Spatial simulation and LCA evaluation on the plastic waste recycling system in Tianjin

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Abstract With the rapid economic development in China, the amount of plastic waste (PW) generated has greatly increased and much of the waste is currently not treated. To reduce greenhouse gas (GHG) emissions from recycling of PW, we estimated the PW flow and considered methods to improve the household PW recycling system in Tianjin by adjusting processes during transportation and establishing a PW recycling factory in Zi’ya Industrial Park. The goal of the study was to identify reasonable improvements for the recycling system and clarify the environmental load. Geographic information system (GIS) technology was used to simulate transport processes for comparing GHG emissions from the transport processes between the present case and an improved case. Life cycle assessment (LCA) was used to compare GHG emissions between a projected scenario and a baseline scenario. Estimated GHG emissions during transport processes in the improved case were reduced by about 12,197 t CO₂ eq per year compared to the present case, equivalent to about 65.9 % of the total emissions in the present case. GHG emissions in the projected scenario were about 101,738 t CO₂ eq less per year than the baseline scenario, equivalent to about 75.5 % of the total emissions in the baseline scenario.

Keywords Plastic waste recycling · LCA · GIS · Transport simulation

Introduction

With the rapid economic development and increase in urbanization in China, the amount of plastic waste (PW) generated has greatly increased, including in Tianjin, which had a population of 12.9 million in 2010. There are two contrasting components of the current PW recycling system in Tianjin [1]: the formal and informal sectors. The formal sector includes recovery centers that are facilities where PW and other valuable waste materials are bought from local residents. When the collected PW reaches a certain amount, it is transported by truck to another facility called a market; these belong to large recycling companies. Due to the limited storage area available in recovery centers, there is a need to speed up the transfer of PW to the market. There are about 900 recovery centers, mainly in densely populated areas. The informal sector consists of waste collectors who conduct illegal collection activities without operating licenses, using bicycles or motorbikes equipped with trailers to travel around rural areas and buy PW and other valuable waste from residents. The collected PW is resold to a market belonging to an individual trader. There are about 100 markets in Tianjin, most of which belong to individual traders. They undertake manual sorting of PW before reselling the sorted material to recycling factories. Due to the lack of compression processing in the markets, the loading ratio of trucks that transport the waste materials can be as low as 50 % of maximum capacity. The PW that is gathered and sorted in Tianjin is mainly resold to recyclers in Wen’an, Hebei Province, which is adjacent to Tianjin. These small-scale recycling factories have
serious environmental problems relating to water and soil pollution.

The circular economy concept has been developed in recent years in China. It is a general term for the activities of reducing, reusing, and recycling during production, circulation, and consumption processes [2]. The enterprise, region, and overall society are the main focuses. Eco-industrial parks, as part of the circular economy, are classified as the regional level. The Zi’ya Environmental Protection Industrial Park was established in 2002 to treat both domestic and imported waste (red circle on the right side, Fig. 1). It was authorized as a National Circular Economy Industrial Park in 2007. Most of the companies in Zi’ya dismantle and sort the waste to provide raw materials for manufacturing companies. Therefore, the PW recycling factory is urgently needed in the industrial park.

Tianjin was chosen as the study target because of both the need for recycling facilities in the area and the relevant data for the study were easily available and reliable. The inefficient nature of the current recycling system was described above, effective improvements of the present system were considered necessary. We considered improvements for the household PW recycling system in Tianjin using recovery centers substitute individual operators, adopting cyclic collection method instead of round-trip method during collection process, adding the compression processing in the transport process and Tianjin would set up a PW recycling factory in Zi’ya in which more effective recycling technology would be applied to substitute Wen’an. The objectives of the study were made as to identify reasonable improvements for the recycling system by spatial simulation and clarify the environmental loads of that by life cycle assessment (LCA). To achieve the first objective, geographic information system (GIS) technology was used to simulate collection and transportation processes, give the distribution map of recoverable PW in Tianjin, determine shortest routes for transportation, and read the transport distances to compare GHG emissions between the improved case and a present case. For the other objective, LCA method was used for the projected recycling scenario and the non-recycling scenario (the baseline scenario) to estimate the environmental effects of the improved recycling system. The system boundaries were, therefore, set differently in the two sections.

