemical recycling.[9] Chemical recycling, on the other hand, involves breaking down the material into its monomer components and reassembling them, which requires more complex processes, additional materials, and energy.[10] Thermal recycling (or energy recovery) involves the incineration of materials to recover thermal energy. Thermal recycling is often used for contaminated, mixed or degraded plastic streams, or where no recycling infrastructure is available. While this can be an efficient form of energy recovery, caution is needed due to the potential emission of harmful gases during incineration.[11] In Japan, in 2021, out of the total plastic production of 10.45 Mt, 8.24 Mt were disposed of.[12] Of the disposed plastic, only 21% underwent mechanical recycling, while over 61% were treated through thermal recycling. The large proportion of thermal recycling shows that further potential for other forms of recycling still exists.

As with most material recycling, plastic recycling processes have a number of typical stages (a high-level flowsheet is shown in Fig. 1). Firstly, the waste plastic must be collected – through municipal recycling schemes or direct user-to-recycler routes. Next, in the case of impure or mixed plastic streams, the plastic(s) must be separated in order to apply the most appropriate downstream recycling process. Separation may include decontamination – mostly washing to remove non-plastics such as soil, metals, and non-plastic organic or biological components. Separated plastics may be crushed, shredded and/or melted to produce pellets or other intermediate products that can be feedstock for new production. Each of these stages has environmental implications that should be considered.

There have been a number of studies on mechanical recycling of plastic waste from an environmental perspective. According to several previous studies, decontamination[13] and extrusion[14,15] processes have been identified as having significant environmental impacts in the mechanical recycling process. In particular, Suzuki *et al.*[16] determined that inadequate wastewater treatment during the decontamination (washing) process can lead to microplastic pollution. If decontamination can be avoided, the environmental performance of material may be enhanced. However previous studies have predominantly considered post-consumer materials,[15,17] which are prone to being contaminated or comingled, while research specifically concentrating on utilizing post-industrial waste materials that can offer an opportunity to source materials with without contamination is limited. Of course, the uncontaminated waste tends to be lower in quantity, so it is natural to focus on larger streams. It can also be an "invisible" waste stream when it is utilized as thermal feedstock or internally incinerated as was found to be the case in the study presented here.

Another strategy for minimizing the requirement for the production of fossil fuel-based plastic is the utilization of bio-based plastic alternatives, as per the seventh of the twelve principles of green chemistry:[4] Use of Renewable Feedstocks.[18,19] Bio-based plastics are materials made from renewable biomass resources[20,21] such as sugarcane, sugar beet, maize and so on. While these raw materials are considered environmentally friendly as they are not derived from fossil fuels, there is ongoing debate regarding the environmental impact of their cultivation.[22,23] Therefore, a comprehensive environmental impact assessment that takes into account the specific production and usage processes and location is necessary.[18]

Research on recycling and environmental impact assessment of waste plastics using LCA is actively progressing (see Table 1). LCA is widely used to assess which materials and recycling strategies are more sustainable across the lifecycle of a product or process. Previous studies have demonstrated that mechanical recycling of plastics can provide significant environmental benefits compared to virgin production, particularly when substituting composites;[14] recycling of plastic

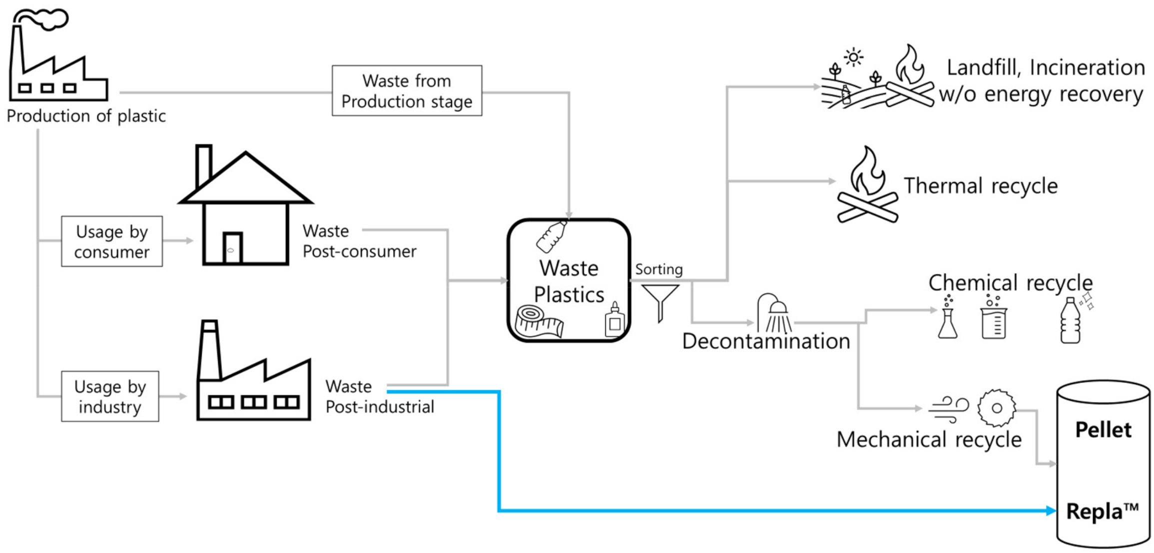

Fig. 1 Treatment of waste plastics (post-consumer and post-industrial) and Repla™.

Table 1 Literature review on recycling of plastic waste

Type of recycling (mechanical, chemical, thermal)	Materials or scenarios considered	Ref.
Mechanical	Mixed waste plastic (polyethylene, polypropylene, polystyrene, polyvinyl chloride, polyethylene terephthalate)	31
	Mixed waste plastic (polyethylene, polypropylene)	14
	Plastic film, recycling, landfill disposal, and incineration	24
	Polyethylene terephthalate	32
	Polyethylene (film)	15
	High density polyethylene	13
	High density polyethylene, polyethylene terephthalate	17
Mechanical, thermal	Printed plastic waste, incineration	26
	Polyethylene, incineration	27
	Polyethylene terephthalate	33
Mechanical, chemical	Polypropylene rigid, polystyrene rigid, mixed polyolefins rigid, polyethylene films	34

films offers clear advantages over landfilling or incineration by reducing impacts though virgin material substitutions;[24] and process steps such as washing and the choice of waste treatment scenarios critically influence the overall environmental performance of recycling.[15] However, none of these studies consider the possibility of avoiding the decontamination process. Despite the general perception of post-industrial plastic waste as homogeneous and uncontaminated, and thus expected to have evident environmental benefits,[25,26] only a few attempts have been found to assess the environmental impact of its recycling. Huysman *et al.*[27] studied post-industrial polyethylene but did not specify whether the decontamination process would be carried out. Horodytska *et al.*[26] concluded (unsurprisingly) that post-industrial waste recycling without decontamination has a lower environmental impact compared to recycling with decontamination, but they did not include a comparison with other alternatives, such as bio plastic. Our study aims to fill this gap by conducting an LCA of the mechanical recycling of uncontaminated post-industrial waste plastic (hereafter Repla™), comparing its environmental performance to virgin polyethylene and bio-based polyethylene in the specific context of a real case study in Japan (where both of these types of material substitutions are being encouraged by the government). Repla™ is mechanically recycled material from off-cut sheets of polyethylene-polystyrene type polymer sheets with mixes at a ratio of 97 : 3 (PE : PS), which were originally used as semiconductor cover tape. It is off-cut or scrap waste sourced directly from factories producing or utilizing the original material, implying (and verified) that it is not significantly contaminated. The material is disposed of by an actual factory in Japan and would otherwise be combusted with some potential for heat recovery in the factory. According to the factories, the film is composed of a multi-layered structure which is a composite of PE and PS typically. Although the film consists of multiple layers of different plastics, for the sake of calculation, we assume that it includes only polyethylene. This is because the polystyrene content is approximately 3%, a proportion deemed environmentally insignificant in the context of LCA and functionally acceptable in the final products examined (plastic bags). Furthermore, while bio-based polyethylene exists and is available for comparison, there is currently limited information on bio-based polystyrene, rendering a meaningful comparison infeasible. As mentioned earlier, Japan incinerates over 60% of its plastic waste. Utilizing these materials as raw materials for new plastic bags instead of incineration can help reduce Japan's incineration rates.

In this study, we assessed the environmental impacts of Repla™, comparing its production to that of conventional polyethylene (Virgin-PE) and bio-polyethylene (Bio-PE). Furthermore, we examined the environmental impacts of producing plastic bags using these materials. Our findings indicate that Repla™ which is formed from uncontaminated post-industrial waste plastic is more environmentally friendly than the other alternatives on many environmental indicators. The environmental superiority of the Repla™ over Bio-PE is notably innovative. Furthermore, this research highlights the importance of recycling as an environmentally responsible approach to plastic production. By recycling, the environmental impacts typically associated with the production of Virgin-PE were prevented. Therefore, this research underscores the pressing need for a transition towards a circular economy that prioritizes recycling and resource efficiency. In doing so, it provides valuable insights into how green chemistry can be applied to the design and production of more sustainable materials, ultimately contributing to a greener and more circular global economy.

