PEF plastic synthesised from industrial carbon dioxide and biowaste

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Abstract:

Polyethylene furandicarboxylate (PEF) is considered as a renewable-based solution to its fossil-based counterpart polyethylene terephthalate (PET). However, due to its lengthy and energy intensive production process, PEF has not been established at a commercial scale. Here we present a novel study on PEF produced from industrial carbon dioxide (CO_2) emissions and non-food derived biomass to provide an alternative for PET. We assess PEF production from an energy consumption, environmental impacts and production cost point of view at an industrial scale using mass and energy balance, life cycle assessment and payback period. The results show that emissions and energy consumption can be reduced up to 40.5% compared to PET. Abiotic Depletion (Fossil) (6.90×10^4 MJ), Global Warming Potential (3.75×10^3 kg CO_2 equivalent) and Human Toxicity Potential (2.18×10^3 kg 1,4 dichlorobenzene equivalent) are the three most significant impacts in producing 1 tonne of PEF. By applying optimal design and mature technology, PEF produced from industrial CO_2 and bio-wastes could be a feasible and competitive substitute to PET and other materials.

Keywords: Biomass, Carbon dioxide, Polyethylene furandicarboxylate, Environmental impact, Production cost, Industrial scale

Both carbon capture and storage (CCS) and carbon capture and utilisation (CCU) technologies aim to reduce atmospheric CO_2 emissions[1,2]. The main difference lies in the destination of captured CO_2—CCS stores CO_2 (underground or in the form of mineral carbonates) whilst CCU utilises CO_2 directly (as a working fluid in producing dry ice, refrigeration *etc.*; a solvent for enhanced oil recovery (EOR); or a feedstock for products indirectly converted from CO_2 *e.g.* feedstocks for urea production)[3-5]. Global Warming Potential (GWP) of CCS is lower than that of CCU from life cycle perspective, 0.276 tonne CO_2 equivalent·tonne^{-1} CO_2 removed compared with 0.495 tonne CO_2 equivalent·tonne^{-1} CO_2 utilised for EOR, for instance[6,7].

Status of PEF production pathways

Industrial production plants represent the third largest source of CO_2 emissions in 2014[8]. There is an increasing interest in shifting raw materials from fossil fuels to bio-based feedstocks, e.g. bio-plastics to reduce greenhouse gas (GHG) emissions[9]. Using biomass and CO_2 as raw materials via carbon fixation for chemicals production is a technically feasible concept. It has a positive influence on CO_2 reduction and carbon-neutral chemicals production[10,11]. Among all plastics, polypropylene carbonate (PPC) and polyethylene terephthalate (PET) are petrochemical-based; polylactic acid (PLA) is bio-based whilst polyethylene (PE) and polyethylene furandicarboxylate (PEF) can be either. PPC is the first polymer synthesised at a ktonne scale from CO_2 copolymerisation with fossil fuel-based propylene oxide[12]. Currently, global production of PET bottles can reach up to 15 Megatonne·year^{-1}, representing roughly 0.2% of global primary energy consumption[13]. The main advantage of PEF is its superior performance under severe heat conditions, gradually replacing PET and resulting in 5.9% of global plastic production[14]. Similar to purified terephthalic acid (PTA) being an important component of PET production, bio-based 2,5-furandicarboxylic acid (FDCA) is crucial for PEF production[14]. Various pathways for PEF and FDCA production are shown in Fig. 1[15]. One conventional PEF production route is converting fructose derived from plants into FDCA in a four-step process followed by a reaction with ethylene glycol (EG). Currently, Banerjee et al.[16] reported that FDCA can also be produced by reacting 2-furoic acid (FC) with CO_2 in the presence of caesium carbonate. Eerhart et al.[14] indicated an approximately 50% saving in energy and reduction in CO_2 for a combined use of petrochemical and biobased products and a reduction of 14% for bioplastic products.

Novel PEF production pathway

The novel route of PEF production from industrial CO_2 and bio-waste[17] presented in Fig. 1 consists of four conversion steps: from xylan to furfural, FC, FDCA, and finally PEF. The first two steps are well-established processes existed for decades while the last two steps exist only in experimental and pilot plant studies[18,19]. PEF from biowaste doesn't compete with food sector and the industrial CO_2 could be used as a raw material to achieve carbon mitigation. While producing the plastic, it could further reduce the amount of waste. Comparably, PEF from 5-hydroxymethylfurfural (HMF) using sugar and glucose as the raw materials takes the advantages of less energy consumption and high conversion efficiency whereas food is used to produce HMF which is sensitive to feedstock cost. This paper aims to assess the novel PEF production pathway at an industrial scale covering CO_2 emissions, energy consumption, environmental impacts and production costs, which have bridged the knowledge gap for biowaste and carbon utilisation. A step-by-step process diagram of the PEF production from xylan to furfural, FC, FDCA and PEF combined with relevant chemical equations is shown in Fig. 2. The processes are detailed in Supplementary Note 1.

