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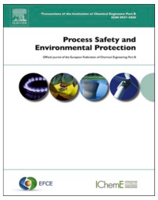

Optimal sorting and recycling of plastic waste as a renewable energy resource considering economic feasibility and environmental pollution

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ABSTRACT

This work suggests an optimal strategy to sort and recycle plastic waste as a renewable energy resource with maximizing economic feasibility and mitigating environmental pollution. To derive the optimal sorting and recycling strategies of plastic waste, a novel optimization model is developed; it calculates the overall profit by subtracting the profit of recycling plastic from the total annualized cost. Then the model is used to identify the optimal strategy to sort and recycle plastic waste as a renewable energy resource in mixed-integer nonlinear programming that maximizes the overall profit. In the derived optimal sorting and recycling strategy, high-density polyethylene is recycled to produce downgrade plastic; low-density polyethylene, polypropylene, and polystyrene are recycled as pyrolysis oil; and polyethylene terephthalate is recycled to produce refuse plastic fuel. The derived optimal case can significantly increase the overall profit by about 3,137% (i.e., 35 US$/1 kg of recycled plastic), and 492% (i.e., 29 US$/1 kg of recycled plastic) compared to conventional case in South Korea and Japan respectively.

1. Introduction

The demand for plastics has rapidly increased in many industries because of their versatility, and easy production. Consequently, plastic waste is discharged in massive quantities; estimates of plastic waste discharged into rivers, lakes, and seas is 9–23 million t per year globally (Borrelle et al., 2020; Masuda et al., 2001). Thus, the importance of plastic waste recycling is increasing (Shah et al., 2015; Zhang et al., 2020). Plastic waste is a mixture of different types, so it must be sorted into before it is recycled (Gundupalli et al., 2017; Hearn and Ballard, 2005; Lim and Cho, 2003). Economically-viable sorting and recycling of plastic will yield a cheap and abundant source of valuable chemicals and renewable energy (Gadaleta et al., 2020). However, current systems to sort and recycle plastic waste are not optimized, so their costs are high. Thus, only 27.2 wt% of plastic waste is recycled, whereas 36.4 wt% is landfilled, and 36.4 wt% is incinerated (Vieira et al., 2022). Therefore, the soil and air pollution according to the landfilled plastic and the significant amount of SO_x, NO_x, and CO_2 emitted in the incineration of waste plastic is serious. The types of recycled plastic have different uses depending on the product (e.g., downgrade plastic, pyrolysis oil, and refuse plastic fuel) that is produced (Kim et al., 2020; Krauklis et al., 2021; Shaha et al., 2020; Yaqoob et al., 2021). Methods to recycle plastic waste are classified into material, chemical, and thermal types (Zhuo and Levendis, 2014). They have very different capital and operating costs according to the throughput of the plastic waste of each method (Huang et al., 2002). Therefore, to improve plastic waste recycling, it is crucial to derive optimal sorting and recycling strategy for plastic waste that indicate which plastics will be sorted to be recycled and how the plastic will be recycled according to each recycling method considering economic feasibility.

1.1. Literature review

Previous studies only focused on improving the recycling efficiency of plastic waste in each recycling method. Ugoamadi and Ihesiulor (2011) proposed optimal design and construction of plastic recycling machines to minimize the limitations of the conventional recycling machine, ensuring adequate waste management. As a result, the operating speed of the recycling machine is derived optimally at 268 rpm, and the recycling efficiency is about 97%. Mehat and Kamaruddin (2011) improved the mechanical properties of products made from

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Nomenclature

Sets

i	Type of plastic = {LDPE, HDPE, PP, PS, PET}.
s	Sorting method = {Thermal adhesion sorting, Float-sink sorting, Dry zig-zag sorting, Electrostatic sorting, Froth flotation sorting}.
r	Recycling method = {Material recycling, Recycling via pyrolysis, Recycling as refuse derived fuel, Energy generation via incineration}.

Parameters

AOT	Annual operating time of recycling methods [h].
$pri_i^{plastic}$	Price of plastic i [US\$/kg].
$Cal_i^{pyrolysis}$	Calorific value of pyrolysis oil derived to plastic i [kJ/kg].
$Yield$	Yield of pyrolysis oil [%].
EST	Efficiency of steam turbine generator [%].
$Cal_i^{plastic}$	Calorific value of pyrolysis oil derived to plastic i [kJ/kg].
$pri^{pyrolysis}$	Price of pyrolysis oil [US\$/kg].
pri^{RPF}	Price of refuse plastic fuel [US\$/kg].
$pri^{electricity}$	Price of electricity [US\$/kWh].
AF	Annuity factor [y].
RP	Rate of period [%].
NP	Number of period [y].
ρ_{L}	Density of solution in float-sink method [kg/m^3].
ρ_{P}	Density of plastic [kg/m^3].
$REC_s^{sorting}$	Referenced equipment cost of sorting method s [US\$].
$RC_s^{sorting}$	Referenced capacity of sorting method s [kg/h].
$REC^{downgrade}$	Referenced equipment cost of downgrade production [US\$].
$RC^{downgrade}$	Referenced capacity of downgrade production [kg/h].
$REC^{pyrolysis}$	Referenced equipment cost of pyrolysis oil production [US\$].
$RC^{pyrolysis}$	Referenced capacity of pyrolysis oil production [kg/h].
REC^{RPF}	Referenced equipment cost of RPF production [US\$].
RC^{RPF}	Referenced capacity of recycling of RPF production [kg/h].
REC^{power}	Referenced equipment cost of incineration process [US\$].
RC^{power}	Referenced capacity of incineration process [kg/h].
CCF	Capacity correction factor.
$pri^{disposal}$	Price of disposal PVC [US\$/kg].
pri^{NaCl}	Price of NaCl [US\$/kg].
QN_s	Quantity of NaCl consumption per sorted plastic in sorting method s.
W_i	Total amount of waste plastic i [kg/h].
s	Speed of a sorting machine [kg/y].
$pri^{Ethanol}$	Price of ethanol [US\$/kg].
QE_s	Quantity of ethanol consumption per sorted plastic in sorting method s.
$pri^{deformaing\ agent}$	Price of deforming agent [US\$/kg].
QDA_r	Quantity of deforming agent consumption per sorted plastic in recycling method r.
pri^{alum}	Price of alum [US\$/kg].
QA_r	Quantity of alum consumption per sorted plastic in recycling method r.
pri^{H3PO4}	Price of H_3PO_4 [US\$/kg].
QH_r	Quantity of H_3PO_4 consumption per sorted plastic in recycling method r.
$\mathrm{pri}^{\mathrm{urea}}$	Price of urea [US\$/kg].
QU_r	Quantity of urea consumption per sorted plastic in recycling method r.
pri^{NaH}	Price of NaH [US\$/kg].
QNA_r	Quantity of NaH consumption per sorted plastic in recycling method r.
$pri^{nitrogen}$	Price of nitrogen [US\$/kg].
QNT_r	Quantity of nitrogen consumption per sorted plastic in recycling method r.
pri^{CaO}	Price of CaO [US\$/kg].
QCA_r	Quantity of CaO consumption per sorted plastic in recycling method r.
E	Electricity consumption of a sorting machine [kW].
QEL_r	Quantity of electricity consumption per sorted plastic in recycling method r.
pri^{water}	Price of water [US\$/kg].
QW_r	Quantity of water consumption per sorted plastic in recycling method r.
pri^{diesel}	Price of diesel [US\$/kg].
QD_r	Quantity of diesel consumption per sorted plastic in recycling method r.
$pri^{light\ oil}$	Price of light oil [US\$/kg].
QLO_r	Quantity of light oil consumption per sorted plastic in recycling method r.
pri^{LPG}	Price of LPG [US\$/kg].
$QLPG_r$	Quantity of LPG consumption per sorted plastic in recycling method r.
$pri^{recycled\ oil}$	Price of recycled oil [US\$/kg].
$QREO_r$	Quantity of recycled oil consumption per sorted plastic in recycling method r.