Japan has outlined a roadmap aiming to introduce up to 2 million tons of bioplastics across various industries by 2030 to promote sustainable plastic usage.[28] This initiative encourages plastic-manufacturing companies to transition to bioplastics and provides subsidies to successful adopters.[29] However, this research presents a recycling method that can be capable of utilizing materials with lower environmental impacts than bioplastics. Specifically, this study demonstrates that recycling post-industrial polyethylene, which is typically incinerated in Japan, can be environmentally advantageous over other plastics. This is the first study to practically analyze uncontaminated post-industrial polyethylene recycling in Japan. This provides both a scientific novelty and a practical contribution that can inform future strategies in Japan's plastic industry and government policy.

Methodology

This study conducted an LCA following the standardized procedures from ISO 14044 (ISO, 2006[30]). LCA, as a tool, enables the quantitative analysis of environmental impacts by considering the amounts of substances input and output throughout the life cycle of a product. It is widely recognized and commonly used for several reasons. Firstly, it allows for simultaneous analysis of various impact categories, unlike other environmental assessment tools such as carbon footprints or water footprints (which are in some cases limited scope LCA).

Secondly, LCA considers the lifecycle of the material, product or process, aiming to ensure that the burdens are considered holistically without burden shifting across lifecycle stages. Thirdly, it is advantageous to identify processes of heightened environmental impact within the product lifecycle, as this facilitates scenario analysis for utilizing substitutes to change those processes. LCA includes such characteristics, therefore it has been employed to conduct comparative analyses of the environmental impacts between Repla™ and its substitutes. The process of LCA consists of four main steps: (1) definition of goal and scope, (2) inventory analysis, (3) impact assessment, and (4) interpretation of the results.

The following sections provide a detailed description of each stage (interpretation is left till later in the paper).

Goals, scope and system boundary

The objective of this research is to assess the environmental impacts of distinct three polyethylene feedstocks and their utilization in production of plastic bags. Therefore, the research scope encompasses feedstock sourcing, transportation, processing, and production. Two functional units are defined since this study investigates the environmental impacts of two sequential stages which are plastic pellet production and plastic shopping bag production. Hence, the functional units will be one ton (1 t) of plastic pellets and one ton (1 t) of plastic shopping bags. Because the plastic shopping bags are not commonly recycled due to quality restrictions for the next product cycle, this study undertook a "cradle-to-gate" assessment which do not consider the end-of-life stage of a product. The system boundaries are shown in Fig. 2 for the three material streams considered here.

It must be noted that each of the substitute materials is considered as a maximum 50% mixture with virgin plastic. The recycled material, Repla™, must be mixed with other materials when converted into an end product to ensure the quality of the final product. ISO 15270 recommends a maximum 25% of recycled plastics to maintain the mechanical properties of the plastic product.[35] Plastic bags (the end-product in this paper) are required to have good mechanical performance, with holding capacity, elongation, and tear resistance the most important characteristics.[36] A study found that mechanical properties of a high-density polyethylene (HDPE) and low-density polyethylene (LDPE) plastic product varies with different mixing ratio of recycled plastics. The relative elongation of HDPE and LDPE products sharply decreases as recycled plastic ratio increases up to 50% but then relatively stabilizes beyond this ratio.[37] To verify whether higher mixes may be possible, we conducted mechanical property tests to assess the suitability of various mixing ratios of Virgin-PE and Repla™ for plastic bag production. Specifically, we examined the sealing strength (N [kgf]), representing the maximum load when the heat-sealed portion is peeled off, and the tensile strength (MPa) required to reach the point of material failure. When Repla™ and Virgin-PE were mixed at a ratio of 87 : 23, both the sealing strength and the tensile strength were inadequate for utilization as plastic bags (see Table S1 in SI). Therefore, the ratio of Repla™ was reduced, resulting in blends of 60 : 40 and 40 : 60 with Virgin-PE, both of which passed the standards Consequently, a realistic blending ratio of 50 : 50 was adopted. From an economic standpoint, in Japan, the provision of plastic bags free of charge is legally prohibited, but if the bags contain 25% or more of bio-based materials, free provision is permitted.[38] This has led to high demand however, at present, the raw material procurement cost of Bio-PE is approximately 1.8 to 2 times higher than that

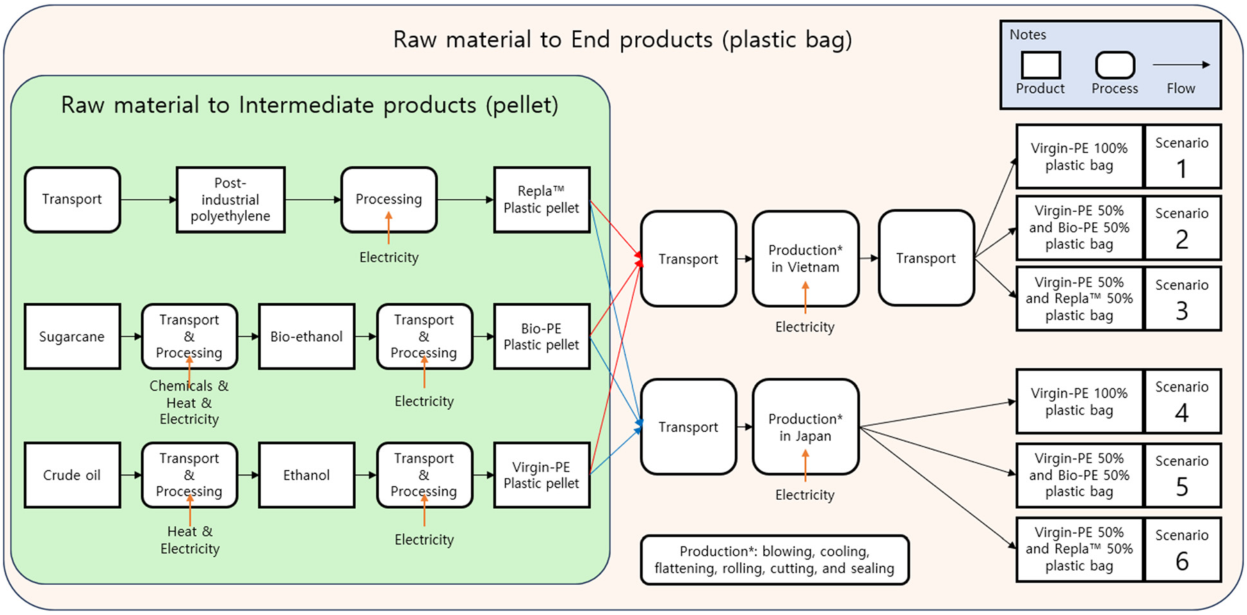

Fig. 2 System Boundary of this study encompasses from raw material to end-product production (cradle-to-gate).

of Virgin-PE,[39] posing a cost issue for manufacturers. To facilitate a more intuitive comparison with Repla™, the same 50 : 50 ratio was employed. As a result, scenarios 1 and 4, utilizing only Virgin-PE, were set as control groups. Scenarios 2 and 5 represented the use of a 50 : 50 mix of Virgin-PE and Bio-PE, while scenarios 3 and 6 involved a 50 : 50 blend of Virgin-PE and Repla™. These selections were based on comprehensive considerations of the mechanical properties of the final product, Japanese policies, and cost factors mentioned above.

Two production locations were also investigated: in Japan and in Vietnam. Japan is the consumer country considered in this study, and the source of the recycled material, as the company is currently based in Japan. However, Japanese plastic bags are often sourced outside of the country – in this case, Vietnam is a typical producer, and one anticipated for potential consideration by companies in Japan using Repla™. The selection of the plastic production sites, and the input material production sites is therefore not arbitrary, as it reflects the reality of the specific case study context. However, the results can be adapted to alternative production sites and transport routes with relatively minimal effort.

Inventory analysis

In this study, three different feedstocks are considered, each sourced through distinct processes. Firstly, Repla™ originates from an actual factory in Japan as a post-industrial mainly-polyethylene waste and is transported to domestic processing facilities. Following transportation, it undergoes mechanical recycling including processes cutting, extrusion, cooling, and packing. Because it is not extensively contaminated, the process of decontamination (washing) is not necessary, although some minor contaminants are removed during the recycling process. The inventory analysis for the Repla™ was conducted iteratively by visiting the facility and measuring inputs and outputs directly. It should be noted that, as the feedstock for Repla™ was a waste stream (destined for disposal or incineration), only the environmental burdens associated with the transport and treatment after it leaves the source factory are considered. The second feedstock Bio-PE is produced from sugarcane in Brazil. It undergoes fermentation to obtain bio-ethanol, which is then processed and combined to bio-polyethylene.[40] This material is produced in Brazil and imported to Japan or Vietnam to produce plastic bags. The inventory analysis data for Bio-PE was referenced from relevant studies.[23] The third feedstock, Virgin-PE, is derived from petroleum and ecoinvent database[41] was utilized to source its inventory. All data was compiled in SimaPro software (SimaPro version 9.5.0.0, ecoinvent database version 3.9.1 released in 2023). Tables 2, 3, and 4 show the inventory data for Repla™, Bio-PE and Virgin-PE respectively.

