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Assessing the Transition of Municipal Solid Waste Management Using Combined Material Flow Analysis and Life Cycle Assessment

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Abstract. Faced with the challenges to deal with increasingly growing and ever diversified municipal solid waste (MSW), a series of waste directives have been published by European Commission to divert MSW from landfills to more sustainable management options. The presented study assessed the transition of MSW management in Nottingham, UK, since the enforcement of the EU Landfill Directive using a tool of combined materials flow analysis (MFA) and life cycle assessment (LCA). The results show that the MSW management system in Nottingham changed from a relatively simple landfill & energy from waste (EfW) mode to a complex, multi-technology mode. Improvements in waste reduction, material recycling, energy recovery, and landfill prevention have been made. As a positive result, the global warming potential (GWP) of the MSW management system reduced from 1,076.0 kg CO₂-eq./t of MSW in 2001/02 to 211.3 kg CO₂-eq./t of MSW in 2016/17. Based on the results of MFA and LCA, recommendations on separating food waste and textile at source and updating treatment technologies are made for future improvement.

Keywords: Municipal Solid Waste, Material Flow Analysis, Life Cycle Assessment, Global Warming Potential, Future Improvement.

1 Introduction

Landfill used to be the main option for disposal of municipal solid waste (MSW) in Europe and is still the most widely adopted MSW management method worldwide. But it is the least sustainable MSW treatment due to its high contamination potentials, such as high greenhouse gas (GHG) emission resulted from the decomposition of biodegradable fraction, water and soil pollution resulted from leachate emission, resources depletion resulted from unrecycled valuable materials [1 – 5]. To mitigate the environmental impacts of landfills and to deal with the increased quantity and ever diversified composition of MSW the EU Landfill Directive was introduced in 1999

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(EU Directive 99/31/EC). This directive emphasizes the reduction of landfilled biodegradable municipal waste (BMW). Since then, as illustrated in Fig.1, waste directives have been successively introduced by European Commission to improve the sustainability of MSW management in Europe by diverting waste from landfills to more environmentally friendly management options at the upper layers of waste management hierarchy such as recycling and energy recovery, thus to facilitate the development of circular economy. Management targets were set in these directives. As response, waste management policies, regulations and targets have been developed by England and Nottingham City Council (Fig. 1).

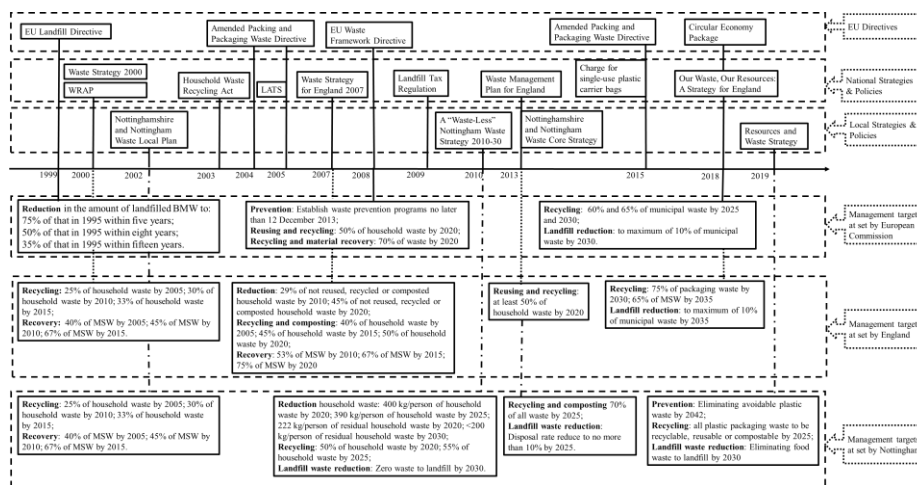


Fig. 1. Timeline of waste management regulations, as well as management targets, developed by European Commission, England and Nottingham City Council.