Continuous variables

$Overall\ profit$	Overall profit of sorting and recycling system [US\$/y].
$Profit$	Profit of recycling system [US\$/y].
$P^{downgrade}$	Profit of downgrade-plastic [US\$/y].
$P^{pyrolysis}$	Profit of pyrolysis oil [US\$/y].
P^{RPF}	Profit of RPF [US\$/y].
P^{power}	Profit of power generation [US\$/y].
MQ_i	Quantity of recycled plastic i as material recycling [kg/h].
PQ_i	Quantity of recycled plastic i as pyrolysis oil [kg/h].
RQ_i	Quantity of recycled plastic i as refuse-derived fuel [kg/h].
RE_i	Quantity of remained plastic i [kg/h].
TAC	Total annualized cost [US\$/y].
EAC	Equivalent annual cost [US\$/y].
TCI	Total capital investment [US\$/y].
FCI	Fixed capital investment [US\$].
SUC	Start up cost [US\$/y].
WCI	Working capital investment [US\$/y].
TPC	Total product cost [US\$/y].
$Cequipment$	Equipment cost of sorting and recycling system [US\$].
$ECsorting$	Equipment cost of material recycling [US\$].
$EC^{downgrade}$	Equipment cost of sorting system [US\$].
$EC^{pyrolysis}$	Equipment cost of recycling via pyrolysis [US\$].
EC^{RPF}	Equipment cost of recycling as refuse-derived fuel [US\$].
EC^{power}	Equipment cost of incineration process [US\$].
$C^{raw\ material}$	Raw material cost [US\$/y].
C^{nacl}	NaCl cost [US\$/y].
$C^{ethanol}$	Ethanol cost [US\$/y].
$C^{deforming\ agent}$	Deforming agent cost [US\$/y].
C^{alum}	Alum cost [US\$/y].
C^{H3PO4}	H_3PO_4 cost [US\$/y].
C^{urea}	Urea cost [US\$/y].
C^{NaH}	NaH cost [US\$/y].
$C^{nitrogen}$	Nitrogen cost [US\$/y].
C^{CaO}	CaO cost [US\$/y].
$C^{Ca(OH)2}$	$Ca(OH)_2$ cost [US\$/y].
$C^{utility}$	Utility cost [US\$/y].

$C^{sorting-elect}$	Electricity cost of sorting system [US\$/y].
$C^{recycling-elect}$	Electricity cost of recycling system [US\$/y].
C^{water}	Water cost [US\$/y].
C^{fuel}	Fuel cost [US\$/y].
C^{diesel}	Diesel cost [US\$/y].
$C^{light\ oil}$	Light oil cost [US\$/y].
C^{LPG}	LPG cost [US\$/y].
$C^{recycled\ oil}$	Recycled oil cost [US\$/y].
$C^{disposal}$	Disposal cost [US\$/y].

Binary variables

MS_i	1 when plastic i is recycled at material recycling system otherwise 0.
PS_i	1when plastic i is recycled at recycling system via pyrolysis otherwise 0.
RS_i	1 when plastic i is recycled as refuse-derived fuel otherwise 0.

plastic based on the Taguchi optimization method. The results reveal that the product made of 25% recycled polypropylene (PP) and 75% virgin PP exhibits a better flexural modulus than the virgin form. Burat et al. (2009) developed froth flotation to separate the polyethylene terephthalate (PET) and polyvinyl chloride (PVC) to improve recycling efficiency. The proposed froth flotation method separates the PVC and PET at 98.8 wt% and 99.7 wt%, respectively. Wu et al. (2020) conducted statistical pentagonal design experiments in a microreactor system to find optimum conditions for cracking the plastic mixture into oils. The experiment results show that the oil yields of polyethylene (PE), PP, and polystyrene (PS) reached nearly complete conversion, and the yield of PET and acrylonitrile butadiene styrene (ABS) is low. Soury et al. (2009) present the novel optimization method to design an I-shape profile used in wood-plastic pallets. The optimization result shows that the produced pallet was less than 20 kg, whereas its strength against bending and distributed smooth restraint loading were greater than 500 kg and 2000 kg, respectively.

1.2. Contribution

Despite the numerous contributions of improving plastic waste recycling of each recycling method, several significant challenges remain. First, the previous studies have focused only on increasing recycling efficiency, and have not considered the overall costs of system to sort and recycle the waste. Most plastics are landfilled or incinerated because these methods are more economical than sorting and recycling. Landfill causes soil contamination and severe water pollution due to micro-plastics from landfill leachate (He et al., 2019; Su et al., 2019). The incineration of plastic waste discharges the air pollutants such as hydrogen chloride (HCl), hydrogen cyanide (HCN), nitrogen oxides (NO_x), sulfur oxides (SO_x), volatile organic compounds, and greenhouse gas such as CO and CO_2 (Verma et al., 2016). These pollutants cause air pollution that can have devastating effects on the human body and the environment. Thus, reducing the cost of recycling plastic waste may help to reduce pollution caused by landfilling and incineration. Furthermore, the previous studies did not consider which plastics should be sorted to be recycled, or how they can be recycled. Each type of plastic in the waste has a different value when recycled, and the values vary among recycling methods. In addition, different recycling methods have significantly various capital and operating costs according to the throughput of the plastic waste. Therefore, to improve plastic waste recycling, the plastics must be sorted and recycled optimally maximizing economic feasibility and mitigating environmental pollution, but few studies have considered this problem.

To solve these challenges, this work optimize the sorting and recycling of plastic waste as a renewable energy resource, maximizing the overall profit of a system that sorts and recycles plastic waste, by considering economic feasibility and environmental preservation. The novelty of this work can be summarized as follows:

1) It is the first attempt to optimize the plastic waste sorting and recycling system by deriving an optimal sorting and recycling strategy of plastic waste as a renewable energy resource maximizing economic feasibility and mitigating environmental pollution caused by landfilled plastic and air pollutants according to incineration of plastic.
2) The results allow us to increase the plastic waste recycling by maximizing the overall profit of the plastic waste sorting and recycling system with mitigation of environmental pollution. Thus, it can also yield tremendous economic improvements and environmental protection effects.
3) Finally, this study provides valuable insight to increase the cleanliness and cost-effectiveness of production, and help to protect the environment.

2. Methods

Fig. 1 shows the overall sorting and recycling system of plastic waste as a renewable energy resource. Since plastic waste is a mixture, so before it is recycled, it is sorted by type. For this purpose, six sorting methods are considered here: 1) thermal-adhesion sorting; 2) float-sink sorting; 3) dry zig-zag sorting; 4) electrostatic sorting; 5) froth flotation sorting; and 6) NIR spectrum sorting. Each sorting method classifies the plastic according to difference in physical properties.

2.1. Sorting systems

1) Thermal-adhesion sorting exploits the difference in softening temperatures for each material (Lim and Cho, 2003). At its softening temperature, a plastic adheres to the surface, and other plastics that do not soften do adhere. This difference in reaction is by controlling the surface's temperature step-by-step, to segregate plastics sequentially. The thermal-adhesion sorting has the advantage of separating one plastic from waste plastic mixtures, but it cannot separate thermosetting plastics.
2) Float-sink sorting exploits differences in plastics' specific gravity ρ_P (Bauer et al., 2018). Plastic wastes are dumped input into a liquid solution, then its specific gravity ρ_L is adjusted; plastics sink if they have $\rho_P > \rho_L$, and float otherwise. The float-sink sorting can also sort one plastic from waste plastic mixtures, but it is impossible to sort the plastics with a specific gravity difference of less than 0.1.
3) Dry zig-zag also exploits the differences in plastics' ρ_P (Howell, 1992), but uses an upward flow of air to separate them. A stream containing mixed material is dropped into a sorting chamber in which the air is rising. Objects lighter than a threshold θ are blown through a top exit, and objects heavier than θ drop through the bottom exit. The dry zig-zag sorting can sort one plastic from waste plastic mixtures, but it cannot sort the plastics with a specific gravity difference of less than 0.1.
4) Electrostatic sorting exploits the difference in the work function of conducting plastics (Tilmatine et al., 2009). First, plastic flakes are charged when they contact a tribo-charging device. Then the individual particles are suspended in an electrostatic field, and separated according to the magnitude of their charge. Electrostatic sorting has the advantage of being able to sort at a low operating cost without any water or additives consumption but it can sort only one plastic from two plastics.