Results

GHG emissions and energy consumption. The mass and energy balance of PEF production process and inputs/outputs of the combined heat and power (CHP) for steam production are demonstrated in Supplementary Tables 1-3. Based on GWP required from life cycle assessment (LCA) in this study, GHG emissions for PEF using EG from maize are projected in line with Ref. [20]. Fig. 3 shows that GHG emissions and energy consumption of novel PEF production pathway are within the range if compared to other bioplastics reported in Ref. [14]. PEF+ is synthesized from the processes using bio-based FDCA and EG produced from maize. The novel pathway in this study shows an up to 1.86 tonne reduction of GHG emissions per tonne of PEF production, which is close to or lower than those of PET and other plastics with the exception of PEF, PEF+, and high density polyethylene (HDPE) in Ref. [14]. The excess CO_2 emissions produced in the latter can be up to 2.2 tonne of CO_2 when compared to the case of PEF+. This is mainly because PEF processes proposed in Ref. [14] are all in lab scale whilst food (instead of waste as in this study) is used as the raw material for other plastic products without considering upstream and downstream processes which may cause a large increment of GHG emissions[21]. As for energy consumptions, the results show that the PEF production pathway using EG from maize has the lowest energy consumption *i.e.* 46 GJ per tonne of PEF production, indicating the most

significant improvement, *i.e.* 40.5% when compared with PTT. Also, the PEF production pathway using EG from petrochemical has low energy consumption *i.e.* 58 GJ per tonne of PEF production, which is close to or lower than that of most bioplastics except some materials e.g. PEF^{+}. This could be explained by similar reasons for GHG emissions i.e. maturity of production steps and non-food raw material. Besides, GHG emissions reduction is not proportional to energy consumption. For example, energy consumption of PEF from EG-maize in this paper is reduced by 37.5% when compared with that of PTT. With regard to GHG emissions, the aforementioned performance is reduced by 42.3%. The main reasons for that are illustrated as follows: the proposed pathway consumes CO_2 in the processes and GHG emissions are evaluated in terms of a life-cycle prospective, which are the comprehensive results after LCA based on mass and energy balance. There is vast potential for the proposed pathway of PEF production to further reduce GHG emissions using other renewable energy sources e.g. solar, wind, and geothermal energy that could replace the CHP completely or partially used in this study. The results in Fig. 3 are limited on operating information in the step 3 of PEF production e.g. pressure, temperature, yield taken from lab-scale experimental results and the required energy consumption replaced by that of PET polymerisation.

Environmental impacts. The life cycle impact assessment (LCIA) results and the contribution of individual life cycle stages towards impact categories assessed in this study are illustrated in Fig. 4(a), showing that Abiotic Depletion (Fossil), Global Warming Potential, and Human Toxicity Potential (labelled as II, VI and VII respectively) are the three most significant environmental burdens in producing 1 tonne of PEF, *i.e.* 6.90×10^{4} MJ, 3.75×10^{3} kg CO_2 equivalent and 2.18×10^{3} kg DCB equivalent respectively. The three impacts are largely attributable to the production process of natural gas required for operating the PEF plant, the operation and maintenance of the CHP system and the production process of EG required for producing PEF respectively. Fig. 4(a) also shows that all impact categories are primarily caused by the operation stage—operating the CHP system is mainly responsible for most impact categories with the exception of Abiotic Depletion (Fossil) and Global Warming Potential, which are largely caused by the operation of the PEF production plant, indicating that other life cycle stages are relatively insignificant whilst natural gas driven CHP is not an ideal option from an environmental perspective despite of its maturity. Besides, compared to base case, a sensitivity analysis is conducted using 11 scenarios to assess sensitivity of LCIA results as shown Fig. 4(b) which is to investigate life cycle inventory analysis (LCI) quality and assumptions made in the study by manipulating the magnitude of electricity supplied by CHP, CO_2 reused and natural gas consumption for 1 tonne of PEF production. Results show that every 10% change in these variables would, respectively, result in approximately