Since the implementation of the EU Landfill Directive, studies have been conducted to identify the gaps and difficulties of achieving the MSW management goals [3, 5, 6], to analyze the development of waste management legislations and practices [2, 5, 7, 8], and to evaluate the environmental impacts of waste management strategies [8 – 11]. However, the performance of MSW management from a transitional perspective under the guidance of EU waste directives has seldom been investigated and assessed.

Material flow analysis (MFA) and life cycle assessment (LCA) are often used tools to assess the performance of MSW management, but they were often separately and independently applied. MFA is a robust, transparent, and useful tool in measuring the performance of an MSW management system by identifying and analyzing the pathways of waste streams, but it alone cannot sufficiently and comprehensively assess or support an MSW management strategy in view of certain goals, such as protection of human health and mitigation of global impact [12]. Even though, MFA provides well-grounded inventory for LCA [12, 13]. A Combination of MFA and LCA could identify the minor changes but might have long-term and/or significant damage and the most promising processes and flows for improvements.

Therefore, the present study investigates and assesses the transitioning MSW management in Nottingham, UK via identifying and quantifying the MSW flows and the associated global warming potential (GWP) using a tool of combined MFA and LCA. Three historical MSW management situations in 2001/02, 2006/07 and 2016/17 corresponding to three transitional stages in Nottingham in response to the EU waste directives were investigated and assessed. The novelty and contributions of this study can be summarized as follows:

- Application of a combined MFA and LCA approach to evaluate the performance of MSW management system at the meso level.
- Assessment of an MSW management from the vision of development.
- An insight into the effectiveness of waste regulations and policies.
- Assistance to local government in planning and decision making.
- Experiences for cities alike.

1.1 Case Study

Nottingham is located in the central UK (52° 57' N and 1° 09' W). It was chosen as the study city because its MSW management strategy has been changed for several times in response to the EU and national waste regulations since 2000, and ambitious MSW management targets (e.g., recycling 55% of household waste by 2025, and achieving “zero waste to landfill” by 2030) have been set by the local authority (Fig. 1). Techniques and technologies including kerbside collection which separately collect recyclable materials and garden waste at source, material recovery facility (MRF) which sort and process recyclable materials from mixed recyclables or residual waste, and production of refuse-derived fuel (RDF) have been successively introduced into Nottingham for improving the sustainability of MSW management in the city.

2 Methodologies

A combination of MFA and LCA was applied in this study to quantitatively assess the transition of the MSW management system in Nottingham together with its environmental performance throughout the period from 2001/02 to 2016/17. MFA approach was applied to analyze the waste flows and stocks into, within and from the MSW management system. The performing of MFA is based on the first law of the thermodynamics entailing conservation of matter and energy [14, 15]. It is expressed as: mass in = mass out + stocks [13]. Through material balance, the sources, flows, accumulations and changes of wastes become visible [13]. MFA was performed using the free software STAN v2.6 (<http://stan2web.net/>). The associated GWPs of the waste streams described and quantified by the MFA were assessed using LCA.

2.1 Goal and Scope

The goals of this study were threefold: (1) to identify and quantify the waste flows in the MSW management situations at different stages of the transition; (2) to quantitatively assess the GWP of each situation; (3) to identify the successes and failures in the transition, and potential improvements. For consistency with targets set in waste regulations and available data, MSW was conceptualized as household waste which

includes all waste collected from household sources and street cleaning. Separately collected commercial waste, industrial waste and healthcare waste were excluded from the scope of assessment. Functional unit of LCA was defined as the treatment of one ton of MSW, to ensure the situations were comparable to each other.