These inventory data were utilized to first calculate the impact of the production of the intermediary product of plastic pellets. Subsequently, six different scenarios were derived, each involving varying proportions of feedstocks and production locations. Scenarios 1, 2, and 3 consider production in Vietnam, while scenarios 4, 5, and 6 consider production in Japan. Regarding mix ratio, scenarios 1 and 4 use 100% of Virgin-PE. Scenarios 2 and 5 mix Virgin-PE 50% with Bio-PE 50%. Lastly, scenarios 3 and 6 combine Virgin-PE 50% with Repla™ 50%. These distinct configurations in terms of locations and mixing ratios are designed to clarify the differences of environmental impacts under expected alternative supply chains. It should be noted that the ratio of 50% of non-Virgin-PE was taken as an upper limit due to existing

Table 2 Inventory analysis data of Repla™[a]

Flows	Amount	Unit	Ref.
Output			
Repla™	1000	kg	—
Inputs			
Post-industrial waste polyethylene plastics	1000	kg	Measured
Textile, nonwoven polypropylene {GLO[b]}| for ESA case | cut-off, S[c] (for packaging)	1.99	kg	Measured
Steel, chromium steel 18/8 {GLO}| for ESA case | cut-off, S	0.06	kg	Measured
Electricity, medium voltage {JP[b]}| market[d] for electricity, medium voltage | cut-off, S (for processing of shredder and extruder)	505	kWh	Measured
Transport, freight, lorry, unspecified {RoW[b]}| transport, freight, lorry, all sizes, EURO6 to generic market for transport, freight, lorry, unspecified | cut-off, S (from the source factory to the processing facility)	90	tkm[e]	Measured
Emissions			
NMVOC, non-methane volatile organic compounds, JP	0.005	kg	Assumed
Plastics, macro, terrestrial	0.005	kg	Assumed
Wastes			
Scrap steel {RoW}| market for scrap steel | cut-off, S	0.06	kg	Measured

[a] Inventory analysis data of Repla™ was directly measured by the authors and esa Inc. [b] GLO is a global market dataset that represents products traded on a global scale, assuming one worldwide average supply mix; RoW is a regional market dataset that covers all countries except those explicitly modeled with their own datasets. For example, if Europe, the US, and Japan have specific markets, all other regions are grouped under RoW; JP means Japan. [c] Cut-off, S[43] means allocation, cut-off by classification (system process). This is the standard cut-off model in ecoinvent, provided as aggregated datasets (system processes). In this model, the burdens from producing a material end at the point of discard (cut-off), and secondary materials enter the next product system without carrying upstream burdens. [d] Market[42] means a market dataset which represents the average consumption mix of a product in a given region, including domestic production, imports from other regions, average transport distances, and product losses during distribution. A market dataset does not transform a product but serves as a bridge between producing and consuming activities. [e] tkm (tonne-kilometers) is a unit used to quantify the amount of cargo moved and the distance it travels in logistics and transportation.

targets and guidelines and performance characteristics of the product.

Impact assessment

The ReCiPe method (specifically ReCiPe 2016, Midpoint (H) v1.1) is used for impact assessment in this study, as one of the major impact assessment methods. Impact assessment in LCA can be categorized into midpoint and endpoint, where the former provides a specific environmental concern while the latter provides an aggregated impact on the three areas of protection, namely human health, ecosystem quality, and resource scarcity.[44] In this work we conducted midpoint and endpoint impact assessments to provide better relevancy for decision makers.[45]

Table 3 Inventory analysis data of Bio-PE

Flows	Amount	Unit	Ref.
Output			
Bio-PE	1000	kg	23
Inputs			
Water, unspecified natural origin, BR[a]	1000	kg	23
Ethanol, without water, in 95% solution state, from fermentation {BR}| market for ethanol, without water, in 95% solution state, from fermentation | cut-off, S	1740	kg	23
Sodium {GLO}| market for sodium | cut-off, S	2.9	kg	23
Hexane {GLO}| market for hexane | cut-off, S	19	kg	23
Butene, mixed {RoW}| market for butene, mixed | cut-off, S	44	kg	23
Electricity, high voltage {BR}| market group for electricity, high voltage | cut-off, S	390	kWh	23
Diesel {BR}| market for diesel | cut-off, S	2540	kg	23
Transport, freight, lorry 3.5–7.5 metric ton, EURO3 {BR}| market for transport, freight, lorry 3.5–7.5 metric ton, EURO3 | cut-off, S	139.81	tkm	23
Emissions			
Methane, air	0.7	kg	23
Hydrogen, air	0.31	kg	23
Nitrogen, total, air	42.5	kg	23
Acetaldehyde, water	2.61	kg	23
Butadiene, water	4.83	kg	23
Ethylene oxide, water	63.7	kg	23
Ethanol	31.9	kg	23
Sodium compounds, unspecified	4.34	kg	23
Water	1680	kg	23

[a] BR means Brazil.

Table 4 Inventory analysis data of the Virgin-PE[a]

Flows	Amount	Unit	Ref.
Output			
Virgin-PE	1000	kg	41
Inputs			
Crude oil	982.71	kg	41
Water	3587.41	m^3	41
Natural gas	653.65	m^3	41
Shale	615.81	kg	41
Coal	323.6	kg	41
Gangue	166.97	kg	41
Electricity	698.16	kWh	41
Emissions			
Radon-222, air	36.74	MBq[b]	41
Carbon dioxide, air	1935.73	kg	41
Hydrogen-3, water	1.04	MBq	41
Water	3559.01	m^3	41

[a] Inventory analysis data for virgin-PE is taken from the ecoinvent database.[41] Market data was used to include impacts for the associated transportation within the respective country or region, where specific transport routes are not known. [b] MBq (Mega Becquerels) is a unit of measurement used in radioactivity to quantify the rate of radioactive decay in a substance.

The results of our LCA calculations across all midpoint categories are presented in Fig. 3. While the subsequent analysis was undertaken for all categories, we have used three impact categories or indicators in this paper to demonstrate both the impacts of the feedstocks and the plastic bag production: Global warming (GW), fossil resources scarcity, and human

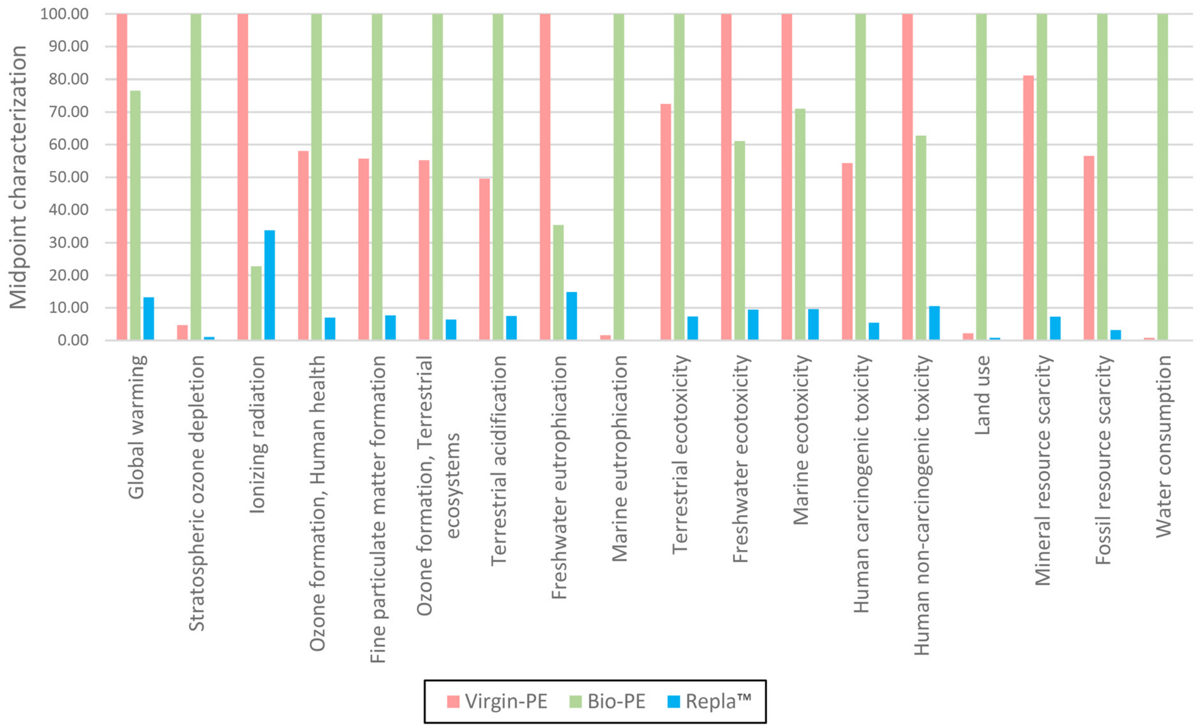

Fig. 3 Midpoint characterization comparisons of plastic pellets.

carcinogenic toxicity. These categories were chosen with the intention to illustrate the results, while the full category results are presented in the SI. Global warming was selected because climate change is perhaps the most pressing global environmental issue and requires urgent attention across all sectors. Human carcinogenic toxicity was included because it provides a direct and tangible measure of potential impacts on human health. Cancer is the second leading cause of death, according to the American Cancer Society.[46] Furthermore, it has a higher weighting factor than human non-carcinogenic toxicity to disability adjusted life-years (DALY) in the ReCiPe[44] method. Finally, fossil resource scarcity was chosen due to the fossil-based nature of the plastics studied, making this impact category highly relevant for assessing potential resource savings from using recycled materials instead of Virgin-PE. Midpoint categories were chosen for the main comparison due to the higher level of scientific agreement and certainty on midpoint modelling, but endpoints are also provided for comparison.