17% and approximately 7% of differences respectively in LCIA results of Abiotic Depletion (Fossil) and Global Warming Potential, which are the two impact categories affected most significantly by these variables. As illustrated in Fig. 4(c), a similar pattern is also shown by carbon and GHG intensities—the former accounts for carbon emissions from PEF production only whilst the latter considers GHG involved in all processes. The results indicate that, for the scenarios assessed in this study, (i) the influences of electricity supply by CHP and natural gas consumption are more profound than that of CO_2 reused in the process; and (ii) utilising CO_2 generated from the production process can reduce but not fully offset the environmental impacts of consuming electricity and natural gas during the production process itself, i.e. fraction of CO_2 that can be utilised is 14.12%. The similarity in the pattern of results shows that the LCI quality is of a satisfactory level. The sensitivity analysis in 11 additional scenarios present the strength of this LCA study. The influence of downstream process of EG production cannot be further assessed due to the limitation of using existing dataset available in GaBi software. The location and the end of life scenario of the production plant as well as transport and distribution of PEF produce are anticipated to affect the LCIA results; however, their significance, which could be paramount or trivial, cannot be investigated in this study due to limited data availability and time constraints.

Economic potential. As illustrated in Fig. 5(a), scale factor varies from 0.5 to 0.9 with a higher likelihood occurring between 0.6 and 0.8 indicating a capital investment range of \$237.8─281.8 million. Fig. 5(b) indicates the impact of PEF prices on payback period for a plant capacity of 50 ktonne·year^{-1}. The price is selected based on total capital cost for PEF production. It is worth noting that the payback period is less than 5 years when market price is higher than \$4·kg^{-1}. As might be expected, the lower the PEF market price is, the longer the payback period becomes. For example, the payback period is 50 years or more when the PEF market price is lower than \$3·kg^{-1}. Within the 0.6-0.8 scale factor range, the PEF market price cannot be as low as that of PET; otherwise, the payback period will become unacceptable. This is mainly because the proposed pathway of PEF production is not commercialised with possible technical barriers e.g. efficient catalyst, cost of material, thermochemical stability and conversion efficiency. If the barrier could be overcome, a low market price will be achieved. Besides, it is indicated that the PEF market price has stronger influence over payback period than capex scale factor in this study because the chosen capacity ratio is not very high.

Besides, the payback period can be reduced with plant capacity as shown in Fig. 5(c) where 0.6 is applied as the capex scale factor. Two relatively low prices *i.e.* \$3 kg^{-1} and \$3.4 kg^{-1} are used in the analysis since the other price in

Fig. 5(b) must result in the lower payback period. It indicates that the payback period will decrease remarkably with plant capacity at a relatively low PEF price, which proves the feasibility to shorten the payback period with increased plant capacity. For a higher price, plant capacity has limited influence on the payback period. Thus, both plant capacity and the selling price are compromised in designing an industrial plant for the novel pathway.

Fig. 6 shows PEF production costs under various conditions in which Fig. 6(a) is to compare the costs of this study and three cases in Ref. [22] at a capacity of 100 ktonne·year^{-1}. Negative Y-axis indicates annual revenue of the by-products and excessive electricity; positive Y-axis represents annual costs of capital recovery, feedstocks, chemicals (*i.e.* raw materials), Operating and management (O&M) *etc.*; and the red dot presents the production cost of PEF, per tonne. The cost of PEF production via novel pathway is about \$2435 tonne^{-1} which is in the range of \$2370─4879 tonne^{-1} reported in Ref. [22]. The production cost of PET is \$1800 tonne^{-1} at the expense of 50% additional CO_2 emissions compared to PEF production via novel pathway proposed in this study.

The novel PEF pathway employs CO_2 at 99.5% purity as a raw material. CO_2 can be captured from various sources including PEF production supply chains and power plants. The main practical obstacles in incorporating a post-combustion CO_2 capture plant are large energy consumption, high capital cost and operating cost, which depend on the exhaust gas conditions. The concentration of CO_2 in industrial exhaust gases varies from one to another. For instance, in descending order, 97%, 77%, 22%, 10–15% and 3–4% volume per volume (v·v^{-1}) from ammonia and ethylene oxide plants, hydrogen production plants, sulphur production plants, coal power plants and gas turbines, respectively[23]. Thus, CO_2 prices vary with its concentration in the flue gases. The impact of CO_2 prices on the production cost of PEF is analysed as shown in Fig. 6(b) which ranges \$45–70 tonne^{-1} considering CO_2 from natural gas and coal power plants[24,25]. It is found that PEF production cost increases only by 1.6% from \$2430 tonne^{-1} to \$2475 tonne^{-1} when CO_2 price varies up to \$90 tonne^{-1}. Results show that CO_2 price has marginal impact on the PEF production cost. Therefore, CO_2 from various sources including coal and natural gas power plants could be employed.