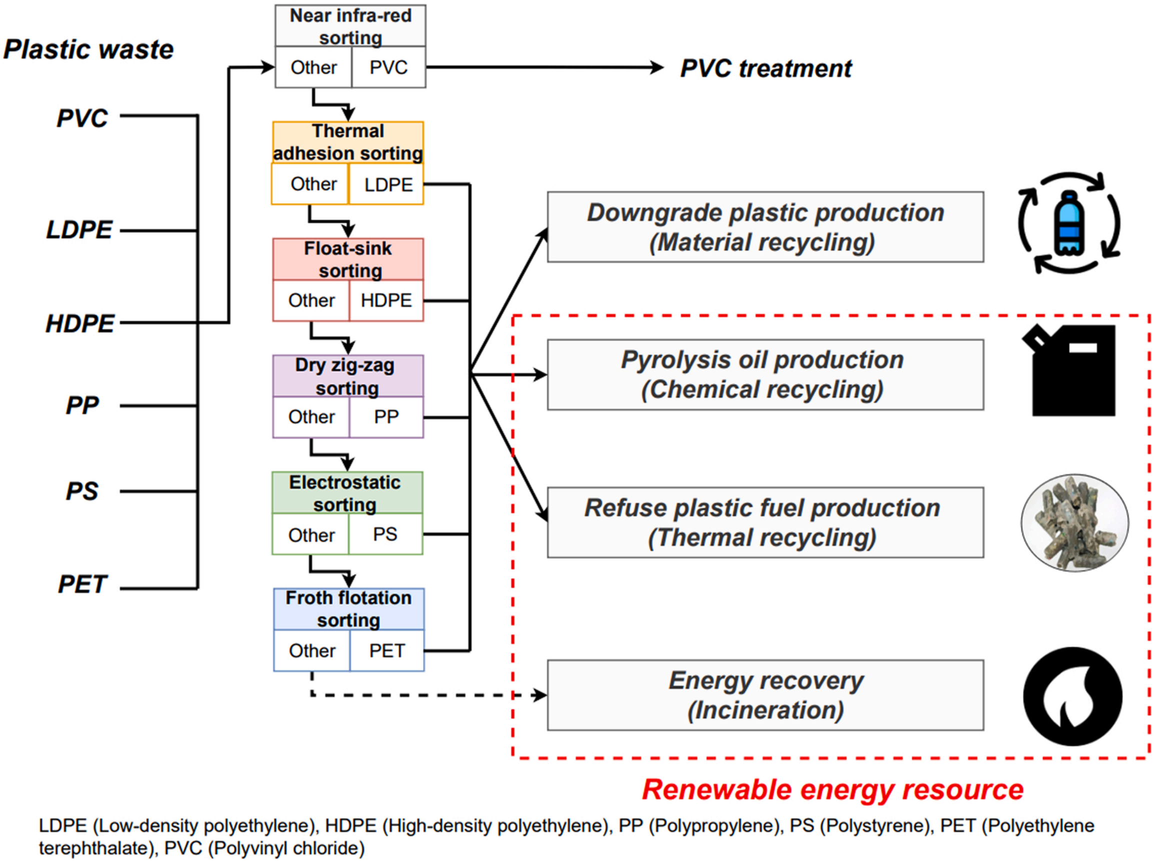

Fig. 1. Overall sorting and recycling system of plastic waste as a renewable energy resource.

5) Froth flotation sorting exploits difference in the plastics' hydrophobicity (Fraunholcz, 2004). First, the plastic waste is dumped into the froth flotation machine, which contains a liquid solution of sodium sulfonate in water. The sinking rate is determined by the hydophobicity. The froth flotation sorting can sort the plastics with a specific gravity difference of less than 0.1, but to sort the plastic, the surface of waste plastic should be treated.
6) NIR spectra sorting exploits differences in NIR absorption by wavelength (Wu et al., 2020). Near-infrared absorption is weaker than infrared absorption, so absorption by multiple harmonics and combined wavelengths overlap; as a result, the spectra are complex. Using these characteristics, waveforms of various plastics are registered in the database, compared with measurement spectrum, and discriminated. The NIR spectra sorting can separate mixed plastics individually, but it has the disadvantage that the cost for separation, such as equipment cost, is significantly high.

2.2. Recycling system

After sorting, the sorted plastic is recycled to produce valuable products or to generate energy. In this study, four recycling methods are considered: 1) downgrade-plastic production (e.g., material recycling); 2) pyrolysis oil production (e.g., chemical recycling); 3) refuse plastic fuel (RPF) production (e.g., thermal recycling); and 4) energy recovery by incineration.

1) Downgrade-plastic production recycles plastic waste to reusable plastics by using processes such as separation, sorting, packaging, washing, crushing, and mixing while maintaining the their chemical structure (Khair and Matsana, 2021). In downgrade-plastic production, each sorted type of plastic waste is dissolute at high temperatures, then regenerated as reusable downgrade plastic.
2) Pyrolysis oil production recycles plastic waste to form pyrolysis oil, which is a renewable fuel. The process uses a pyrolysis reactor, an oil separator, and a condenser while pyrolyzing the plastic waste (Gopinath and Devan, 2020). Each type of plastic waste is pyrolyzed at high temperatures in a pyrolysis reactor. The oil condenses in the condenser, then separated in the oil separator.
3) RPF production recycles plastic waste to reusable fuel by crushing and palletization (Shaha et al., 2020). Each type of waste plastic is crushed, then the crushed plastic is palletized as reusable fuel.
4) Incineration produces heat energy by burning plastic waste (Lea, 1996). Plastic has a high calorific value, so incineration recovers some thermal energy. However, the incineration of plastic waste discharges pollutants such as HCl, HCN, NO_x, SO_x, volatile organic compounds, and greenhouse gas such as CO and CO_2 (Verma et al., 2016). These pollutants cause air pollution and an have devastating effects on the human body and the environment.

Recycled plastic has different values depending on the kind of final product. In addition, different sorting and recycling methods have significantly various capital and operating costs according to the throughput of the plastic waste in each recycling method. Therefore, to improve plastic waste recycling as a renewable energy resource maximizing economic feasibility and to mitigate environmental pollution caused by landfilled plastic and air pollutants according to incineration of plastic, requires optimization of the sorting and recycling strategy, while considering sorting and recycling methods simultaneously.

2.3. Model formulation

This section addresses the optimization model with each variable and parameter. The suggested mathematical model is composed of an objective function with several constraints. The proposed model is an extension of a previous optimization model (Nakatani et al., 2017) of an overall sorting system. The previous model is modified to consider the cost and profit of each recycling method, according to the selection of the recycled plastic type. Then the proposed optimization model uses mixed-integer nonlinear programming (MINLP) to identify the waste-sorting and recycling strategy that maximizes the overall profit. Most of the constraints and objective function are presented below. The rest of the equations with additional details regarding the proposed model are described in the electronic supplemental information (ESI).

2.3.1. Objective function

The objective function is set to maximize the overall profit *Overall profit* of recycled plastic, as determined by subtracting the profit *Profit* of the recycling system from the total annualized cost *TAC* of the sorting and recycling system (Ahn et al., 2020):

$$\textbf{Maximize}\ Overall\ profit\ = Profit\ - TAC \tag{1}$$

2.3.1.1. Profit from recycled plastic. Each type of sorted plastic is recycled to produce downgrade plastic, pyrolysis oil, RPF, and energy. However, PVC generates corrosive gases such as HCl when it is recycled, so in this study, we assumed that PVC is first separated from other types of plastics and is not recycled, but is disposed of to maintain the chlorine concentration.

Profit is calculated by summing the profit $P^{downgrade}$ of downgrade-plastic, the profit $P^{pyrolysis}$ of pyrolysis oil, the profit P^{RPF} of refuse plastic fuel (RPF), and the profit P^{power} gained by power generation by incineration:

$$Profit = P^{downgrade} + P^{pyrolysis} + P^{RPF} + P^{power}. \tag{2}$$

$P^{downgrade}$ is obtained by selling the downgrade plastic produced by recycling, and is calculated by multiplying the price $pri_i^{plastic}$ of downgrade plastic i, the quantity MQ_i of recycled plastic i as downgrade plastic, and annual operating time AOT of the of recycling method (Nakatani et al., 2017):

$$P^{downgrade} = \sum_i pri_i^{plastic} \cdot MQ_i \cdot AOT, \tag{3}$$

where MQ_i is determined by multiplying a binary variable MS_{i} related to the downgrade-plastic i production and the amount Wi of waste plastic:

$$MQ_i = MS_i \cdot W_{\mathrm{i}}, \tag{4}$$

where $MS_i = 1$ when plastic i is recycled as downgrade plastic, and 0 otherwise.