Scientific relevance

The collection of PW was modeled as a Vehicle Routing Problem (VRP). A VRP can be described as the problem of designing reasonable delivery or collection routes from one or several depots to a number of geographically scattered demand points, subject to side constraints [3]. The collection of municipal PW is within the scope of reverse logistics [4]. In practice, a combination of the two types of collection in the routing problem (demand on both arcs and nodes) also exists, which makes it a general routing problem [5]. To model the VRP in a realistic manner, distance matrices between locations were generated with Microsoft MapPoint [6]. The municipal solid waste management system of St. Petersburg, Russia was modeled in a similar manner to evaluate the introduction of alternative waste treatment facilities [7]. For PW collection, drop-off
collection is a typical node-routing problem. In Tianjin, householders sell their PW to the nearby recovery centers, the collection trucks will go to the recovery centers to collect the PW and return to the intermediate disposal site for the sorting, finally, the sorted PW will be transported to the recycling factory. So the transportation processes can be modeled as a node-routing problem.

GIS technology has been utilized in some cases of waste management systems. For example, Senthil et al. used a GIS to determine the spatial distribution of existing waste bins and to suggest the optimum locations of waste bins using a weighted mean center [8]. Dragan et al. introduced a two-stage optimization approach to reduce transportation costs for students [9]. Kyessi and Mwakalinga used a GIS to set up a least-cost route for solid waste collection and also compared the results with an existing route [10]. Tavares et al. developed GIS 3-D route modeling for optimizing municipal solid waste collection vehicle routing for minimum fuel consumption in a case study of waste collection and transportation [11]. Bhambulkar used the Network Analyst function of GIS to obtain the shortest route for solid waste collection [12]. They considered different collection schemes, locations, or routes according to different purposes, and calculated the shortest distance possible for each purpose. In this study, ArcGIS 10.0 software was used to simulate the different collection methods and different loading ratios in PW transport processes to find reasonable improvements to the current PW recycling system. The maximum possible mitigation of GHG emission was used as the core criterion during the whole resolution process.

In this study, the system in Tianjin was considered a node-routing problem. To demonstrate the superiority of the improvements suggested, we compared the transport distance and GHG emissions between two cases based on the distance calculated by GIS resolution. In particular, the different methods of collection in the primary transport processes and the different loading ratios in the secondary transport processes were compared for the present and improved cases. Finally, the calculated transport distance was applied to the transport process in the LCA.

**Estimation of PW flow**

To evaluate ways to improve the PW recycling system, we first had to estimate current PW flow. To clarify the amount of PW in Tianjin, an investigation was conducted on the PW composition in the local recovery center in August 2011. Information about PW was also obtained from local enterprises, statistical yearbooks, and web sites. We determined that annual PW flow is made up of six primary components and estimated them as follows.

1) We summarized the flow amount and direction to be 1,481,749 t of PW imported from foreign countries via Tianjin Port in 2011, of which about 658,550 t was imported by local companies and the rest was transported outside of Tianjin [13]. After pre-treatment, most of the waste was transported outside of Tianjin for recycling.

2) With the cooperation of local PW buyers in August 2011, we conducted an investigation in a recovery center that covered about 2500 households. PW composition data were obtained by weighing the PW that was collected in one week. The PW was divided into 16 categories in the center, and the weight and proportion of each category of PW was obtained. The total weight of recovered PW was about 501.6 kg. We used this value to calculate the per-capita recovery amount for this center. Multiplying this per-capita figure by the total population of Tianjin, we estimated the amount of household PW to be about 35,760 t per year. Residents of Tianjin are aware of the value of waste polyethylene terephthalate (PET) containers. Therefore, they sell them to collectors or recovery companies rather than giving them to the recovery center, so PET waste is not included in the estimation. For several reasons, including limited storage space, low incentive for participation, and the troublesome process of separating PW, some PW is discharged as municipal solid waste. Therefore, the actual amount of PW generated is much larger than the estimated recovery amount.

3) The amount of PET waste generated in Tianjin in 2010 was estimated using national PET consumption data for China in 2010 [14] divided by the population of China multiplied by the population of Tianjin and the recovery ratio (assumed to be 90 %). The resulting amount was about 25,331 t.

4) The amount of PW that was generated from industrial losses was derived from two types of loss: production loss and processing loss. Production loss was calculated by referring to a production loss calculation method that was used in the material flow of plastic production in Japan [15]. The production loss ratio in Japan in 2010 was estimated from the production loss divided by the synthetic resin production volume [16]. We used this ratio and multiplied it by the synthetic resin production amount of Tianjin in 2010 to arrive at an estimated production loss of about 43,255 t in Tianjin.