A comparison based on a single bottle can further provide insights into this analysis from the perspective of consumers or minimising plastic bottle usage. Compared to PET, PEF has (i) better oxygen, CO_2 and H_2O barriers (*i.e.* 6, 3 and 2 times more superior, respectively); and (ii) higher resistance to mechanical strain[26,27]. According to Refs. [28,29], the wall thickness of a conventional high impact polystyrene (HIPS) cup can be reduced from 0.89 mm to 0.66 mm if impact-modified PLA is used due to the higher stiffness of PLA than that of HIPS. Likewise, a thinner PEF bottle with reduced mass (and material) can be produced due to its superior properties compared to PET, leading

to a corresponding lower PEF bottle selling price. A sensitivity analysis is carried out to determine the maximum mass of a PEF bottle that can make its selling price more competitive than that of PET. The production cost of a 237 ml PET bottle is \$0.162[30], is derived from the total production cost of 1 tonne of PET, *i.e.* \$1800 tonne^{-1}. For simplicity (and assuming that bottle manufacturing costs are mainly material), assuming that the average mass of a 237 ml PET bottle is 9 g, the production cost of one PEF bottle could be the same as that of a PET bottle when the mass of a PEF bottle is reduced by 25.9% from 9 g to 6.67 g, as shown in Fig. 6(c). As such, the PEF production cost per bottle could be the same or lower than that of PET, depending on the mass of a PEF bottle due to its better properties (although the production cost of 1 tonne of PEF is more expensive than that of PET, as discussed earlier).

Discussion

A novel PEF pathway employing industrial CO_2 and biowaste is presented which could be a sustainable alternative for its counterpart, PET. In this study, GHG emissions, energy consumption, environmental impacts and production cost of novel PEF production pathway at an industrial scale are evaluated based on actual lab-scale experimental studies and limited by the database of software. The results show that GHG emissions and energy consumption of the novel pathway are in the same range of other bioplastics. However, it is worth noting that the proposed alternative does not compete with food sector, which has a large advantage in some countries where primary food is scarce now or in the future. By using this novel pathway, GHG emissions and energy consumption can be reduced by up to 40.5% when compared to those of PET production. Whilst all environmental impacts are primarily caused by the operation stage, the influence of electricity supply and natural gas consumption by the CHP system over the assessed environmental impacts is more profound than that of industrial CO_2 utilisation. More insights would be gained from future case studies if transport, treatment and disposal of used lubricating oil, distribution and use of PEF produce, surplus electricity, and alternative end of life scenarios are assessed in LCA. If renewable energy or carbon capture is incorporated with natural gas-powered CHP, more potentials of this novel pathway could be further explored. The process requires CO_2 of high purity which increases its price depending on the sources. Nevertheless, the price of CO_2 has a marginal impact on the production cost of PEF. The current production cost of PEF is higher than that of PET. The cost for PEF production can be reduced by optimal design and mature technology. Based on 15 million tonnes of global PET bottle market per year *i.e.* 1/3 of the global PET production, the novel PEF production pathway not only offers a viable solution to reuse biomass within an industrial zone but also employs local GHG emissions

196 which will reduce overall carbon foot print in the future. Different technologies for sustainable plastic e.g. bioplastic
197 development, biorecycling of PET and partially using post-consumer resin PET are gathering the momentum and
198 could be mutually complemented.
199
200 **Methods**
201 The process modelling is carried out by using the chemical engineering process simulation tool, Aspen Plus
202 version 9. A non-random, two-liquid model (NRTL) property method is used in the modelling[31,32] based on operating
203 conditions reported in the literature from actual lab-scale experiments and pilot plant studies[33-35]. During the
204 simulation, processes are up-scaled to determine mass balance and identify the energy demands. Supplementary Figure
205 1 illustrates the PEF production model where the relevant operating conditions are shown in Supplementary Table 4.
206 The physical properties of xylan, FC, PDCA and PEF are not available in the standard Aspen Plus properties databases.
207 As such, these components are defined as conventional solids in Aspen Plus, as summarised in Supplementary Table
208 5. Information required for conventional solids are heat of formation, density, boiling points, molecular weights and
209 molecular structures, which are taken from Refs. [36-39]. The heat capacity values of FC, FDCA and PEF are estimated
210 using the atomic element contribution method of Hurst and Harrison[38,40].
211 **Combined heat and power.** A CHP system powered by natural gas is considered and simulated in Aspen Plus to
212 generate the required steam and electricity. The related parameters and conditions are obtained from the simulation
213 data of Thermoflow. The natural gas driven CHP system consists of a gas turbine with a heat recovery steam generator
214 (HRSG), and a steam turbine. The gas turbine is a GE LM6000 PC SPRINT selected from the list of commercial
215 machines available in Thermoflow. The flue gas from the turbines flows into the HRSG where steam is generated to
216 feed a steam cycle and to the PEF process, as shown in Supplementary Figure 2. Additional steam at 12.7 bar is
217 produced in the HRSG. The stream mixes with the exhaust steam of the high-pressure steam turbine to provide thermal
218 energy to the PEF production process.
219 The quantity of CO_2 attributable to steam and electricity is estimated using Equations (1)─(3):