Results

The results are presented on the basis of each functional unit: pellets and end-product plastic bags. We compare Bio-PE and Virgin-PE with Repla™ at the pellet level. Each feedstock's characterized and normalized impacts were compared for each level using ReCiPe Midpoint.[44] The endpoint impacts were also investigated. We primarily focus on three impact categories: GW, human carcinogenic toxicity, and fossil resource scarcity, among the various impact categories that can be analyzed using the ReCiPe method. GW is assessed by quantifying the emissions of greenhouse gases and converting them into CO_2-eq. Human carcinogenic toxicity is assessed by calculating the emissions of carcinogenic substances as equivalents of 1,4-dichlorobenzene (1,4-DCB). Fossil resource scarcity is assessed using oil eq. and considers the consumption of limited fossil resources such as oil, coal and natural gas.

At the pellet level

Midpoint characterization results show that Repla™ performed well compared to other feedstocks, as seen in Fig. 4

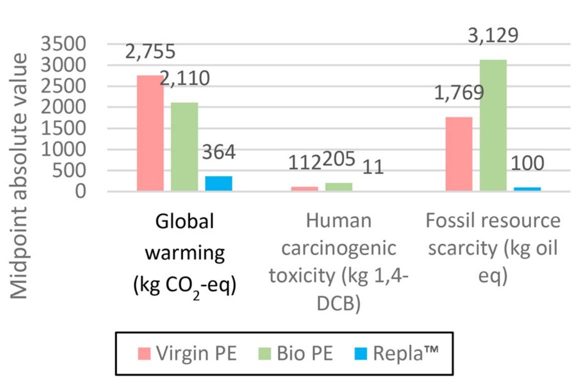

Fig. 4 Midpoint characterization impact assessment of plastic pellets on the selected indicators (absolute value).

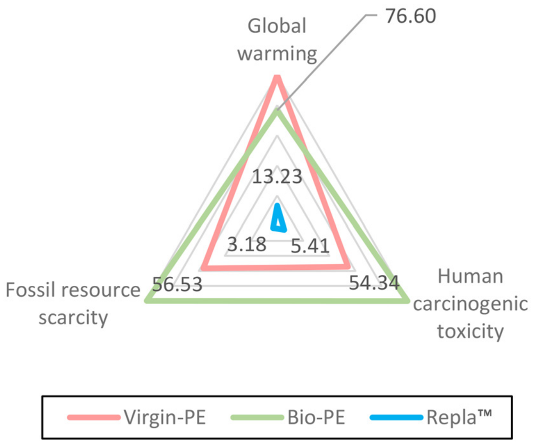

Fig. 5 Midpoint characterization impact assessment of plastic pellets on the selected indicators (normalized value).

and 5 which shows the absolute values and normalized values, respectively. It is shown that the GW of Repla™ is noticeably lower with only 364 kg CO_2-eq. per 1 ton of Repla™ where 94% of it is attributed to its electricity use. On the other hand, the emissions were 2110 kg CO_2-eq. and 2755 kg CO_2-eq. for Bio-PE and Virgin-PE, respectively. Accounting for the biogenic carbon from ethanol production would only reduce Bio-PE equivalent carbon emissions to 1977 kg CO_2-eq. This suggests that Repla™ has approximately 87% lower GW compared to Virgin-PE and 82% or 83% lower than Bio-PE depending on whether biogenic carbon is included. Normalized to the maximum emission, where the maximum is 100, then the Virgin-PE's GW is 100, followed by Bio-PE 76.6, and Repla™ 13.23. Repla™'s low equivalent carbon dioxide emission is due to its use of post-industrial waste plastics as feedstock which only involves the collection from industries, while Bio-PE is produced from sugarcane and Virgin-PE from crude oil, both relying on carbon-intensive processes of production. Bio-PE production involves the use of 2.54 kg of diesel for each kilogram of Bio-PE as shown in Table 3, while Virgin-PE uses crude oil, and coal intensively as shown in Table 4. This use of fossil fuels is a significant contributor to some of the key impact categories, and we have considered a number of alternatives to reduce these. Electricity use was found to be the dominant contributor to all the environmental impact categories for Repla™. Process contributions are provided in Fig. S1 of the SI.

For human carcinogenic toxicity, Repla™ emits 11 kg 1,4-DCB eq., while Bio-PE emits 205 kg 1,4-DCB eq. and Virgin-PE emits 112 kg 1,4-DCB eq. In normalized terms, the Virgin-PE's human carcinogenic toxicity is 54.34, Bio-PE 100, and Repla™ 5.41. Thus, Repla™ exhibits significantly lower human carcinogenic toxicity compared to both Bio-PE and Virgin-PE, owing to its low resource consumption. In the case of Bio-PE, for example, half of its 1,4-DCB eq. emissions come from the production of its bioethanol while the quarter comes from the heat fuel in the pellet production. An interesting result can be seen when comparing Bio-PE and Virgin-PE, where the consumption of fossil resources was actually higher in Bio-PE due to its use of intensive use of diesel (2.54 kg diesel per kg of Bio-PE) in the pellet production as informed in Table 3. Bio-PE consumes 3129 kg oil eq., Repla™ consumes only around 100 kg oil eq., and Virgin-PE consumes 1769 kg oil eq. From normalized point of view, Bio-PE's fossil resource scarcity is 100, followed by Virgin-PE is 56.53, and Repla™ is 3.18.

As shown in Fig. 5, the midpoint results indicate that Virgin-PE has the highest impact on global warming, while Bio-PE exhibits the highest burdens in fossil resource scarcity and human carcinogenic toxicity. However, when these midpoints are extended and aggregated to the endpoint level in Fig. 6, Bio-PE consistently shows the highest impacts across all three areas of protection—human health, resources, and ecosystems.

At the end-product level

The result of the six scenarios is shown in Fig. 7. And Fig. 8 shows the impact of changing the material mix. For consistency, we show the effect of changing material mix when the production is undertaken in Vietnam.

From the material mix comparison shown in Fig. 8, it can be clearly seen that the 50 : 50 Repla™ and Virgin-PE mix yield better results compared to the 50 : 50 Virgin-PE and Bio-PE mix. The reason for this is that the Bio-PE used as the reference uses a large amount of diesel in its production.[23] For example, 83% of the GW and 94% of the fossil resource scarcity impact in the Bio-PE production is due to this fossil fuel use as shown in Fig. S1 in SI. The impact of production location changes is less obvious as can be seen in Fig. 7. The GW and fossil resource scarcity impacts were actually a little higher when the production was done in Vietnam, which indicates the sea transportation emissions are bigger than the power mix emission gap. The overall production in Japan will have a lower environmental impact compared to Vietnam as can be seen in the SI. For example, Japan's power mix has a lower ozone formation and fine particulate matter emission, but higher ionizing radiation compared to Vietnam's.

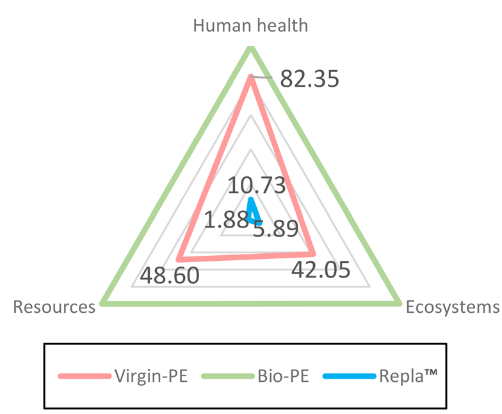

Fig. 6 Endpoint impact assessment of plastic pellets on the selected indicators (normalized value).