Processing loss was calculated in two ways. One was calculated by multiplying the amount of synthetic resin for processing use in Tianjin by the processing loss ratio supplied by a local company (a machinery
plastic-parts maker). This method yielded a total processing loss of about 48,737 t. The other was estimated by multiplying the processing loss ratio of Japan [15], which yielded a loss of about 91,299 t. The total amount of PW that was generated from industrial losses in 2010 was therefore about 91,992–134,554 t.

5) According to statistical data [17], the consumption of plastic film for agricultural use was about 12,640 t in 2009 in Tianjin.

6) The PW from dismantling industries includes two components: PW from dismantled waste home appliances and those from waste vehicles in Tianjin. The composition and recovery amounts of the five main home appliances (TVs, refrigerators, washing machines, air conditioners, and computers) in Tianjin were obtained from data acquired from May 2009 to October 2010 from four major waste dismantling factories [18]. The amount of PW that was generated from dismantling the waste home appliances was about 8649 t. The amount of waste vehicles was estimated from statistical data [19], and this amount was multiplied by the composition ratio of plastics that was obtained from our investigation to an automobile manufacturer in Tianjin. The estimated amount of PW that was generated from waste vehicles was about 572 t. The total volume of PW from the dismantling industries was therefore about 9221 t.

The entire PW flow is shown in Fig. 2. From the investigation, it was clearly understood that the PW from five of the components had relatively complete distribution channels or limited collection amounts. Therefore, we focused on household PW that is showed in Table 1 as the evaluation target in this study.

**Effect of an improved transport system**

To distinguish the collection and transport process, we call the collection process as primary transport process, the transport process as the secondary process. To improve the whole recycling system, the recovery centers will substitute the waste collectors in the whole city, the recovery frequency will be added in the primary transport process to fulfill a cyclic collection method rather than the round-trip method where collection vehicles return on the same route that they went out on, compression processing will be conducted to increase to about 100 % of the truck capacity in the intermediate disposal sites and a recycling factory will be set in Zi’ya. We call this the improved case (Fig. 3).

The present case is defined using recovery centers instead of a waste collector for collecting PW, with round-trip collection during the primary transport process; a loading ratio of 50 % is used during the secondary transport process without compression processing, and the final destination is Wen’an. To allow comparisons, the number of facilities in the two cases is the same, and the loading ratio is assumed to be 100 % during the primary transport process in both cases to clarify the effect of different

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**Fig. 2** Estimation of PW flow in Tianjin

- **Discharge source**
  - Import at Tianjin Port 1,481,749 t
  - Household 35,760 t
  - Waste PET 28,146 t
  - Industry 91,992–134,554 t
  - Agriculture 18,531 t
  - Dismantling 9,221 t

- **Recovery stage**
  - Collection companies
  - PET Intermediate disposal sites
  - Local
  - North China
  - South China
  - Outside of the city
  - Abroad

- **Treatment and disposal**
  - Sale destination

- **Local**

- **Abroad**
collection methods. Different loading ratios are used for the secondary transport processes in the two cases, to focus on the effect of changes in loading ratio. As estimated in previous chapter the amount of household PW recovery was 35,760 t that is used as the evaluation objective in this chapter. GHG emissions from the primary and secondary transport processes are calculated.

Visualizing and analyzing transport processes are useful for optimizing PW collection plans and making suggestions for the locations of new PW recycling facilities. The scheme on resolution processes [20] for the distribution of recoverable PW, transport distance, environmental load, and GHG emissions from transport processes are shown in Fig. 4. In the following sections, the resolution process is described in detail.

Owing to varying population densities in urban and rural areas, the resolution area was separated into two parts: the central six regions (central urban area) and the surrounding 10 regions (rural area). According to the data, we estimated the necessary number of recovery centers as 1465, by dividing the total population by the population covered by one center (Table 2). There are six regions that belong to central urban areas. Based on the existing zoning conditions, we assumed there to be six sites in the central urban areas. About 491 centers were needed for central urban areas according to the calculations. However, we adjusted this to 486 to ensure proper allocation by six sites. The number of centers in rural areas was assumed to be 979. Parameters for transport processes were determined as shown in Table 3. The recovery frequency was set for each type of site. We calculated that four centers would be visited in one trip. This ensured that the amount of centers covered by one site would be allocated properly and that distance limitations were considered for the common waste collection case. We assumed there to be 40 sites in rural areas. Taking into consideration local traffic regulations banning large vehicles in city areas, the use of 2-t trucks for primary transport in central urban areas and 4-t trucks in rural areas was assumed. A 4-t truck was assumed to be used for secondary transport processes in the entire area.

Available data for the study included the Tianjin administrative map, a major road map, the overall urban planning map for 2005–2020, and the per-capita data on the generation of PW.