$P^{pyrolysis}$ is the profit obtained by selling pyrolysis oil, and is calculated from the amount of power generated according to the oil's calorific value $Cal_i^{pyrolysis}$. The calorific value of pyrolysis oil generated by recycled plastic differs according to the type of plastic that it is derived from. The yield of pyrolysis is different from the operating condition of the pyrolysis reactor. In this work we assumed that the pyrolysis yield was 40.1% (Chandrasekaran et al., 2018). Thus, $P^{pyrolysis}$ is determined by multiplying $Cal_i^{pyrolysis}$ of pyrolysis oil generated from plastic i, the quantity PQ_i of recycled plastic i as pyrolysis oil, AOT, the efficiency (EST) of the steam turbine generator, and the price $pri^{pyrolysis}$ of pyrolysis oil (Chandrasekaran et al., 2018; Daimijn et al., 2001; Gregorio, 2012; Othman et al., 2008; Sanz-Calcedo et al., 2011), then summing over i:

$$P^{pyrolysis} = \sum_i \mathrm{Cal}_{\mathrm{i}}^{\mathrm{pyrolysis}} \cdot PQ_i \cdot AOT \cdot Yield \cdot EST \cdot pri^{pyrolysis}, \tag{5}$$

where PQ_i is determined by multiplying binary variables PS_i related to pyrolysis oil production, and the amount of waste plastic:

$$PQ_i = PS_i \cdot W_{\mathrm{i}} \tag{6}$$

where $PS_i = 1$ when plastic i is recycled as pyrolysis oil, and 0 otherwise.

P^{RPF} is a profit of selling the RPF as a result of thermal recycling, and it is determined by multiplying the price pri^{RPF} of RPF by the quantity RQ_i of recycled plastic i as RPF, and AOT (Ganesh and Vignesh, 2013), then summing over i:

$$P^{RPF} = \sum_i pri^{RPF} \cdot RQ_i \cdot AOT, \tag{7}$$

where RQ_i is determined by multiplying binary variables RS_i related to the RPF production, and the amount of waste plastic:

$$RQ_i = RS_i \cdot W_{\mathrm{i}} \tag{8}$$

where P^{power} is a profit of power generation calculated by the amount of power by incineration that can be generated due to the calorific value $Cal_i^{plastic}$ of each type i of plastic. Each type of plastic waste has a different $Cal_i^{plastic}$, and we assumed that the residual unsorted plastic incinerated to generate power. Thus, P^{power} is calculated by multiplying $Cal_i^{plastic}$ of waste plastic i, the quantity PQ_i of unsorted plastic i, AOT, EST, and the price $pri^{electricity}$ of electricity (Areeprasert et al., 2017; Othman et al., 2008), then summing over i:

$$P^{power\ generation} = \sum_i \mathrm{Cal}_{\mathrm{i}}^{\mathrm{plastic}} \cdot RE_i \cdot AOT \cdot \mathrm{EST} \cdot \mathrm{pri}^{electricity} \tag{9}$$

where RQ_i is calculated by subtracting the W_i from the sum of MQ_i, PQ_i andRQ_i:

$$RE_i = W_i - (MQ_i + PQ_i + RQ_i) \tag{10}$$

Parameters used in the calculations (Tables S.1, S.4–9 in ESI) were obtained from the literature.

2.3.1.2. Total annualized cost of sorting and recycling system. To estimate the cost of the sorting and recycling system, the total annualized cost *TAC* is calculated; it indicates the adjusted cost that occurs equally in every year of the project lifetime, which would give the same net present cost as the actual cash-flow sequence. The *TAC* is determined by summing the equivalent annual cost *EAC* and total product cost *TPC* (Lim et al., 2021d, 2021a, 2021b):

$$TAC = EAC + TPC. \tag{11}$$

First, *EAC* is calculated from the total capital investment *TCI* and annuity factor *AF* (Kim et al., 2021; Lim et al., 2021c):

$$EAC = \frac{TCI}{AF}, \tag{12}$$

where *TCI* is the capital investment, including but not limited to, costs of equipment, land, and installation. *TCI* is calculated by summing the fixed capital investment *FCI*, working capital investment *WCI*, and start-up cost *SUC* (Lim et al., 2022; Lim and Kim, 2020):

$$TCI = FCI + WCI + SUC. \tag{13}$$

FCI is the initial cost of starting the manufacturing facility, and generally includes building cost, plumbing cost, installation cost of equipment, and more. In this work, the *FCI* is estimated from the total equipment cost of the sorting and recycling system:

$$FCI = 3.33 \cdot C^{equipment} \tag{14}$$

where $C^{equipment}$ is the sum of the equipment cost $EC^{sorting}$ of the sorting system, equipment cost $EC^{downgrade}$ of downgrade-plastic production process, equipment cost $EC^{pyrolysis}$ of pyrolysis oil production process, equipment cost EC^{RPF} of the RPF production process, and equipment cost EC^{power} of the incineration process:

$$C^{equipment} = EC^{sorting} + EC^{downgrade} + EC^{pyrolysis} + EC^{RPF} + EC^{power}. \tag{15}$$

$EC^{sorting}$ includes the equipment cost of thermal adhesion sorting, float-sink sorting, dry zig-zag sorting, electrostatic sorting, and froth flotation sorting, and it is determined from referenced equipment cost:

$$_{EC}sorting = \sum_{s}\sum_{i} REC_{s}^{sorting} \cdot \left(\frac{(MQ_i + PQ_i + RQ_i)}{RC_{s}^{sorting}}\right)^{\mathrm{CCF}}, \tag{16}$$

where $REC_s^{sorting}$ denotes referenced equipment cost of sorting method s, $RC_s^{sorting}$ denotes the referenced capacity of sorting method s, and CCF denotes the capacity correction factor.

$EC^{downgrade}$ is composed of the equipment cost of grinding, washing, drying, and granulation, and is calculated from the referenced equipment cost (Gardoni and Guarino, 2016; Ferrada et al., 2002; Lim et al., 2021a):

$$_{EC}downgrade = \sum_{i} REC^{downgrade} \cdot \left(\frac{MQ_i}{RC^{downgrade}}\right)^{\mathrm{CCF}}, \tag{17}$$

where $REC^{downgrade}$ denotes referenced equipment cost of downgrade-plastic production process, and $RC^{downgrade}$ denotes the referenced capacity of the downgrade-plastic production process.

$EC^{pyrolysis}$ is determined from the referenced equipment cost of the pyrolysis oil production process, which is composed of the pyrolysis reactor, oil separator, pretreatment process, and condenser (Ferrada et al., 2002; Patel et al., 2020):

$$_{EC}pylorysis = \sum_{i} REC^{pyrolysis} \cdot \left(\frac{PQ_i}{RC^{pyrolysis}}\right)^{\mathrm{CCF}}, \tag{18}$$

where $REC^{pyrolysis}$ denotes the referenced equipment cost of the pyrolysis oil production process, and $RC^{pyrolysis}$ denotes the referenced capacity of the pyrolysis oil production process.

EC^{RPF} is composed of the equipment cost of crushing and palletization and is calculated from the referenced equipment cost (Ferrada et al., 2002):

$$_{EC}RPF = \sum_{i} REC^{RPF} \cdot \left(\frac{RQ_i}{RC^{RPF}}\right)^{\mathrm{CCF}} \tag{19}$$

where REC^{RPF} denotes referenced equipment cost of RPF production process, and RC^{RPF} denotes the referenced capacity of the RPF production process.

$EC^{incineration}$ is determined from the referenced equipment costs, including those of the stack, superheater, economizer, and cooling tower (Midilli et al., 2021):

$$_{EC}incineration = \sum_{i} REC^{incineration} \cdot \left(\frac{RE_i}{RC^{incineration}}\right)^{\mathrm{CCF}} \tag{20}$$

where $REC^{incineration}$ denotes referenced equipment cost of the incineration process, and $RC^{incineration}$ denotes the referenced capacity of the incineration process.