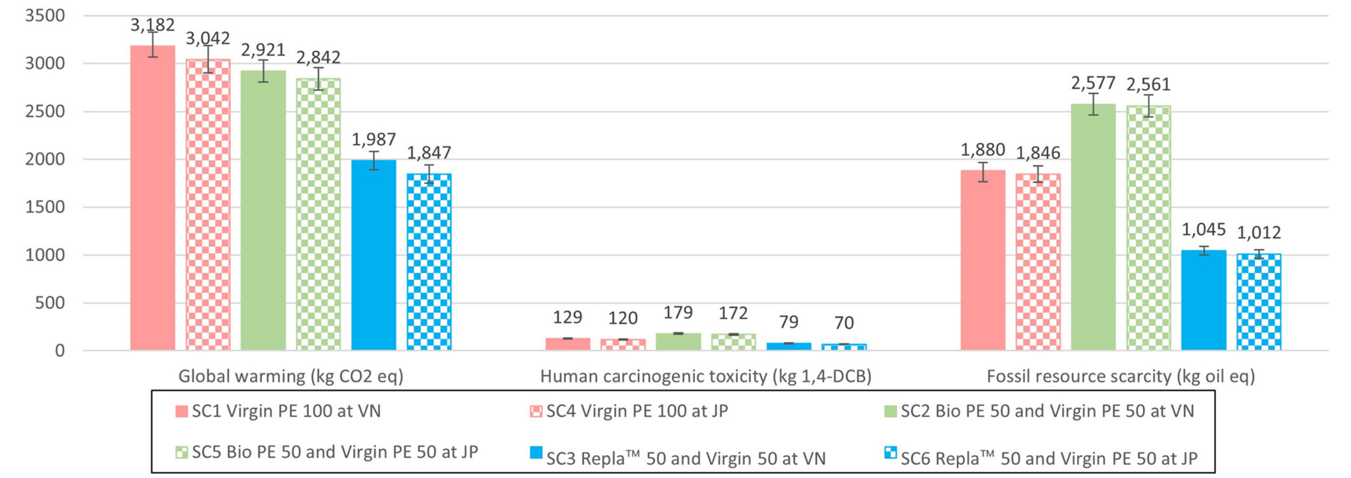

Fig. 7 Effect of changing production location on the selected indicators for different material mix with error bar from Monte Carlo analysis.

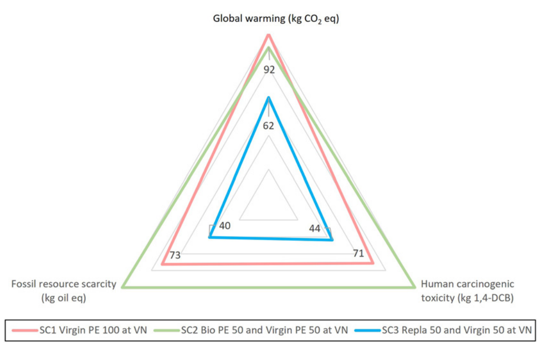

Fig. 8 The effect of changing material mix on the selected midpoint indicators.

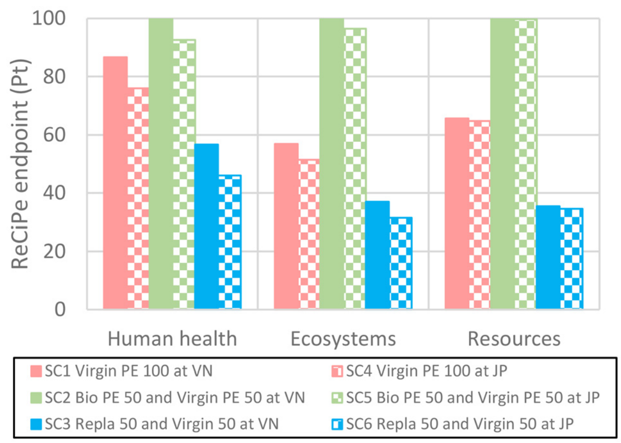

Fig. 9 Endpoint impact assessment of plastic bags.

Furthermore, our results show that although production location may induce a small environmental impact, the material mix would ultimately determine the environmental impact. Scenario 6 – production of plastic bags in Japan using 50 : 50 mix Repla™ and Virgin-PE results in the overall lowest environmental, human health, and resources impact as shown in Fig. 9. A deeper understanding can be gained by referring Fig. 10 which illustrates the transition from scenario 1 and 2 to scenario 6. When mixing 50% of Repla™ to Virgin-PE and changing the production location from Vietnam to Japan, 42% reduction of CO_2-eq. in total from 3182 kg CO_2-eq. to 1847 kg CO_2-eq. is observed. In terms of human carcinogenic toxicity, the emissions of 1,4-DCB eq. decrease approximately 61%, from 181 kg 1,4-DCB eq. to 70 kg 1,4-DCB eq. Regarding fossil resource scarcity, the consumption of oil eq. decreases 61%, from 2586 kg oil eq. to 1011 kg oil eq., almost halving the resource utilization. Fig. 9 emphasizes that, at the product stage, the inclusion of a Repla™ consistently leads to lower scores across all three endpoint areas of protection.

Uncertainty analysis

To ensure that the comparative results across the six scenarios (SC1–SC6) are not biased by deterministic assumptions, an uncertainty analysis was performed using Monte Carlo simulation in SimaPro. A total of 10 000 iterations were conducted for each scenario, which allowed for the propagation of parameter uncertainties through the entire life cycle model.

The choice of probability distributions and parameters was guided by standard practices[47] in life cycle uncertainty analysis. For all input flows, uncertainties were parameterized using the pedigree matrix approach and distribution was set as lognormal. This method quantifies data quality along five dimensions; reliability, completeness, temporal correlation, geographical correlation, and further technological correlation; and assigns a flow-specific uncertainties. The resulting uncertainties ranged from approximately 1.05 to 1.24 (Table S9). These flow-level uncertainties were propagated

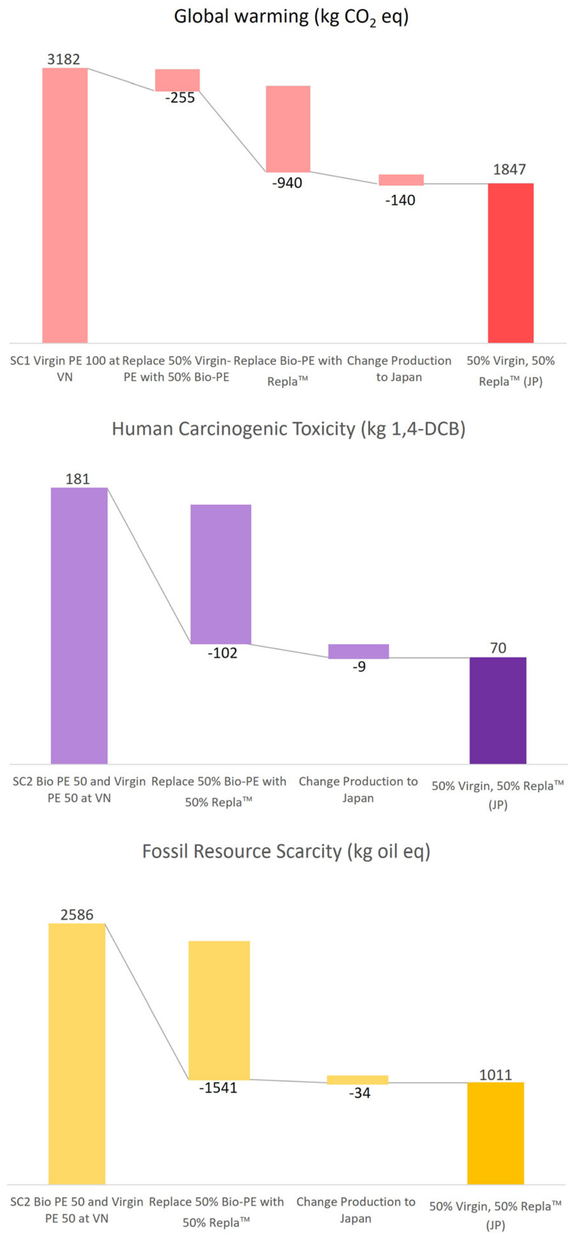

Fig. 10 Impacts of changing material mix and production location on selected indicators.

through the Monte Carlo simulations, resulting in scenario-level output distributions whose spread reflects the combined influence of all contributing inputs.

As can be seen in Fig. S2, illustrating the overall probability distributions of the six scenarios, four scenarios (SC1, SC2, SC4, and SC5) form a higher impact cluster, whereas SC3 (Repla™ 50% and Virgin PE 50% at VN) and SC6 (Repla™ 50% and Virgin PE 50% at JP) constitute a distinctly lower impact cluster, with no overlap between them. This indicates that even after accounting for input uncertainties, the separation between the lower impact cluster and higher impact cluster remains statistically robust.