Residential area data were obtained from the overall urban planning map for 2005–2020, and residential population data were got from the Tianjin administrative map. The population distribution was made by the residential area data and population data. The recoverable PW distribution map (Fig. 5) was derived from the population distribution map by multiplying population by the recovery density for the relevant areas. The Properties function was used here and the result map was expressed by $100 \times 100$ m raster data.

Using the Dot Density of Properties function in the GIS software, we obtained the alternative locations for 1465 recovery centers. Maximum possible mitigation of GHG emissions was used as the core criterion during the whole resolution process. Therefore, we adjusted the center locations so that they were as close to roads as possible. Based on the road map, a 50-m buffer zone for roads in urban areas and a 200-m buffer zone for roads in rural areas were established. We checked all the center locations and adjusted some of those within the nearest buffer zones. When determining the recovery range, the central urban

### Table 1 PW flow estimation in Tianjin and evaluation target for GIS&LCA

| Discharge source                  | Amount   | Unit | Description                                                                 |
|----------------------------------|----------|------|-----------------------------------------------------------------------------|
| Imported PW from Tianjin Port    | 1,481,749| t    | 658,550 t of it is imported by local companies                               |
| Household PW                     | 35,760   | t    | It is the evaluation target (GIS resolution and LCA) in this paper           |
| PET waste                        | 25,331   | t    | The recovery ratio of PET waste is assumed as 90 %                           |
| PW from industry loss             | 91,992–134,554 t | t | The processing loss ratio from local company and Japan’s data is referred, respectively |
| PW from agriculture              | 12,640   | t    | The recovery ratio of agriculture PW is assumed as 100 %                     |
| PW from dismantling industry     | 9221     | t    | This amount includes the PW from dismantling of the waste home appliances and the waste vehicles |
area was separated into six groups corresponding with the boundaries of the central six regions. The centers in the central urban area were allocated properly with one intermediate disposal site for 81 centers. The centers in rural areas were divided into 40 equal groups, with each group sharing one intermediate disposal site. The centers in rural areas were allocated so that each site covered 24 centers and the last site shared 43 centers. The mean center function was used to determine the reasonable position of each site. The mean center is the average \( x \)- and \( y \)-coordinate of

| Item                                                                 | Amount          | Unit          |
|----------------------------------------------------------------------|-----------------|---------------|
| Collected weight of PW from one recovery center during the investigation | 501.65          | kg            |
| The number of families covered by the center                          | 2500            | family        |
| The recovery period during the investigation                          | 7.5             | day           |
| Population of Tianjin                                                | 12,938,224      | person        |
| Total number of families in Tianjin                                   | 3,661,848       | family        |
| PW recovery per-capita                                               | 0.00757225      | kg/person/day |
| The necessary number of recovery centers needed for entire area by calculation | 1465             | place         |
| Population of central urban area                                     | 4,343,040       | person        |
| The number of centers needed for central urban areas by calculation  | 491             | place         |
| The number of centers in central urban areas assumed in this study    | 486             | place         |
| The number of intermediate disposal sites in central urban areas     | 6               | place         |
| Population of rural area                                             | 8,595,184       | person        |
| The number of centers needed for rural areas by calculation          | 974             | place         |
| The number of centers in rural areas assumed in this study           | 979             | place         |
| The number of intermediate disposal sites in rural areas             | 40              | place         |
all centers in the area covered by one site. When placing
the sites on the road map, positions were adjusted into
buffer zones so that sites were located near roads. The
derived recovery range map is shown in Fig. 6.

Transport distances (km) were calculated using the
following formula:

\[ D_t = D_{pr} + D_{pc} + D_{sr} + D_{sc} \]

where \( D_t \) is the total distance during the transport processes in:

1. Central urban areas
   - Primary transport distance: \( D_{pr} \)
   - Primary transport in central urban areas: \( D_{pc} \)
   - Secondary transport distance: \( D_{sr} \)
   - Secondary transport in central urban areas: \( D_{sc} \)

2. Rural areas
   - Primary transport distance: \( D_{pr} \)
   - Primary transport in central urban areas: \( D_{pc} \)
   - Secondary transport distance: \( D_{sr} \)
   - Secondary transport in central urban areas: \( D_{sc} \)

To calculate the distance with the GIS software, the
transport process was divided into two stages in both
central urban areas and rural areas:

1. The primary transport process is divided into many
   trips. In central urban areas, one trip is defined as a
   route that starts from an intermediate disposal site,
   collects PW from three centers, and returns back; in
   rural areas, four centers are passed in one trip. The
   recovery frequency is a policy variable that can be
   adjusted. One trip in secondary transport process is
   defined as a route that starts from the intermediate
   disposal site, transports PW to the recycling factory,
   and returns back to the intermediate site.