$$E_{\text{steam}} = m_{\text{steam}}[h - h_0 - (T_0 + 273.15)(s - s_0)], \quad (1)$$

$$E_{\text{power}} = P, \quad (2)$$

$$m_{\text{CO}_2,\text{steam}} = [m_{\text{CO}_2,\text{total}}] \frac{E_{\text{steam}}}{E_{\text{steam}} + E_{\text{power}}} \quad (3)$$

where m_{steam}, h and s are the mass flow rate ($kg \cdot s^{-1}$), the enthalpy ($kJ \cdot kg^{-1}$) and the entropy of steam ($kJ \cdot kg^{-1} \cdot K^{-1}$); h_0 is the enthalpy input of water at 15 ºC under ambient conditions whilst s_0 is the entropy of water ($kJ \cdot kg^{-1} \cdot K^{-1}$) at T_0, which is the ambient temperature (ºC); P is the power generated by the CHP (kW), $m_{CO_2,steam}$ is the mass flow rate of CO_2 generated by steam which is consumed during PEF production ($tonne \cdot h^{-1}$); and $m_{CO_2,steam}$ is the total CO_2 generated by the CHP ($tonne \cdot h^{-1}$).

Life cycle assessment. PEF production using the proposed novel pathway is then assessed from a LCA perspective to estimate its environmental impacts covering the four iterative phases of LCA, namely goal and scope definition, LCI, LCIA and life cycle interpretation in compliance with the Standards established by the International Organisation for Standardisation (ISO) *i.e.* ISO14040 and 14044[41,42]. The key elements are highlighted here: (1) the product system of this LCA study is the PEF production plant integrated with the CHP system powered by natural gas; (2) the function is to produce PEF using EG from petrochemicals for 30 years; (3) the functional unit is 1 tonne of PEF (which is defined in line with Ref. [14]); (4) the system boundary covers construction, operation and maintenance, and end-of-life phases of the product system including upstream and downstream processes if relevant data are available in GaBi Professional Database whilst excluding (i) transport (in line with Ref. [14]); (ii) treatment and disposal of used lubricating oil during maintenance; (iii) distribution and use of PEF produce as well as surplus electricity generated by the CHP system; and (iv) co-products of PEF production (*i.e.* furfuryl alcohol and sodium hydrogen sulphate). It is assumed that (i) the product system will operate following the production profile simulated in Aspen Plus consuming natural gas at a rate of 9800 $kg \cdot h^{-1}$ for 8000 $h \cdot year^{-1}$ over 30 years without any defect; (ii) CO_2 produced by the product system during operation will be utilised in the PEF production process at a rate of 1200 $kg \cdot h^{-1}$(based on Aspen Plus simulation outcome) as a feedstock; (iii) steel, which is the primary material used in constructing the product system, is 100% recycled at the end of life; and (iv) the product system is located in Europe. The defined system boundary and the assumptions present the limitations of this study. Using input and output data gathered from Aspen Plus simulation, GaBi Database and literature, LCI is carried out, followed by the development of a simplified LCA model using GaBi software to assess the following impact categories:

(I) Abiotic Depletion (Elements), kg antimony (Sb) equivalent;

(II) Abiotic Depletion (Fossil), MJ;

(III) Acidification Potential, kg sulphur dioxide (SO_2) equivalent;

(IV) Eutrophication Potential, kg phosphate equivalent;

(V) Freshwater Aquatic Ecotoxicity Potential, kg 1,4 dichlorobenzene (DCB) equivalent;

(VI) Global Warming Potential (100 years), kg CO_2 equivalent;

(VII) Human Toxicity Potential, kg DCB equivalent;

(VIII) Photochemical Ozone Creation Potential, kg ethene equivalent;

(IX) Terrestric Ecotoxicity Potential, kg DCB equivalent; and

(X) Odour Potential, kg H_2S equivalent.