WCI is composed of maintaining cost of feedstock, product, and spare parts in the facility, and it is assumed to be 10% of FCI (Jeong et al., 2015):

$$WCI = 0.1 \cdot FCI. \tag{21}$$

Finally, SUC is the cost incurred starting a new process, including the business cost, loan, and technology cost, and it is assumed to be as 20% of FCI (Jeong et al., 2015):

$$SUC = 0.2 \cdot FCI. \tag{22}$$

Second, TPC (Eq. 11) is the cost incurred during production and service, and it is generally composed of raw material, utility, and energy costs. We assumed the PVC is disposed of, to maintain the chlorine concentration, so the TPC is calculated by summing the raw material cost $C^{raw\ material}$, utility cost $C^{utility}$, fuel cost C^{fuel} and disposal cost of PVC $C^{disposal}$ (Lim et al., 2021a):

$$TPC = C^{raw\ material} + C^{utility} + C^{fuel} + \mathrm{C}^{\mathrm{disposal}}, \tag{23}$$

$C^{raw\ material}$ is calculated by summing the NaCl cost C^{NaCl}, ethanol cost $C^{ethanol}$, deforming agent cost $C^{deforming\ agent}$, alum cost C^{alum}, H_3PO_4 cost C^{H3PO4}, urea cost C^{urea}, NaH cost C^{NaH}, nitrogen cost $C^{nitrogen}$, CaO cost C^{CaO} and $Ca(OH)_2$ cost $C^{Ca(OH)2}$:

$$\begin{aligned} C^{raw\ material} = {} & C^{NaCl} + C^{ethanol} + C^{deforming} + C^{alum} + C^{H3PO4} + C^{urea} + C^{NaH} \\ & + C^{nitrogen} + C^{CaO} + C^{Ca(OH)2} \end{aligned} \tag{24}$$

Operation of the float-sink sorting system uses NaCl to control ρ_{L}. The cost C^{NaCl} of the NaCl is determined by multiplying the price pri^{NaCl}, the quantity QN_s of NaCl consumption per sorted plastic in sorting method s, the sum of the sorted plastic i (i.e., the sum of the MQ_i, PQ_i and RQ_i) and total operating time H_s of sorting method s (TRIDGE, 2020):

$$C^{nacl} = \sum_{i}\sum_{s} pri^{NaCl} \cdot \mathrm{QN}_s \cdot \left(MQ_i + PQ_i + RQ_i\right) \cdot H_s \tag{25}$$

where H_s is calculated from a binary variable TS_i that is related to the sorting method and the amount of waste plastic:

$$H_s = \sum\nolimits_{i=1}^{6} TS_i \cdot \frac{W_i}{s}, \tag{26}$$

where $TS_i = 1$ when plastic i is sorted, and 0 otherwise, and s denotes the processing speed of a sorting machine.

Ethanol is used to control the specific gravity of the solution during float-sink sorting; the cost of ethanol is (GlobalPetrolPrives, 2022):

$$C^{ethanol} = \sum_{i}\sum_{s} pri^{ethanol} \cdot QE_s \cdot (MQ_i + PQ_i + RQ_i) \cdot H_s, \tag{27}$$

where $pri^{ethanol}$ denotes the price of ethanol, and QE_s denotes the quantity of ethanol consumption per sorted plastic in sorting method s.

$C^{deforming}$ is the cost to produce downgrade-plastic in the recycling system, and this calculated as:

$$C^{defoaming} = \sum_{i}\sum_{r} pri^{defoaming} \cdot QDA_r \cdot MQ_i \cdot \mathrm{AOT}, \tag{28}$$

where $pri^{deforming}$ denotes the price of deforming agent and QDA_r denotes the quantity of deforming agent consumption per sorted plastic in recycling method r.

C^{alum} is the cost incurred to produce downgrade-plastic in the recycling system (Alavi and Ansari, 2021):

$$C^{alum} = \sum_{i}\sum_{r} pri^{alum} \cdot QA_r \cdot MQ_i \cdot \mathrm{AOT}, \tag{29}$$

where pri^{alum} denotes the price of alum and QA_r denotes the quantity of alum consumption per sorted plastic in recycling method r.

H_3PO_4 is required to produce downgrade plastic, and the cost is (Pereira et al., 2017):

$$C^{H3PO4} = \sum_{i}\sum_{r} \mathrm{pri}^{H3PO4} \cdot QH_r \cdot MQ_i \cdot AOT, \tag{30}$$

where pri^{H3PO4} denotes the price of H_3PO_4, and QH_r denotes the quantity of H_3PO_4 consumption per sorted plastic in recycling method r.

Urea is also required to operate downgrade-plastic production, and the cost is (Antonetti et al., 2017):

$$C^{urea} = \sum_{i}\sum_{r} pri^{urea} \cdot QU_r \cdot MQ_i \cdot \mathrm{AOT} \tag{31}$$

where $\mathrm{pri}^{\mathrm{urea}}$ denotes the price of urea and QU_r denotes the quantity of urea consumption per sorted plastic in recycling method r.

C^{NaH} is the cost incurred to produce downgrade plastic, pyrolysis oil, and RPF, and is calculated from the sum of the quantity of recycled plastic i as downgrade plastic, pyrolysis oil, and RPF (Pereira et al., 2017):

$$C^{NaH} = \sum_i \sum_r pri^{NaH} \cdot \mathrm{QNA_r} \cdot (MQ_i + PQ_i + RQ_i) \cdot \mathrm{AOT}, \tag{32}$$

where pri^{NaH} denotes the price of NaH, and QNA_r denotes the quantity of NaH consumption per sorted plastic in recycling method r.

$C^{nitrogen}$ required to operate the pyrolysis oil and RPF production process, and thus it is calculated from the sum of the quantity of recycled plastic i as pyrolysis oil and RPF (Fontes et al., 2010):

$$C^{nitrogen} = \sum_i \sum_r \mathrm{pri}^{nitrogen} \cdot QNT_r \cdot \left(PQ_i + RQ_i \right) \cdot AOT, \tag{33}$$

where $pri^{nitrogen}$ denotes the price of nitrogen and QNT_r denotes the quantity of nitrogen consumption per sorted plastic in recycling method r.

C^{CaO} is the cost incurred to operate the pyrolysis oil and RPF production process, and it is also calculated from the sum of the quantity of recycled plastic i as pyrolysis oil and RPF (Pääkkönen et al., 2019):

$$C^{CaO} = \sum_i \sum_r pri^{CaO} \cdot \mathrm{QCA_r} \cdot RQ_i \cdot AOT \tag{34}$$

where pri^{CaO} denotes the price of CaO and $\mathrm{QCA_r}$ denotes the quantity of CaO consumption per sorted plastic in recycling method r.

$C^{Ca(OH)2}$ also required to operate pyrolysis oil and RPF production process (Donneys-Victoria et al., 2018):

$$C^{Ca(OH)2} = \sum_i \sum_r \mathrm{pri}^{Ca(OH)2} \cdot \mathrm{QCA2_r} \cdot RQ_i \cdot AOT, \tag{35}$$

where $pri^{Ca(OH)2}$ denotes the price of $Ca(OH)_2$ and $\mathrm{QCA2_r}$ denotes the quantity of $Ca(OH)_2$ consumption per sorted plastic in recycling method r.

$C^{utility}$ is calculated by summing the electricity cost $C^{sorting-elect}$ in the sorting system, electricity cost $C^{recycling-elect}$ in recycling system and water cost C^{water} in the recycling system:

$$C^{utility} = C^{sorting-elect} + C^{recycling-elect} + C^{water}, \tag{36}$$

$C^{sorting-elect}$ is electricity cost required to operate the overall sorting system (Nakatani et al., 2017):

$$C^{sorting-elect} = E \cdot H \cdot \mathrm{pri}^{electricity} \tag{37}$$

where E denotes the electricity consumption of the sorting machine and $pri^{electricity}$ denotes the price of electricity.

$C^{recycling-elect}$ is electricity cost required to operate the overall recycling system and incineration process, and is calculated from the quantity of recycled plastic i and quantity of remaining plastic i (Nakatani et al., 2017):

$$C^{recycling-elect} = \sum_i \sum_r pri^{electricity} \cdot QEL_r \cdot \left(MQ_i + PQ_i + RQ_i + RE_i \right) \cdot AOT, \tag{38}$$

where QEL_r denotes the quantity of electricity consumption per sorted plastic in recycling method r.

C^{water} also required to operate the overall recycling system and incineration process, and is calculated from the quantity of sorted plastic i and quantity of recycled plastic i (Lim et al., 2021b):

$$C^{water} = \sum_i \sum_r pri^{water} \cdot QW_r \cdot \left(MQ_i + PQ_i + RQ_i + RE_i \right) \cdot AOT, \tag{39}$$

where pri^{water} denotes price of water and QW_r denotes the electricity consumption per sorted plastic in recycling method r.