2. To achieve distance calculation, the distance of one
   trip in primary transport was divided as the
   road traveling distance plus two times of the distance
   between the center and the nearest road of which.
   In the beginning of the distance resolution, the shapefile
   of the road map was made as network dataset in
   ArcCatalog10. The Network Analyst tools in the
   GIS software were used to create new route, add
   nodes, set up the shortest recovery routes, and read
   the road traveling distance from each new route. A
   shortest route for one trip in primary transport.

Table 3  Parameters for the
transport processes in the
improved case

| Item                                      | Amount   | Unit     |
|-------------------------------------------|----------|----------|
| In the central urban area                 |          |          |
| PW recovery per-capita                    | 0.00757  | kg/person/day |
| Population of central urban area          | 4,343,040| person   |
| Total recovery amount per year            | 12,003,610| kg       |
| Recovery frequency                        | 36       | times/year|
| Amount of recovery centers                | 486      | place    |
| Recovery amount in one center per trip    | 686      | kg       |
| Capacity of truck for primary transportation| 2000  | kg       |
| Loading ratio for the whole transportation | 100     | %        |
| Amount of intermediate disposal sites     | 6        | place    |
| Centers that are covered by one site      | 81       | place    |
| Centers that will be visited in one trip  | 3        | place    |
| Amount of trips in one recovery cycle per site | 27   | trip     |
| Capacity of truck for secondary transportation| 4000  | kg       |
| In the rural area                         |          |          |
| Population of rural area                  | 8,595,184| person   |
| Total recovery amount per year            | 23,755,994| kg       |
| Recovery frequency                        | 24       | times/year|
| Amount of recovery centers                | 979      | place    |
| Recovery amount in one center per trip    | 1011     | kg       |
| Capacity of truck for primary transportation| 4000  | kg       |
| Loading ratio for the whole transportation | 100     | %        |
| Amount of intermediate disposal sites     | 40       | place    |
| Centers that are covered by one site      | 24       | place    |
| Centers that will be visited in one trip  | 4        | place    |
| Amount of trips in one recovery cycle per site | 6    | trip     |
| Capacity of truck for secondary transportation| 4000  | kg       |
The process established was started from one site, went through the nearest road toward the first nearest center and then moved to the next nearest one from the first center, in central urban area one trip passed 3 centers, returned back; 4 centers were passed for rural area in one trip. The shortest route to the factory map (Fig. 7) for secondary transport process was established by the similar method. The black square shows the location of Zi’ya. The Near Function tool was then used to read the distance that was traveled during one trip from each center to the nearest road (Fig. 8). \( D_{pr} \) or \( D_{pc} \) was obtained using the summary distance for all trips including the road traveling distance and the distance from center to the nearest road multiplying by the transportation frequency. The sum of \( D_{pr} \) and \( D_{pc} \) equals to the entire primary transport distance. The entire secondary transport distance was obtained in a similar manner.

3) The calculation details are shown in Table 4, and the distance calculation result is shown in Fig. 9. As a reference value, the result for the present case (100% loading ratio in the secondary transport process) has also been supplied.

Table 4 shows that the transport times for the primary transport process in the improved case are longer than those in the present case due to different collection methods, while transport times for the secondary transport process are shorter in the improved than in the present case due to different loading ratios. The distance of a trip visiting all centers or sites during both primary and secondary transport processes in the improved case are shorter than in the present case. The total distance saving in the improved case is 3,200,072 km, which is equivalent to about 65.6% of the total distance traveled in the present case (50% loading ratio). Comparison between the present case (50% loading ratio) and the improved case in Fig. 9 shows that the distance saving by the primary transport process accounts for about 2.4% of the total distance traveled in the present case (50% loading ratio). Through the comparison between the present case (50% loading ratio) and the present case (100% loading ratio), the reduction in distance traveled from the secondary transport process in rural
areas accounts for 33.5 % of the total distance in the present case (50 % loading ratio) and the total distance saving accounts for about 46.6 % between the two present cases. The lower loading ratio for the secondary transport process in the present case leads to more trips being required. Comparing the improved case and the present case (100 % loading ratio) shows that the reduction in distance traveled in the secondary transport process accounts for about 16.6 % of the total distance traveled in the present case (50 % loading ratio). From the above results, it can be concluded that increasing the loading ratio is the most effective method to reduce distance traveled. The cyclic collection method can reduce distance traveled in the primary transport process than the round-trip method. The reduction in distance traveled due to improvements in rural areas is more significant than that in central urban areas under this condition.