The LCIA methodologies available in GaBi *i.e.* CML2016 and "Odour" are applied for the assessment of the impact categories (I)–(IX) and (X) respectively. More information about the defined goal and scope, LCI, the developed LCA model and the fundamental concept of LCIA methodologies is available in Supplementary Tables 6–7 and Supplementary Figures 3–4.

Economic analysis. Economic analysis of the novel PEF production pathway is carried out by applying a payback method in line with mass and energy balance. A process model has been developed for the production capacity of PEF estimated from Aspen Plus model *i.e.* 21.4 ktonne·year^{-1} from waste. The analysis considers direct, indirect, variable operating and fixed costs which may incur during plant construction, operation and maintenance (see Supplementary Tables 8–11). The plant capacity of 21.4 ktonne·year^{-1} for analysis cannot compete with the PET price of \$1.51 kg^{-1} at 2017[43]. Considering the pilot plant developed by Avantium and BASF which has a capacity of 50 ktonne PEF·year^{-1}, the capacity is used for further evaluation[44]. The costs increase with plant capacity, in which the correlation is expressed is Equation (4)[45], as follows:

$$\text{Cost of plant size 2} = \text{Cost of plant size 1}\left(\frac{\text{Plant size 2}}{\text{Plant size 1}}\right)^{\text{scale factor}}, \quad (4)$$

where the scale factor for the capex cost is primarily 0.6─0.8[46]. The scale factor depends on plant complexity from technical and technological perspectives, novelty and scalability level. It is 0.6 for mature technology and above provided novel technology is adopted. Supplementary Tables 12 and 13 present the installation costs of PEF and PET production plants. It can be inferred that the installation cost of a PET production plant can be 5─6 times cheaper than that of a PEF plant. This is mainly due to the maturity of PET technology where underpinning supply chains are more developed and its supporting industry is familiar with the technology. Likewise, it would be expected that the total cost of establishing a PEF production plant will decline when PEF production technology becomes mature which is related with various factors e.g. efficient catalyst, cheap material, good thermal and chemical stability, easy to operation and maintenance, etc. After determining a scale factor, annual utilities and raw material costs for a specific

plant size, PEF market prices will dictate the operating income which impacts on payback period directly. In this study, a sensitivity analysis is performed for production capacity of 50 ktonne·year^{-1} using bagasse as a raw material. Total investment cost is extrapolated using Equation (4).

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

L.J. A.D. J.C. A.M. A.R. and A.S designed the study. L.J. A.D. J.C. provided the analysis. L.J. A.D. J.C. interpreted the data and wrote the paper. L.J. finalized the writing of the paper.

Competing interests

The authors declare no competing interests.

Figure Caption

Fig. 1. PEF production pathways (adapted from Ref. [15]).

Fig. 2. The PEF production pathway from wastes and industrially captured CO_2.

Fig. 3. Comparison of performance of various bioplastics including PEF (a) GHG emissions; (b) energy consumptions[14] (**Petrochem. PET**: petrochemical PTA and petrochemical EG; **Petrochem. PET+**: petrochemical PTA and biobased EG from maize; **PEF**: PEF produced from fructose and HFCS**; PEF+**: bio-based FDCA and EG produced from maize; **HDPE**: petrochemical HDPE; **PHA**: polyhydroxyalkanoates; **PTT**: petrochemical PTA and bio-based PLA (maize) 1, 3-propanediol; **PLA**: polylactic acid; and **PE**: polyethylene).

Fig. 4. The results of (a) LCIA for the base case scenario at different life cycle stages; (b) sensitivity analysis where 11 scenarios (S1–S11) assessing three variables (electricity supply, natural gas consumption and CO_2 reused in producing 1 tonne of PEF) are compared; and (c) a comparison of carbon intensities for these scenarios.

Fig. 5(a) Capital investment versus capex scale factor for a plant capacity of 50 ktonne·year^{-1}; (b) The effect of PEF price on payback period within the range of scale factor from 0.6 to 0.8; (c) Payback period versus plant capacity.

Fig. 6. PEF production cost (a) compared with other cases; (b) based on a range of CO_2 prices; (c) based on 237 ml PET bottle.