The Monte Carlo results are reported as mean values accompanied by 95% confidence intervals in the Table 5 and the Fig. 7. This statistical framing is crucial because it enables an assessment of whether differences among scenarios are significant rather than coincidental.

Another noteworthy finding is that while the absolute values of the impacts shifted slightly when expressed as ranges instead of point estimates, the deterministic results presented earlier in this study were always located within the Monte Carlo confidence intervals. This consistency provides reassurance that the previously reported trends were not artefacts of fixed parameter assumptions but rather reflect robust underlying differences in the modelled systems.

In summary, the incorporation of uncertainty analysis strengthens the validity of the conclusions drawn from the scenario comparison. By explicitly quantifying the range of possible outcomes and demonstrating the statistical robustness of the results, the study provides decision-makers with greater confidence in prioritizing recycling-oriented pathways over virgin-material-dominated options.

Alternative materials and their trade-offs

The three selected impacts were used for indicative comparison between the three alternative materials – Repla™, bio-PE and virgin-PE – however, the full set of midpoint categories can be seen in Fig. S3. Of the 18 categories for environmental impact, all showed Repla™ as the lowest impact, and in 12 of those categories the bio-PE was the highest impact, while in the remaining 6 it was virgin PE that was the worst. For the two categories of human health impact, carcinogenic toxicity impact was bio-PE > Virgin-PE > Repla™, while for the non-carcinogenic toxicity order was Virgin-PE > bio-PE > Repla™. Four categories of resource use the order was bio-PE > Virgin-PE > Repla™. Thus, in all cases, it was preferable to use

Table 5 Uncertainty analysis (Monte Carlo simulation) results

Scenario	Mean	Low (2.5%)	High (97.5%)	Standard deviation
Global warming (kg CO_2-eq.)				
SC1	3182	3042	3330	74
SC2	2921	2810	3034	58
SC3	1987	1894	2083	48
SC4	3042	2901	3185	72
SC5	2842	2731	2958	58
SC6	1847	1754	1944	49
Human carcinogenic toxicity (kg 1,4-DCB)				
SC1	129	124	135	3
SC2	179	171	186	4
SC3	79	75	83	2
SC4	120	114	125	3
SC5	172	165	180	4
SC6	70	66	73	2
Fossil resource scarcity (kg oil eq.)				
SC1	1880	1797	1966	44
SC2	2577	2466	2690	57
SC3	1045	1001	1090	23
SC4	1846	1762	1932	43
SC5	2561	2450	2676	58
SC6	1012	966	1058	24

Repla™ as much as possible. However, with the mix of recycled material limited to 50%, then the final 50% could potentially be made-up of bio-PE if the material was found to have sufficient mechanical properties. In this case, there is a trade-off of impacts between global warming, ionizing radiation, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity and human non carcinogenic toxicity (total 6 categories) for which virgin-PE is the worst, and the remaining 12 categories for which bio-PE is the worst. Even with further actions being taken to improve bio-PE, then these trade-offs will likely persist, although they may be improved in favour of bio-PE potentially. Most of the policy around plastic recycling and replacement is associated with global warming mitigation and resource intensity reduction or resources security, so the scenarios of bio-PE produced with bagasse or waste plastic substituted for the diesel used in the production process are the only tested alternatives that would make bio-PE preferable to virgin material as the remaining 50% mixed with Repla™.

Scenario analysis

As mentioned earlier, most of the impacts of Repla™ production is attributed to the electricity consumption. The impact could be further reduced by using less fossil-based electricity. Japan's power mix in 2030 is planned to be made up of 36–38% renewables, nuclear 20–22%, natural gas 20%, coal 19%, and oil 2%.[48] To compare this potential future mix, the proportion of fossil-based energy was reduced from the mix used in the ecoinvent database (69%), which was based on the 2018 level, to 56%. The 2030 planned power mix which entails doubling the renewable – largely solar and wind – proportion from the 2020 level, is reasonable if reflecting the increase from 1.5% in 2016 to 3.1% in 2020.[49]

The planned power mix in 2030 was used and a significant reduction on human health was found around 39%, followed by resources impacts by 47%. Additionally, the larger renewables in the power mix led to a 42% lower ecosystem impact as shown in Fig. 12. Of course, the impact of energy production from a fully renewable mix could be expected to even-further enhance the environmental benefit of Repla™ usage, as most impacts across all categories are associated with electricity consumption in this process. As such, we simulate the impact of Repla™ production by using 100% renewable energy from solar and found that indeed all impacts were reduced. In this case, resources benefited the most since the impact was reduced by 79%, followed by human health impact 71%, and ecosystem impact 70%.

The use of diesel in production was the main reason for the high impacts of Bio-PE production in all indicators. For this reason, we consider the effects of changing the use of diesel to natural gas which is typically a cleaner fuel in combustion. Our results show that the replacement could indeed reduce the negative impacts of the Bio-PE production on global warming. The effect on global warming was found that it was reduced by 1%, however the impact on resources and the effect on ecosystems increased 6% and 14% respectively. We also explored the use of waste as substitutes for diesel. In this case, the use of bagasse combustion and plastic waste incineration. Usage of waste was found to significantly reduce resources impact by 94%. The effects on human health

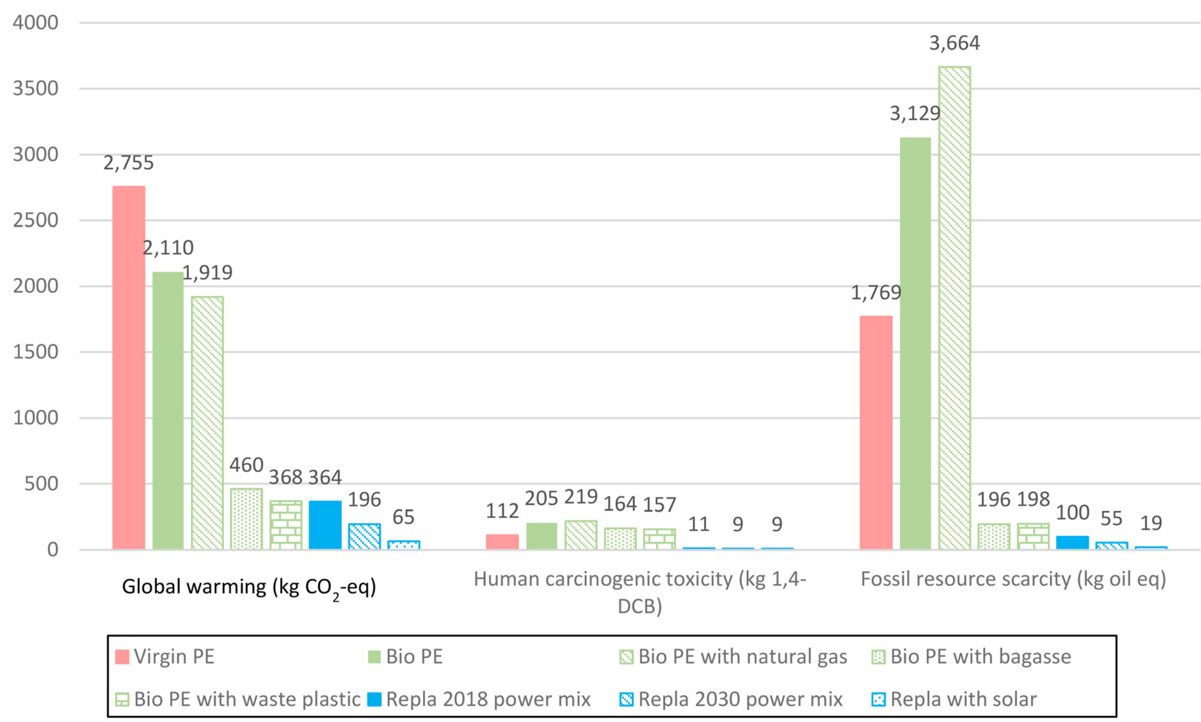

Fig. 11 Midpoint impact analysis of pellets with higher renewables.