Vehicle fuel consumption was estimated based on the distance obtained using the improved t-kilometer method [21]. That value was then multiplied by a GHG emission coefficient to obtain total GHG emissions from the transport processes as shown in Fig. 10. The data on compression processing refer to one type of compression packing machine with a processing capacity of 0.1 t/h (power = 5 kW). If we adopt the improved case instead of the present case (50 % loading ratio), mitigation of GHG emissions will be about 12,197 t CO2 eq per year, equivalent to about 65.9 % of total emissions in the present case. GHG emissions from the primary transport process in the improved case are less than in the present case, accounting for about 5.2 % of the total emissions in the present case (50 % loading ratio). Through the comparison between the present case (50 % loading ratio) and the present case (100 % loading ratio), mitigation of GHG emissions from the secondary transport process account for about 50.7 % of total emissions in the present case (50 % loading ratio) and compression machine in the present case (100 % loading ratio) increases GHG emissions, accounting for about 5.4 % of total emissions in the present case (50 % loading ratio). Mitigation of GHG emissions from compression processing is about 45.3 % of total emissions in the present case (50 % loading ratio). Through the comparison between the improved case and the present case (100 % loading ratio), mitigation of GHG emissions from
Table 4  Result of distance calculations for the improved and the present case

| Improved case | Primary transport times per year | Primary transport distance of a trip visiting all centers (km) | Secondary transport distance of a trip from all sites to the factory (km) | Secondary transport times per year | Sum   |
|---------------|---------------------------------|---------------------------------------------------------------|---------------------------------------------------------------------|-----------------------------------|-------|
| Central urban areas (6) | 36                              | 1431                                                          | 368                                                                | 500                               | 419,230 |
| Rural areas (40) | 24                              | 7268                                                          | 3643                                                               | 149                               | 1,259,991 |
| Total distance |                                  | 1,679,222 km                                                  |                                                                     |                                   |       |

Present case

| Primary transport times per year | Primary transport distance of a trip visiting all centers (km) | Secondary transport distance of a trip from all sites to the factory (km) | Secondary transport times per year | Sum   |
|---------------------------------|---------------------------------------------------------------|---------------------------------------------------------------------|-----------------------------------|-------|
| Central urban areas (6) | 13                              | 3975                                                          | 639                                                              | 999   | 1,379,875 |
| Rural areas (40) | 6                               | 19,987                                                        | 5451                                                             | 299   | 3,499,419 |
| Total distance |                                  | 3,200,072 km                                                  |                                                                     |       |       |

Fig. 9  Total distance in transport processes

![Distance(km)](image)

Fig. 10  Total GHG emissions in transport processes

![GHG emissions(kg)](image)
the improved case is about 15.4% of total emissions in the present case (50% loading ratio). From the above results, we can conclude that compression processing is the most important factor for mitigation of GHG emissions. The cyclic collection method can reduce the GHG emissions rather than the round-trip method. Locating the recycling factory in Zi’ya instead of Wen’an is also effective for mitigation of GHG emissions. The reduction in GHG emissions due to improvements in rural areas is more significant than that in central urban areas under this condition. The higher loading ratio in the improved case determines the lower vehicle fuels consumption that causes the reduction effects of GHG emissions more significant than total distance traveled.

Environmental effect of the recycling system

To carry out the LCA, a projected scenario was defined to include the following processes: recovery, recycled resin manufacture, incineration of residue, transportation, and landfill processes. The baseline scenario includes extraction of raw materials, new resin manufacture, recovery, PW (100%) incineration, transportation, and landfill processes. The recovery process here corresponds with the transport process in the previous section, which includes the primary and secondary transport processes. The location of the incineration facility in the baseline scenario is assumed to be the same as the PW recycling factory in Zi’ya in the projected scenario. The inventory data on extraction of raw materials and new resin manufacture are based on data from Japan, so the location of a new resin manufacturing factory is not specified here. For comparison, the number of recovery centers, sites, and the transport routes of the recovery processes of the two scenarios are the same.