2.2 System Boundaries

Setting appropriate boundaries is critical as it affects the data collection and assessment results. In this study, the system boundaries were set to identify the waste flows and to analyze the GWP from the MSW management system in Nottingham. The spatial boundary was the administrative boundary of Nottingham City Council. The temporal boundary was the statistical year from April to March of the next year; for example, April 2001 – March 2002, so that the years to our MSW management situations were expressed to cross two years, i.e. 2001/02. Detailed assumptions included in the assessment boundaries are summarized as follows:

- (1) The MSW management processes include waste generation, collection, transfer, transport, treatment and disposal. Waste treatment facilities were identified from the database of WasteDataFlow (www.wastedataflow.org).
- (2) GHG emissions include the direct emissions from MSW and indirect emissions from energy consumption for transport and operation of treatment and disposal facilities.
- (3) Heat recovered from MSW was assumed to displace the same quantity of heat from natural gas which was the main energy source for home heating in the UK [16].
- (4) Due to the variation of energy mix, the emission factors of electricity production were 0.45kg CO₂ eq./kWh in 2002 [17], 0.47 CO₂ eq./kWh in 2007 [18] and 0.35 CO₂ eq./kWh in 2017 [19].
- (5) GHG emissions from the operation of the Civic Amenity (CA) site and bring sites were not included because data was unavailable.
- (6) Bottom ash from incinerator (BAI) was not considered as a source of GHGs.

2.3 MSW Management Situations

In total, three historical MSW management situations (S1 – S3) had been evaluated and compared in this study.

S1. The MSW management in 2001/02. 2001/02 is the earliest year documenting MSW management data. It is regarded as the beginning of the transition when the Nottinghamshire and Nottingham Waste Local Plan published in response to the EU Landfill Directive. In S1, weekly door-to-door collection was assumed to be provided by the local authority [20]. Source separation was unavailable. Landfilled waste was stored and transferred at transfer station. MSW was either directly disposed in landfills or incinerated in the Eastcroft EfW for energy recovery without pretreatment or material recovery [21]. An CA site and dozens of bring sites were set to collect recyclable materials including paper, glass and metal [21, 22]. BAI, as well as metal in it, was landfilled. Methane collection system at the landfills was not applied.

S2. The MSW management in 2006/07 before the enforcement of the Waste Framework Directive. 2006/07 is the earliest year recording waste flows. In S2, kerbside collection and MRF had been introduced, but kerbside collection had not

been provided to all households. Transfer station was used to store and transfer waste to MRF. Residual waste was either disposed in landfills or incinerated in the Eastcroft EfW for energy recovery without pretreatment. Metal from BAI was recycled. Separately collected garden waste was treated via open windrow composting.

S3. The MSW management in 2016/17. It was the latest year with available data at the time for analyzing. Kerbside collection was further strengthened to serve all households in Nottingham. RDF was produced at MRF. Only residual waste from MRF and fly ash from incinerator were landfilled. BAI was recycled for aggregates.

2.4 Life Cycle Inventory

Collection, Transfer and Transport. Estimated travel distances and life cycle inventories for collection and transport are presented in Table 1. GHG emission factor for each vehicle type was taken from Ecoinvent v3 database. Distances travelled in kerbside collection, bulky waste collection and door-to-door collection were modelled based on the length of accessible street within Lower Layer Super Output Areas (LSOA) Google Earth, the average population within LSOA and MSW generation per capita in Nottingham. Electricity and diesel consumed for the operation of transfer station were 4 kWh/t and 0.84 kg/t, respectively [23]. Distances between LSOA and waste management facilities and distances between facilities were estimated based on their locations using Google Earth and Google map.

Table 1. Travel distances of waste collection and transport, and emission factors applied for each vehicle type.

	Transport distance (km)	Vehicle type	Emission factors (kg CO ₂ eq./tkm)
Kerbside collection	14	Road, lorry 16-32 metric ton	0.177
Bulky waste collection	14	Road, lorry 16-32 metric ton	0.177
CA site collection	0	Road, lorry	0.135
Street cleaning	20 [23]	Road, lorry 3.5 metric ton [24]	0.555
Bring sites collection	20 [23]	Road, lorry	0.135
Door-to-door collection	14	Road, lorry 16-32 metric ton	0.177
Transport	Distance between	Road, lorry	0.135
	waste management	Rail, freight	0.0431
	facilities	Ocean, ship	0.0112

Landfill. Diesel and electricity consumptions for the operation of landfill were 1.8 kg/t and 8 kWh/t, respectively [23]. Methane emitted from landfill was estimated using the method and equations reported by Fong et al. [25]. They estimate the total potentially generated methane based on the mass and composition of landfilled waste. The waste compositions of landfilled waste in S1 – S2 were shown in Table 2.