C^{fuel} required in the recycling system, and it is calculated by summing the diesel cost C^{diesel}, light oil cost $C^{light\ oil}$ and recycled oil cost $C^{recycled\ oil}$:

$$C^{fuel} = C^{diesel} + C^{light\ oil} + C^{recycled\ oil}, \tag{40}$$

C^{diesel} is only required to operate downgrade-plastic production process, and is calculated from MQ_i (Zhang and Jiang, 2022):

$$C^{diesel} = \sum_i \sum_r pri^{diesel} \cdot QD_r \cdot MQ_i \cdot \mathrm{AOT} \tag{41}$$

where pri^{diesel} denotes price of diesel and QD_r denotes quantity of diesel consumption per sorted plastic in recycling method r.

$C^{light\ oil}$ is light oil cost incurred to produce downgrade plastic, RPF, and energy, and it is determined from the quantity of recycled plastic i as pyrolysis oil and RPF and quantity of remaining plastic i (Zhang and Jiang, 2022):

$$C^{light\ oil} = \sum_i \sum_r pri^{light\ oil} \cdot QLO_r \cdot (PQ_i + RQ_i + RE_i) \cdot AOT, \tag{42}$$

where $pri^{light\ oil}$ denotes the price of light oil and QLO_r denotes the quantity of light oil consumption per sorted plastic in recycling method r.

$C^{recycled\ oil}$ is recycled oil cost required to produce downgrade-plastic and RPF (Zhang and Jiang, 2022):

$$C^{recycled\ oil} = \sum_i \sum_r pri^{recycled\ oil} \cdot QREO_r \cdot (PQ_i + RQ_i) \cdot AOT, \tag{43}$$

where $pri^{recycled\ oil}$ denotes price of recycled oil and $QREO_r$ denotes quantity of recycled oil consumption per sorted plastic in recycling method r. Details of parameters used to estimate the total annualized cost of the sorting and recycling system are presented in the ESI.

2.3.2. Constraints

In constraints, the sum of RE_i that are recycled to produce power by incineration is calculated by subtracting the sum of the sorted plastic i (i.e., the sum of MQ_i, PQ_i, and RQ_i) from the sum of W_i excluding PVC:

$$\sum_i RE_i = \sum_i W_i - \sum_i (MQ_i + PQ_i + RQ_i). \tag{43}$$

3. Results and discussion

This section presents the optimal sorting and recycling strategy of plastic waste, considering economic feasibility by maximizing the overall profit of the sorting and recycling system. The proposed optimization problem was solved using GAMS 36.2.0 with Intel® Xeon® CPU E5–1660 v3 @ 3.00 GHz and 64 GB RAM. To compare the economic feasibility of the optimal strategy, we set two cases: (1) the conventional case in South Korea (CCS); (2) the conventional case in Japan (CCJ) and the overall profit of the optimal case, and each conventional case was compared (Korea Environmet Institute, 2008). Then the total amount of plastic waste in Japan and South Korea was equally set to ~4.9 t/h based on Gyeongsan area in South Korea. Table 1 shows the proportion of recycled plastic according to each recycling method in each conventional case.

In both CCS and CCJ, incineration and downgraded plastic production are dominant, and CCJ has a higher proportion of pyrolysis oil production and RPF production than CCS. Then to demonstrate the environmental effect of the derived optimal sorting and recycling strategy, environmental assessment is addressed, and the annual CO_2,

Table 1
Proportion of recycled plastic according to each recycling method in each conventional case.

Recycling methods	Case	
	CCS [wt%]	CCJ [wt%]
Downgrade-plastic production	40	47
Pyrolysis oil production	0.2	6.5
Refuse plastic fuel production	1.8	14
Incineration	57	31

SO_x, and NO_x emissions of each case are compared.

3.1. Optimization results

Fig. 2 shows the amounts of recycled plastic in the CCS. In South Korea, LDPE and HDPE are recycled to produce downgrade plastic, about 1,140 kg/h and 840 kg/h, respectively. And only 98 kg/h of PET is recycled to produce pyrolysis oil and RPF, and most of the plastic, which are HDPE (240 kg/h), PP (1,500 kg/h), PS (600 kg/h), and PET (443 kg/h) are incinerated for energy recovery.

In contrast, Japan dominantly recycles material. recycling is dominant. Fig. 3 shows the amounts of recycled plastic in the CCJ. CCJ recycles 381 kg/h of HDPE, 1,096 kg/h of PP, 283 kg/h of PS, and 540 kg/h of PET to produce downgrade plastic. Only 317 kg/h of PS is recycled as pyrolysis oil production, and 669 kg/h of HDPE is recycled to produce RPF. The remaining plastics LDPE (1,140 kg/h) and PP (404 kg/h) are incinerated to recover energy.

Fig. 4 shows the amount of sorted plastic in the optimal sorting strategy while maximizing overall profit. As a result, all type of plastic is sorted for recycling, and HDPE (1,080 kg/h) is recycled as downgrade plastic production, LDPE (1,140 kg/h), PP (1,500 kg/h), and PS (600 kg/h) are recycled to produce pyrolysis oil, and finally, PET (540 kg/h) is recycled as RPF production. The optimal case indicated that chemical recycling, which is pyrolysis oil production is dominant, and incineration for energy recovery is not the economic method. Table 2 shows the amounts of recycled plastic and overall recycling efficiency in each case.

For comparison (Table 2), the CCS recycles ~2,078 kg/h of plastic, as downgrade plastic, pyrolysis oil, and RPF, and the remaining 2,782 kg/h is incinerated, whereas the CCJ recycles ~ 3,316 kg/h of plastic, which 59% more than in CCS, and the remaining 1,544 kg/h is incinerated. Therefore, CCJ has ~ 25% higher the overall recycling efficiency than CCS, by increasing the amounts of downgrade plastic, pyrolysis oil, and RPF production. In contrast, in the Optimal case, all of the plastic is recycled, so the overall recycling efficiency is 100%. Especially the amount of recycled plastic for pyrolysis oil production is ~ 3,240 kg/h, indicating 66% of total recycled plastic. Fig. 5 shows the profit per 1 kg of recycled plastic in each case.

From Fig. 5, CCS $P^{downgrade} = 0.626$ US\$/kg, $P^{pyrolysis} = 0.048$ US\$/kg, $P^{RPF,} = 0.484$ US\$/kg, and $P^{power} = 0.725$ US\$/kg, so the *Profit* of CCS is 1.884 US\$/kg. In the CCJ, the profits are $P^{downgrade} = 0.706$ US\$/kg, $P^{pyrolysis} = 3.044$ US\$/kg, $P^{RPF,} = 3.856$ US\$/kg, and $P^{power} = 0.443$ US\$/kg, so the *Profit* is 8.049 US\$/kg. In the Optimal case, the profits are $P^{downgrade} = 0.307$ US\$/kg, $P^{pyrolysis} = 33.317$ US\$/kg, $P^{RPF,} = 2.979$ US\$/kg, and $P^{power} = 0$ US\$/kg (because none of the plastic is left to be burned), so *Profit* of the optimal case is 36.603 US\$/kg, which is 3,317% that of CCS, and 492% that of CCJ. $P^{pyrolysis}$ of the optimal case is very high because the calorific value of pyrolysis oil can be maximized according by recycling the LDPE, PP, and PS to produce pyrolysis oil, which has a high calorific value.

Fig. 6 shows the cost per kilogram of recycled plastic differed among the case. In the CCS the costs were $EAC = 0.022$ US\$/kg, $TPC = 0.731$ US\$/kg, and $TAC = 0.753$ US\$/kg. In the CCJ, the costs were $EAC = 0.027$ US\$/kg, $TPC = 0.806$ US\$/kg and $TAC = 0.833$ US\$/kg. Finally, in the derived optimal case the costs were $EAC = 0.066$ US\$/kg, $TPC = 1.055$ US\$/kg, and $TAC = 1.121$ US\$/kg. In the optimal case, the cost of EAC increased about 300% and 244% compared to CCS and CCJ, respectively, because the optimal case significantly increases the amount of plastic that is recycled for pyrolysis production, which has high equipment costs. The *TPC* of the optimal case also increased, by about 144% and 131% compared to CCS and CCJ, respectively. The reason for this increase is that the operating cost of each recycling method is higher than the cost of the incineration process. Finally, Fig. 7 shows the overall profit per 1 kg of recycled plastic in each case.

The *Overall profit* was calculated as: CCS, 1.131 US\$/kg; CCJ, 7.215 US\$/kg; Optimal, 35.48 US\$/kg, i.e., the derived optimal case significantly increased *Overall profit* to about 3,137% compared to CCS and 492% compared to CCJ. In the two conventional cases, the overall cost of sorting and recycling is high due to the unoptimized sorting and recycling system of plastic waste. Thus, these cases landfill or incinerate most of the plastics. However, in the optimal case, although the *TAC* of the optimal value slightly increased, the *Overall profit* was increased significantly. Therefore, we believe that the results can yield excellent economic advantages and environmental protection by improving the economic feasibility of plastic recycling by maximizing the overall profit of the sorting and recycling system.