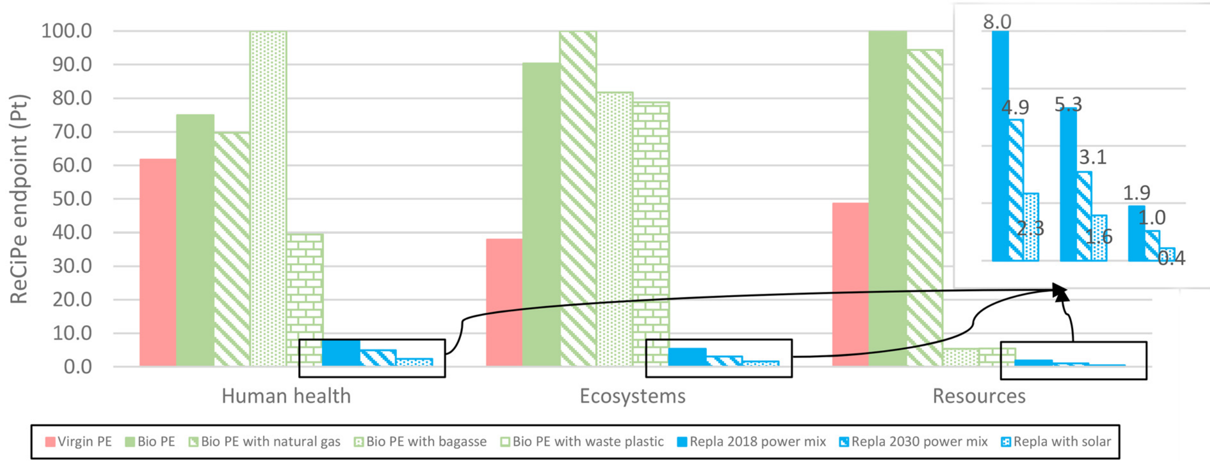

Fig. 12 Endpoint impact analysis of pellets with higher renewables.

decreased 20% and global warming was reduced 81%. Thus, using bagasse and plastic waste could be a good alternative in reducing the selected indicators which are global warming, human carcinogenic toxicity, and fossil resource scarcity in Bio-PE as shown in Fig. 11 and 12.

The end point comparison is shown in Fig. 12 between the alternatives shows a better illustration on the overall impacts on the ecosystem, human health, and resources which indicates that Repla™ is still showing better results compare to others.

Comparison with previous studies

Our results, particularly regarding global warming, were compared to previous studies. According to Choi *et al.*,[50] the carbon footprint of packaging film made from LDPE (low density polyethylene) and its recycling process was calculated as 6820 kg CO_2-eq. for their functional unit. This is approximately 4108 kg CO_2-eq. per 1 ton using our functional unit. Additionally, according to Ahamed *et al.*,[51] HDPE plastic bag had 2935 kg CO_2-eq. per 1 ton production. Both results are close to our scenario 1 result. Furthermore, Lewis *et al.*[52] analyzed the global warming of an HDPE plastic bag with recycled content as 1837 kg CO_2-eq. per 1 ton which is similar to our scenario 3 result. Lastly, Suarez *et al.*[23] analyzed the GW of 1 kg high density bio polyethylene as 1.73 kg eq. which is benchmark to our scenario 2, although our study did not use pure Bio-PE. Each result from distinct studies is compared with our analysis scenario(s) and summarized in Table 6. These comparisons indicate that our findings are not extremely different from other studies, although it is clear that there are a range of results in previous work. Some of the variation is due to the difference in country (and its energy mix), the difference in mix of recycled/Bio-PE and there is possibly some difference in the assumed production process as well. It should further be noted that we have selected Bio-PE studies, not Bio-PLA studies for comparison, as the final material is most equivalent to other PE options – but there are more studies available that undertake LCA on PLA production.

Conclusions

The recycling of post-industrial plastic waste has the potential to be a solution for the plastic waste issue thanks to its homogeneity and low contamination. However, research on its environmental impact compared to other alternatives is lacking. Therefore, this research aimed to fill a gap in previous investigation regarding the recycling of plastic wastes which do not undergo the decontamination process (post-industrial plastic scrap). To address the gap, a LCA was conducted, comparing it to virgin plastic, and to bio-based plastics which is perceived as sustainable materials. Indeed, we found that recycling post-industrial plastic waste performed better compared to Bio-PE and virgin-PE, in terms of global warming impact, human-carcinogenic toxicity, and fossil resource scarcity. Furthermore, we identified the key contributors to the impacts and strategies to mitigate them.

Conventional virgin-PE, Bio-PE, and Repla™ were compared across the two functional units of the pellet level (intermediate product) and the production of plastic bags (final product) to assess their environmental performance. The LCA results indicated that Repla™ was the best-performing option in terms of global warming, human carcinogenic toxicity and fossil resource scarcity. Specifically, Repla™ emits 87% less CO_2-eq. than Virgin-PE and 83% less than Bio-PE in terms of global warming. In regard to human carcinogenic toxicity, Repla™ makes 90% less 1,4-DCB eq. than Virgin-PE and 95% less than Bio-PE. Regarding fossil resource scarcity, Repla™ consumes 94% less oil eq. than Virgin-PE and 97% less than Bio-PE. It is mainly because Repla™ does not consume crude oil as its raw material. Furthermore, the production of Repla™ needs less energy compared to other feedstocks. Lower electricity consumption compared to virgin-PE and the absence of diesel fuel usage unlike Bio-PE help the Repla™ perform better.

Furthermore, environmental advantages of Repla™ have also been found when it comes to the production context of

Table 6 Comparisons with previous studies

Scenario	Current study GW (kg CO_2-eq. per 1 ton of product)	Benchmark GW (kg CO_2-eq. per 1 ton of product)	Benchmark product	Ref.
Scenario 1 (Virgin-PE)	3128 kg	4108 kg [a]	Packaging film made from LDPE	50
		2935 kg [b]	HPB (HDPE plastic bag)	51
Scenario 2 (Virgin-PE and Bio-PE 50 : 50 mix)	2927 kg	1730 kg [c]	High-density Bio-PE	23
Scenario 3 (Virgin-PE and Repla™ 50 : 50 mix)	1987 kg	1837 kg [d]	HDPE plastic bag with recycled content	52

[a] Original functional unit was 1.66 t (4.15 g × 400 000 pieces), resulting in GW = 6820 kg CO_2-eq. [b] Original functional unit was 6814 t (820 million bag eq.) and the resulting GW was reported to be approximately 20 million kg CO_2-eq. [c] The authors used 1 kg of high-density biopolyethylene as their functional unit. The calculated GW was 1.73 kg CO_2-eq. [d] The authors used approximately 520 pieces (4 kg) of HDPE plastic bag which was the estimated number of bags consumed by a household to carry 70 grocery items home from the supermarket each week for 52 weeks. The resulting GW was reported to be 7.35 kg CO_2-eq.

plastic bags. We compared six distinct production scenarios which vary depending on feedstock mix rates and production location. By changing the production location from Vietnam to Japan, and replacing Bio-PE to Repla™, significant reductions in CO_2-eq. emissions (approximately 42%), 1,4-DCB eq. emissions (61%), and oil eq. consumption (61%) were found. Additionally, we conducted scenario analysis to explore measures for enhancing the utility of the materials considered. The analysis revealed that replacing diesel with natural gas, bagasse, waste incineration for Bio-PE production and substituting power mix sources for Repla™ could further improve their sustainability. Indeed, both switching from diesel to the alternatives for Bio-PE or using 100% renewable electricity for Repla™ is likely to be challenging at a large scale (*i.e.* the scale of the industry), although on a small scale it may be technically achievable. There is a limitation in that it would require significant capital expenditure, which is particularly the case for the 100% renewable electricity case, which may also face technical challenges to maintain reliability.

Overall, the findings indicate that the recycling of post-industrial polyethylene waste without decontamination offers promising environmental advantages over conventional Virgin-PE and Bio-PE. This understanding opens up the possibility of replacing other disposal treatments, such as indiscriminate incineration.

Nevertheless, our study has several limitations. The inventory analysis data for Bio-PE was not directly measured but rather referenced.[23] Similarly, the inventory analysis data for Virgin-PE was sourced from the ecoinvent database.[41] Moreover, when using the ecoinvent database, several data were not region-specific, labeled as GLO (global) or RoW (rest of world), rather than JPN (Japan) or VTN (Vietnam). Additionally, the system boundary was limited to cradle-to-gate, not expanded to cradle-to-grave.

Including solving the above limitations, future work could expand to include mechanical property assessment or economic assessment, not only the environmental impact assessment – following a number of recent plastic recycling LCA studies[53,54] for gauging the efficiency of recycling. Moreover, it is important to extend the analysis beyond just one cycle of recycling for Repla™, exploring its environmental performance over multiple recycling processes to gain more valuable insights of its sustainability, although this would likely only be possible with alternative end-products, as plastic bags are not likely to be a viable recycling feedstock.

Conflicts of interest

Authors affiliated with esa Inc. provided primary data for the current study from direct measurements and estimates of supply chain configurations, technical advice on the process parameters, and provided funding for the LCA evaluation. The LCA was undertaken independently, without influence on the results or evaluation process from the participating companies. The authors declare that they have no other known competing financial interests or personal relationships that have influenced the work reported in this paper.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d5gc02751a.

Acknowledgements

esa Inc. provided funding for the experimental and LCA work undertaken in this study. AK acknowledges support from the MEXT scholarship.