Figure 11 shows the system boundaries for the two scenarios. The functional unit is 35,760 t household PW. The recovery distances were obtained from the GIS analysis. The following formulas were used to conduct the LCA:

\[
E_b = E_n + E_t + E_i + E_{ir} + E_{ia} + E_{il}
\]

\[
= W_r \times D_1 \times ec_2 + W_r \times R \times ec_1
\]

\[
+ \left\{ W_r \times (1 - R) + W_r \times R \times (1 - R') \right\}
\]

\[
\times ec_3 + \left\{ W_r \times (1 - R) + W_r \times R \times (1 - R') \right\} \times R_1 \times D_4
\]

\[
\times ec_4 + \left\{ W_r \times (1 - R) + W_r \times R \times (1 - R') \right\} \times R_1 \times ec_5,
\]

(1)

where \(E_b\): GHG emissions from the baseline scenario (t-CO\(_2\)-eq); \(E_n\): GHG emissions from the new resin manufacturing process; \(E_t\): GHG emissions from recovery process; \(E_i\): GHG emissions from incineration process; \(E_{ir}\): GHG emissions from transport of ash; \(E_{ia}\): GHG emissions from landfill of ash.

\[
E_p = E_t + E_{ir} + E_{ia} + E_{ua} + E_{iu} + E_{il}
\]

\[
= W_r \times D_1 \times ec_2 + W_r \times R \times ec_1
\]

\[
+ \left\{ W_r \times (1 - R) + W_r \times R \times (1 - R') \right\}
\]

\[
\times ec_3 + \left\{ W_r \times (1 - R) + W_r \times R \times (1 - R') \right\} \times R_1 \times D_4
\]

\[
\times ec_4 + \left\{ W_r \times (1 - R) + W_r \times R \times (1 - R') \right\} \times R_1 \times ec_5,
\]

where \(E_p\): GHG emissions from the projected scenario; \(E_{ir}\): GHG emissions from recycling manufacturing process; \(E_{ia}\): GHG emissions from incineration of residue; \(E_{iu}\): GHG emissions from transport of ash.

The remaining term definitions are shown in Table 5, along with parameter settings, units, and data sources. Because data on the input and output of the local PW recycling industry were unavailable, inventory data from Japan’s Plastic Waste Management Institute [22, 23] and the guidelines on total GHG emissions calculation method [24] were used. During calculations for the projected scenario, PW was assumed to be PET waste to be recycled thus the inventory data for PET waste recycling were used.

The results of the LCA are shown in Table 6. GHG emissions in the projected scenario in the LCA are about 101,738 t CO\(_2\) eq less per year than the baseline scenario, which is equivalent to about 75.5% of the emissions from the baseline scenario. The main sources of emission reductions are from PW incineration and new resin manufacturing in the baseline scenario. In the projected scenario, the GHG emissions form the total transport, resin manufacture, and incineration of residue processes account for 16.3, 19.7, and 64% of total emissions, respectively. In the baseline scenario, the GHG emissions from transport, resin manufacturing, and PW incineration processes account for 4.9, 32.1, and 63.9% of total emissions, respectively. In addition, GHG emissions from the new resin manufacturing process in the baseline scenario are greater than total emissions in the projected scenario. Therefore, recycling of PW is highly recommended for mitigation of GHG emissions.

Conclusion and discussion

In this study, the PW flow in Tianjin was estimated according to the investigation. GIS was used to simulate the transport processes and clarify the mitigation effect of GHG emissions for an improved transport system. LCA was conducted to determine the environmental effect of the recycling system. The following results were obtained:
**Table 5** Parameter definitions, settings, and data sources for the LCA