3.2. Environmental assessment

To compare the environmental feasibility of the derived optimal strategy, this section quantified the annual CO_2, SO_x, and NO_x emissions in each case to demonstrate the environmental effect of the derived optimal sorting and recycling strategy. The emission of each air pollutant is calculated per kilogram of recycled plastic and the amount of recycled plastic according to the recycling method in each case. Table 3 shows the emission rate per 1 kg of recycled plastic according to each recycling methods (Park and Choi, 2006).

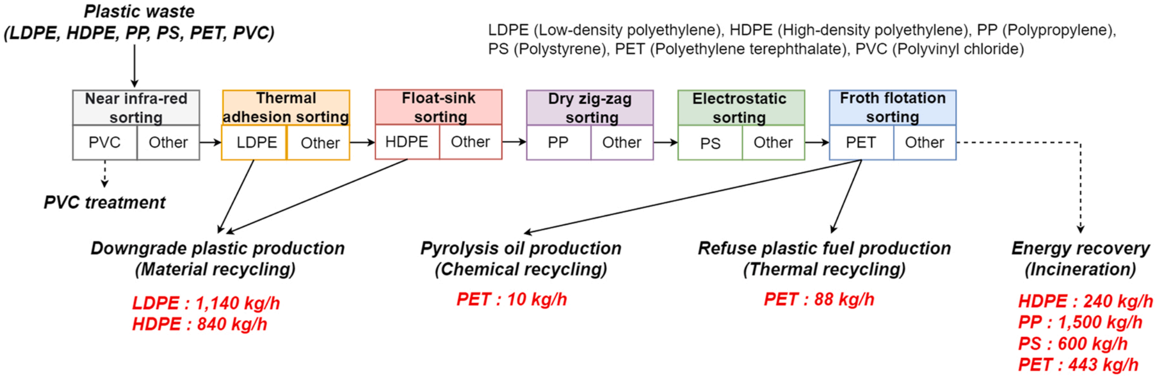

Fig. 2. Amounts of recycled plastic in the CCS.

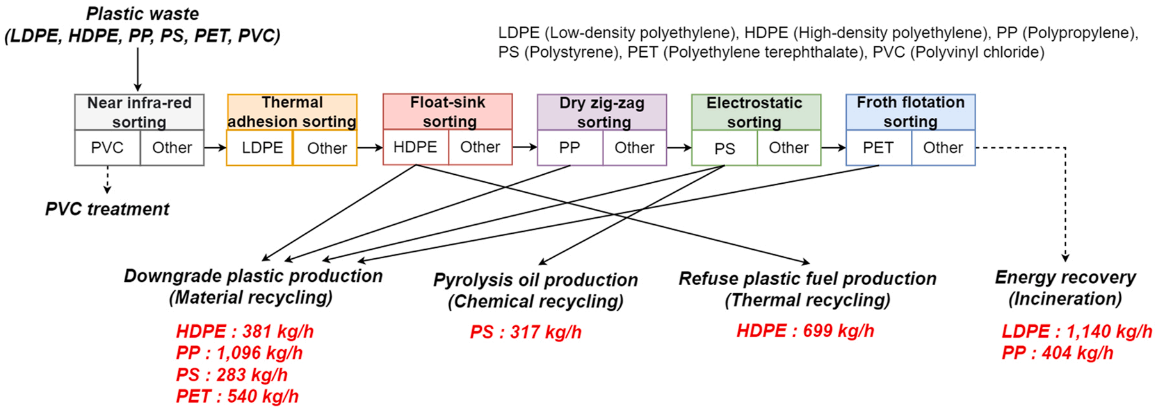

Fig. 3. Amounts of recycled plastic in the CCJ.

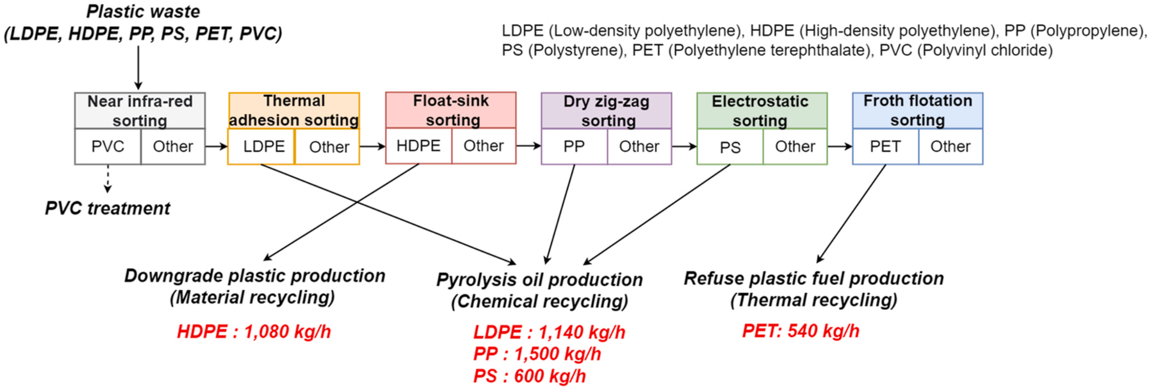

Fig. 4. Amounts of recycled plastic in the optimal case.

Table 2
Amounts of recycled plastic and overall recycling efficiency.

Recycling methods	Case		
	CCS [kg/h]	CCJ [kg/h]	Optimal [kg/h]
Downgrade-plastic production	1,980	2,300	1,080
Pyrolysis oil production	10	317	3,240
Refuse plastic fuel production	88	699	540
Incineration	2,782	1,544	0
Overall recycling efficiency [%]	43	68	100

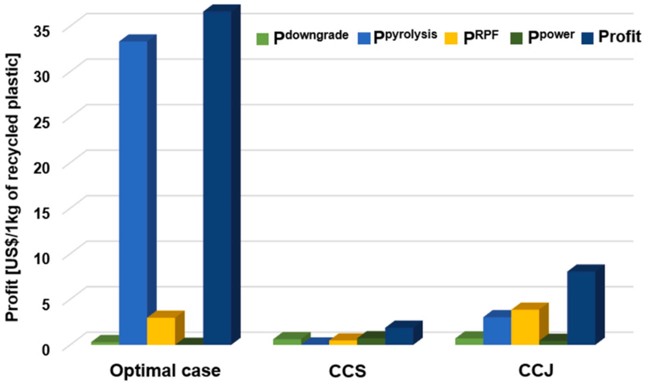

Fig. 5. Profit per 1 kg of recycled plastic in each case.

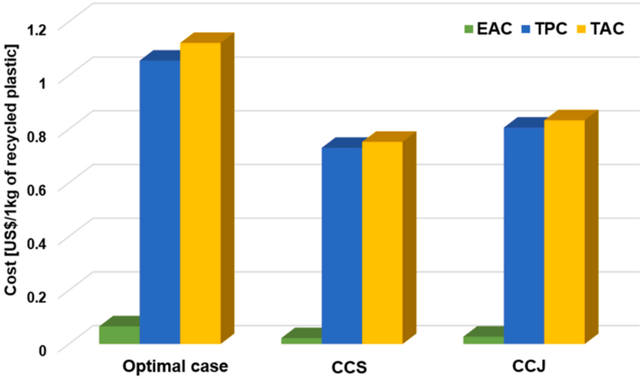

Fig. 6. Cost per 1 kg of recycled plastic in each case.

Fig. 8 shows the annual CO_2 emission in each case. The optimal case emitted less CO_2 annually than CCS and CCJ. For CCS, CO_2 emissions were: downgrade-plastic production, 22,228 t/y; pyrolysis oil production, 70 t/y; RPF production, 314 t/y; incineration, 56,052 t/y. For CCJ, they were: downgrade-plastic production, 25,890 t/y; pyrolysis oil production, 2,222 t/y; RPF production, 2,493 t/y; incineration, 31,109 t/y. Thus, the total CO_2 emissions were: CCS, 78,724 t/y; CCJ, 61,713 t/y.