References

1 Intergovernmental Panel On Climate Change, *Climate Change 2021 – The Physical Science Basis: Working Group I*

Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 1st edn, 2023.
2 JPIF, The Japan Plastics Industry Federation Statistics, https://www.jpif.gr.jp/statistics/, (accessed August 14, 2023).
3 S. Kaza, L. C. Yao, P. Bhada-Tata and F. Van Woerden, *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*, World Bank, Washington, DC, 2018; online edn, Open Knowledge Repository, accessed 27 Nov. 2025, https://hdl.handle.net/10986/30317.
4 P. T. Anastas and J. C. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, Oxford, 2000; online edn, Oxford Academic, 31 Oct. 2023.
5 M. D. Tabone, J. J. Cregg, E. J. Beckman and A. E. Landis, *Environ. Sci. Technol.*, 2010, **44**, 8264–8269.
6 P. T. Anastas and R. L. Lankey, *Green Chem.*, 2000, **2**, 289–295.
7 S. M. Al-Salem, P. Lettieri and J. Baeyens, *Waste Manage.*, 2009, **29**, 2625–2643.
8 I. Vollmer, M. J. F. Jenks, M. C. P. Roelands, R. J. White, T. Harmelen, P. Wild, G. P. Laan, F. Meirer, J. T. F. Keurentjes and B. M. Weckhuysen, *Angew. Chem., Int. Ed.*, 2020, **59**, 15402–15423.
9 H. Jeswani, C. Krüger, M. Russ, M. Horlacher, F. Antony, S. Hann and A. Azapagic, *Sci. Total Environ.*, 2021, **769**, 144483.
10 T. Thiounn and R. C. Smith, *J. Polym. Sci.*, 2020, **58**, 1347–1364.
11 R. Tiwari, N. Azad, D. Dutta, B. R. Yadav and S. Kumar, *Sci. Total Environ.*, 2023, **881**, 163433.
12 PWMI, An Introduction to Plastic Recycling in Japan, https://www.pwmi.or.jp/english/, (accessed August 14, 2023).
13 N. Gandhi, N. Farfaras, N.-H. L. Wang and W.-T. Chen, *J. Renewable Mater.*, 2021, **9**, 1463–1483.
14 F. Gu, J. Guo, W. Zhang, P. A. Summers and P. Hall, *Sci. Total Environ.*, 2017, **601–602**, 1192–1207.
15 M. A. Martín-Lara, J. A. Moreno, G. Garcia-Garcia, S. Arjandas and M. Calero, *J. Cleaner Prod.*, 2022, **365**, 132625.
16 G. Suzuki, N. Uchida, L. H. Tuyen, K. Tanaka, H. Matsukami, T. Kunisue, S. Takahashi, P. H. Viet, H. Kuramochi and M. Osako, *Environ. Pollut.*, 2022, **303**, 119114.
17 K. M. Bataineh, *Adv. Civ. Eng. Mater.*, 2020, **2020**, 1–15.
18 J.-G. Rosenboom, R. Langer and G. Traverso, *Nat. Rev. Mater.*, 2022, **7**, 117–137.
19 A. Shafqat, A. Tahir, A. Mahmood, A. B. Tabinda, A. Yasar and A. Pugazhendhi, *Biocatal. Agric. Biotechnol.*, 2020, **27**, 101540.
20 S. Sid, R. S. Mor, A. Kishore and V. S. Sharanagat, *Trends Food Sci. Technol.*, 2021, **115**, 87–104.
21 I. Tsiropoulos, A. P. C. Faaij, L. Lundquist, U. Schenker, J. F. Briois and M. K. Patel, *J. Cleaner Prod.*, 2015, **90**, 114–127.
22 C. Liptow and A.-M. Tillman, *J. Ind. Ecol.*, 2012, **16**, 420–435.
23 A. Suarez, E. Ford, R. Venditti, S. Kelley, D. Saloni and R. Gonzalez, *J. Cleaner Prod.*, 2023, **395**, 136432.
24 P. Hou, Y. Xu, M. Taiebat, C. Lastoskie, S. A. Miller and M. Xu, *J. Cleaner Prod.*, 2018, **201**, 1052–1060.
25 O. Horodytska, F. J. Valdés and A. Fullana, *Waste Manage.*, 2018, **77**, 413–425.
26 O. Horodytska, D. Kiritsis and A. Fullana, *J. Cleaner Prod.*, 2020, **268**, 122138.
27 S. Huysman, J. De Schaepmeester, K. Ragaert, J. Dewulf and S. De Meester, *Resour., Conserv. Recycl.*, 2017, **120**, 46–54.
28 MOE, Ministry of the Environment, Roadmap for Bioplastics Introduction, https://www.env.go.jp/recycle/roadmap_for_bioplastics_introduction.html, (accessed February 9, 2024).
29 MOE, Ministry of the Environment, Subsidies, *etc.* for Recycled Plastics and Bioplastics Business, https://plastic-circulation.env.go.jp/shien/hojokin, (accessed February 9, 2024).
30 International Organization for Standardization (ISO), *ISO 14044:2006, Environmental management—Life cycle assessment—Requirements and guidelines*, Geneva, Switzerland, 2006.
31 E. Sevigné-Itoiz, C. M. Gasol, J. Rieradevall and X. Gabarrell, *Waste Manage.*, 2015, **46**, 557–567.
32 B. Simon, M. B. Amor and R. Földényi, *J. Cleaner Prod.*, 2016, **112**, 238–248.
33 T. Chilton, S. Burnley and S. Nesaratnam, *Resour., Conserv. Recycl.*, 2010, **54**, 1241–1249.
34 D. Civancik-Uslu, T. T. Nhu, B. Van Gorp, U. Kresovic, M. Larrain, P. Billen, K. Ragaert, S. De Meester, J. Dewulf and S. Huysveld, *Resour., Conserv. Recycl.*, 2021, **171**, 105633.
35 D. Bhattacharya and B. Bepari, *Procedia Eng.*, 2014, **97**, 186–196.
36 F. A. Radini, R. Wulandari, S. J. A. Nasiri and D. A. Winarto, *IOP Conf. Ser.: Mater. Sci. Eng.*, 2017, **223**, 012058.
37 A. I. Rezakalla and S. T. Petrovna, *Mater. Plast.*, 2022, **58**, 210–215.
38 METI, Ministry of Economy, Trade and Industry, Plastic shopping bags are charged Starting July 1, 2020, https://www.meti.go.jp/policy/recycle/plasticbag/plasticbag_top.html, (accessed February 14, 2024).
39 MOF, Ministry of Finance, Tariff revision request on Bio-polyethylene, https://www.mof.go.jp/policy/customs_tariff/tariff_reform/fy2022/keisan/index.html, (accessed February 14, 2024).
40 IfBB, Biopolymers – facts and statistics, Institute for Bioplastics and Biocomposites, https://www.ifbb-hannover.de/en/facts-and-statistics.html, (accessed August 18, 2023).
41 G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz and B. Weidema, *Int. J. Life Cycle Assess.*, 2016, **21**, 1218–1230.
42 Market Activities, https://support.ecoinvent.org/market-activities, (accessed September 18, 2025).

43 System Models, https://support.ecoinvent.org/system-models, (accessed September 18, 2025).
44 M. A. J. Huijbregts, Z. J. N. Steinmann, P. M. F. Elshout, G. Stam, F. Verones, M. Vieira, M. Zijp, A. Hollander and R. van Zelm, *Int. J. Life Cycle Assess.*, 2017, **22**, 138–147.
45 J. C. Bare, P. Hofstetter, D. W. Pennington and H. A. U. De Haes, *Int. J. Life Cycle Assess.*, 2000, **5**, 319.
46 The Global Cancer Burden | American Cancer Society, https://www.cancer.org/about-us/our-global-health-work/global-cancer-burden.html, (accessed September 18, 2025).
47 Uncertainties, https://support.ecoinvent.org/uncertainties, (accessed September 18, 2025).
48 METI, Ministry of Economy, Trade and Industry, Japan's Newest "Strategic Energy Plan" toward Carbon Neutrality by 2050, https://www.enecho.meti.go.jp/en/category/special/article/detail_168.html, (accessed September 27, 2023).
49 JEPIC, Japan Electric Power Information Center, INC., The Electric Power Industry in Japan 2023, https://www.jepic.or.jp/en/data/epijpdf.html, (accessed February 9, 2024).
50 B. Choi, S. Yoo and S. Park, *Sustainability*, 2018, **10**, 2369.
51 A. Ahamed, P. Vallam, N. S. Iyer, A. Veksha, J. Bobacka and G. Lisak, *J. Cleaner Prod.*, 2021, **278**, 123956.
52 H. Lewis, K. Verghese and L. Fitzpatrick, *Packag. Technol. Sci.*, 2010, **23**, 145–160.
53 E. U. T. van Velzen, S. Chu, F. A. Chacon, M. T. Brouwer and K. Molenveld, *Packag. Technol. Sci.*, 2021, **34**, 219–228.
54 J. Martínez-Blanco, A. Lehmann, P. Muñoz, A. Antón, M. Traverso, J. Rieradevall and M. Finkbeiner, *J. Cleaner Prod.*, 2014, **69**, 34–48.