| Term | Definition | Value | Unit | Description or source |
|------|------------|-------|------|-----------------------|
| \( W \) | The amount of PW collected | 35,760 | t/year | Estimated in this study (for 2011) |
| \( R \) | The proportion of collected PW that is suitable for recycling | 85.50 | % | Estimated in this study (for 2011) |
| \( R' \) | The recycling ratio of PW (the recycling ratio of PET waste is referred) | 87.8 | % | Survey data in Japan (Plastic Waste Management Institute) |
| \( e_{c1} \) | GHG emission intensity from new resin manufacturing | 1.61 | t-CO_2–eq/t | Survey data (Japan Environmental Management Association for Industry) |
| \( e_{c1}' \) | GHG emission intensity from recycling manufacturing | 0.21 | t-CO_2–eq/t | Survey data in Japan (Plastic Waste Management Institute) |
| \( e_{c2} \) | GHG emission intensity from transportation of PW | 1.58 | kg-CO_2–eq/t | Survey data in Japan (improved t-kilometer method) |
| \( e_{c3} \) | GHG emission intensity from incineration | 2.41 | t-CO_2–eq/t | Survey data (Japan Environmental Management Association for Industry) |
| \( e_{c4} \) | GHG emission intensity from transportation of the residue or ash | 0.20 | kg-CO_2–eq/t | Survey data in Japan (improved t-kilometer method) |
| \( e_{c5} \) | GHG emission intensity from the landfill of ash | 0.03 | t-CO_2–eq/t | Survey data (Japan Environmental Management Association for Industry) |
| \( R_1 \) | The proportion of incineration ash | 2.13 | % | Survey data in Japan (Plastic Waste Management Institute) |
| \( D_1 \) | Annual total transport distance from transport processes | 1679 | 10^3 km | Distance calculated by GIS |
| \( D_2 \) | Distance from incineration site 1 to landfill site | 51 | km | Distance measured by Google Maps |
| \( D_3 \) | The distance from recycling factory to incineration site | 23.20 | km | Distance measured by Google Maps |
| \( D_4 \) | The distance from incineration site 2 to landfill site | 49.80 | km | Distance measured by Google Maps |
1. GHG emissions during transport processes in the improved case were reduced by about 12,197 t per year compared to the present case, equivalent to about 65.9% of emissions from the present case. The compression processing is the most important factor for mitigation of GHG emissions. The cyclic collection method can reduce the GHG emissions rather than the round-trip method. Locating the recycling factory in Zi’ya instead of Wen’an is also effective for mitigation of GHG emissions. Therefore, these improvements to the system are highly recommended for the mitigation of GHG emissions.

2. Estimated GHG emissions in the projected scenario in the LCA were about 101,738 t CO₂ less per year than the baseline scenario, equivalent to about 75.5% of emissions from the present case. The compression process is important for reducing GHG emissions. The cyclic collection method reduces GHG emissions more than the round-trip method. Locating the recycling factory in Zi’ya instead of Wen’an is also effective for the mitigation of GHG emissions. Therefore, these improvements to the system are highly recommended for the mitigation of GHG emissions.

We have confirmed that improvements for the transport system would be helpful in the mitigation of GHG emissions. To achieve these improvements, however, action is urgently needed. This type of recycling project is vital to protect the environment. Therefore, increasing the recovery ratio and constructing recycling facilities are considered to be key measures to move forward.

GIS and LCA were used to evaluate the projected effects of improvements in PW recycling in Tianjin. These approaches should be useful in developing efficient transportation plans of recycling systems in other areas because decision-makers can use GIS technology to simulate transport processes in advance and solve the VRP problems visually. These methods also could be applied to other relevant transportation and recycling systems.

In the future, it will be necessary to review the GHG emissions factors considering the actual material flow of local industry and, in general, to improve the accuracy of the data and the resulting calculations. In addition, a water pollution evaluation of the Wen’an case should be considered. It may also be useful to conduct a cost analysis of the suggested project and determine the optimal number of intermediate disposal sites.

| Table 6 LCA estimation result |
|-------------------------------|
| **Items**                     | **CO₂** | **CH₄** | **N₂O** | **Unit** |
| **Baseline scenario**         |         |         |         |         |
| Emissions during the crude oil production | 2,510,137 | 44,214 | kg/year |
| Emissions during the crude oil transportation | 1,336,421 | 790 | kg/year |
| Emissions from refinery energy | 8,217,816 | 104 | kg/year |
| Emissions from petroleum processing | 30,286,365 | 403 | kg/year |
| PW transportation process | 5,289,840 | 24.81 | 27.43 | kg/year |
| Incineration of PW | 84,286,088 | 6079 | kg/year |
| Transportation of ash | 15,488 | 0.29 | 0.27 | kg/year |
| Landfill | 22,316 | | | kg/year |
| Total emissions | 131,964,470 | 45,536 | 6107 | kg/year |
| GHG emissions of Baseline scenario (CO₂-equivalent) | 134,813,839 | kgCO₂-eq/year |
| **Projected scenario** | | | | |
| PW transportation process | 5,289,840 | 24.81 | 27.43 | kg/year |
| Recycling manufacture | 6,500,259 | | | kg/year |
| Transportation of residue that cannot be recycled | 82,464 | 1.55 | 1.45 | kg/year |
| Incineration of residue | 20,932,416 | 677.56 | 645.46 | kg/year |
| Transportation of ash | 3771 | 0.07 | 0.07 | kg/year |
| Landfill | 5626 | | | kg/year |
| Total emissions | 32,814,374 | 704 | 674 | kg/year |
| GHG emissions of Projected scenario (CO₂-equivalent) | 33,038,223 | kgCO₂-eq/year |
| Total GHG emissions reduction (CO₂-equivalent) | 101,775,617 | kgCO₂-eq/year |
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