However, for optimal case, CO_2 emissions were: downgrade-plastic production, 12,157 t/y; pyrolysis oil production, 22,706 t/y; RPF production, 1,916 t/y, with no emission from incineration. Consequently, the CO_2 emission of the Optimal case is 36,789 t/y, which is 47% that of CCS and 60% that of CCJ.

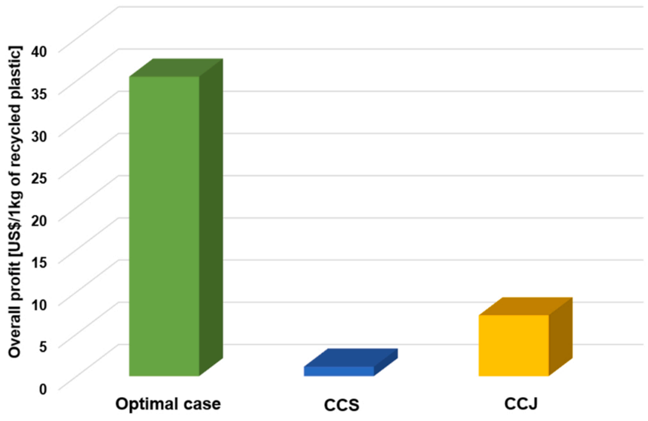

Fig. 7. Overall profit per 1 kg of recycled plastic in each case.

Table 3
Emission rate per kilogram of recycled plastic according to each recycling method.

Recycling methods	Emission type		
	CO_2	SO_x	NO_x
Downgrade-plastic production	1.3	0	3.1×10^{-3}
Pyrolysis oil production	0.8	1.3×10^{-5}	0.4×10^{-4}
Refuse plastic fuel production	0.4	1.3×10^{-5}	0.4×10^{-4}
Incineration	2.3	2.2×10^{-4}	0.9×10^{-5}

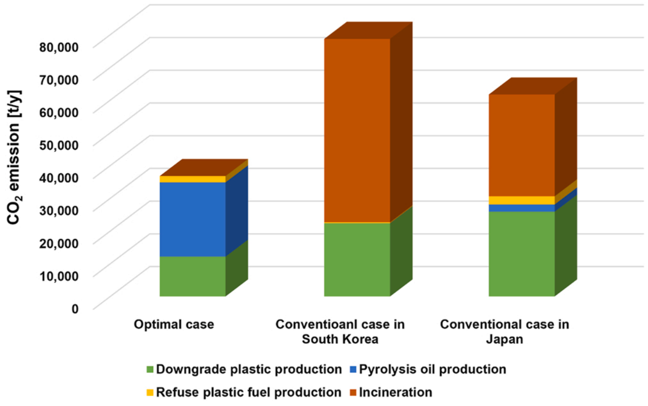

Fig. 8. Annual CO_2 emission in each case.

The CO_2-emission rate per 1 kg of recycled plastic from the material, chemical, thermal, and incineration is about 1.3 kg, 0.8 kg, 0.4 kg, and 2.3 kg (Assessment, n.d.). Incineration of plastic waste emits the most CO_2, and in each conventional case, about 31 – 57% is incinerated, so CO_2 emission is high. However, in the optimal case all of the plastic waste is recycled, so the CO_2-intensive incineration process is avoided, and this case can reduce CO_2 emission significantly.

Fig. 9 shows the annual SO_x emission in each case. The optimal case also reduced annual SOx emission significantly. For CCS, calculated SOx emissions were: pyrolysis oil production, 0.001 t/y, RPF production, 0.009 t/y; incineration, 5.312 t/y. For CCJ, they were: pyrolysis oil production, 0.034 t/y; RPF production, 0.076 t/y; incineration, 2.949 t/y. Therefore, the total SO_x emissions were: CCS, 5.3 t/y; CCJ, 3.1 t/y.

In contrast, for the optimal case, calculated SO_x emissions were: pyrolysis oil production, 0.354 t/y; RPF production, 0.059 t/y, with none from incineration. Accordingly, the SO_x emission of the optimal case is about 0.4 t/y which is about 8% that of CCS, and 14% that of CCJ. The SO_x emission rate per kilogram of recycled plastic is also highest in incineration. Thus, each conventional case in which a large amount of plastic is being incinerated emitted a large amount of SO_2. However, the optimal case can reduce SO_x as all plastic waste is recycled aside from incineration.

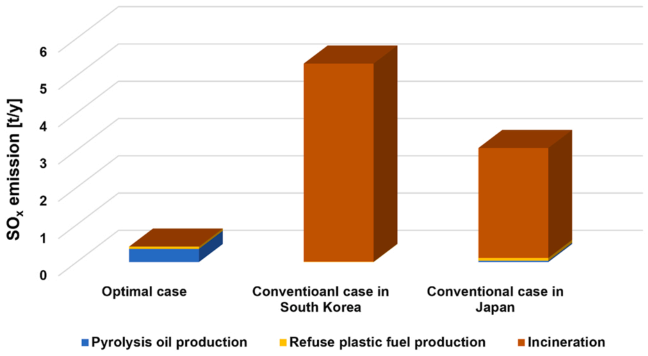

Fig. 9. Annual SOx emission in each case.

Finally, Fig. 10 shows the annual NO_x emission in each case. For CCS, the calculated NO_x emissions were: downgrade-plastic production, 53.77 t/y; pyrolysis oil production, 0.035 t/y, RPF production, 0.308 t/y; incineration, 2.181 t/y. For the CCJ, they were: downgrade-plastic production, 62.46 t/y; pyrolysis oil production, 1.111 t/y; RPF production, 2.449 t/y; and incineration, 1.211 t/y. Consequently, the overall NO_x emissions were large: CCS, 56 t/y; and CCJ, 67 t/y.

However, in the optimal case NO_x emissions were: downgrade-plastic production, 29.33 t/y; pyrolysis oil production, 11.35 t/y; RPF production 1.892 t/y, with no emission by incineration. Thus, the NO_x emission of the optimal case is about 42 t/y, which is 75% that of CCS and 63% that of CCJ.

The NOx emission rate per kilogram of recycled plastic is the highest in material recycling. Thus, each conventional case in which a large amount of plastic is recycled as material recycling, about 40 – 47% emitted a large amount of NO_x. However, the optimal case can reduce a significant amount of NO_x to reduce the downgrade-plastic production.

4. Conclusion

This study found an optimal strategy to sort and recycle plastic waste as a renewable energy resource for maximizing economic feasibility and mitigation of environmental pollution caused by landfilled plastic and air pollutants according to incineration of plastic. This study makes two major contributions to the literature. First, to the best of the author's knowledge, it is the first attempt to optimize the plastic waste sorting and recycling system by deriving an optimal sorting and recycling strategy to improve the recycling of for plastic waste as a renewable energy resource maximizing economic feasibility and mitigating of environmental pollution. Also, the results allow us to increase the

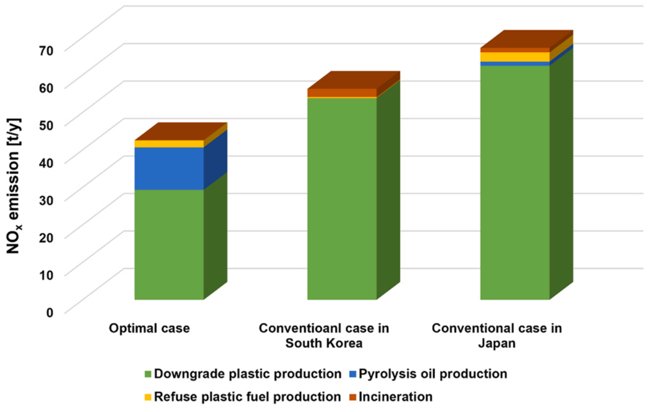

Fig. 10. Annual NO_x emission in each case.

recycling of plastic waste by maximizing the overall profit of the plastic waste sorting and recycling system. In the derived optimal sorting and recycling strategy, HDPE is recycled to produce downgrade plastic; LDPE, PP and PS are recycled as pyrolysis oil; and PET is recycled to produce refuse plastic fuel. The derived optimal case can increase overall profit by ~ 3,137% compared to CCS, and 492% compared to CCJ, and also emission of air pollutants. Thus, this study provides valuable insight into the many recycling industries of waste plastics to achieve clean production, cost-effectiveness, and environmental protection. In many literatures, strategies such as operating condition optimization were proposed to reduce the cost of each sorting method. Thus, in further study, it is crucial to consider the detailed proposed strategies in deriving the optimal solution to maximize economic feasibility.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.psep.2022.11.027.

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