Table 2. Composition of landfilled waste (%).

Composition category	S1	S2	S3	Degradable organic carbon (DOC) content in wet waste
Paper & card	32.0	21.1	19.3	40
Putrescible	21.0	37.6	2.3	15
Plastics	11.0	3.0	2.4	0
Glass	9.0	1.5	10.6	0
Metals	8.0	3.8	1.5	0
Wood	-	11.5	29.6	43
Textiles	2.0	4.5	1.1	24
Other	17.0	17.0	33.2	0
Total	100	100	100	-

Incineration with Energy Recovery. The quantity of CO₂ generated from incinerated waste was calculated based on the mass and composition of it (Table 3) using the method and equations provided by the IPCC [26]. Heat recovered from waste was assumed to substitute the equivalent heat generated from gas boilers with an efficiency of 89%. The efficiency of the Eastcroft EfW was 15.3% for electricity and 28.2% for heat of the lower heating value (LHV) of MSW [27]. Electricity and fuel oil consumed to operate incineration plant were 62 kWh/t and 3.76 kg/t, respectively [28].

Table 3. Composition of incinerated waste (%)

Composition category	S1	S2	S3	Dry matter content of wet weight	Total carbon content in dry weight	Fossil carbon fraction of total carbon
Paper and card	32.0	20.8	10.2	90	46	1
Putrescible	21.0	25.8	34.9	40	38	-
Textiles	2.0	3.3	9.0	80	50	20
Fines (< 10mm)	7.0	3.4	0.4	90	3	100
Dense plastics	6.0	8.0	7.2	100	75	100
Plastic film	5.0	8.1	4.0	100	75	100
Miscellaneous combustibles	8.0	10.9	19.2	40	70	10
Miscellaneous non-combustibles	2.0	3.2	4.7	100	-	-
Non-ferrous metal	2.0	1.3	0.9	100	-	-
Glass	9.0	9.4	3.2	100	-	-
Ferrous metal	6.0	3.3	2.6	100	-	-
Others	0	2.7	3.7	-	-	-
LHV (MJ/kg)	9.6	8.8	6.8	-	-	-

Recycling. Avoided emission by material recycling was estimated based on the England Carbon Metric Report [29]. This report gave a summary about GHG avoided by materials recycling and reusing compared to landfilling of these materials.

Composting. Details of life cycle inventories (LCI) for composting are presented in Table 4. 36% of garden waste was assumed to be non-compostable material [30].

Table 4. LCI for composting.

	Unit	Value	Reference
<i>Pre-treatment input</i>			
Diesel	kg/t	0.1	[23]
Electricity	kWh/t	1.1	[23]
<i>Composting input</i>			
Diesel	kg/t	3.07	[31]
Electricity	kWh/t	0.51	[31]
<i>Process emission</i>			
CH ₄	kg/t	4	[26]
N ₂ O	kg/t	0.24	[26]
<i>GHG emission from production of inorganic fertilizer</i>			
N fertilizer	kg CO ₂ -eq./kg	6.8	[32]
P fertilizer	kg CO ₂ -eq./kg	1.2	[32]
K fertilizer	kg CO ₂ -eq./kg	0.5	[32]
<i>Avoided fertilizer product by applying compost</i>			
N fertilizer	kg/t	3.4	[33]
P fertilizer	kg/t	2.8	[33]
K fertilizer	kg/t	9.7	[33]

Material Recovery Facility. There were two types of MRF in Nottingham. One was designed to sort and process mixed recyclable materials. It consumed 2 kg/t diesel and 35 kWh/t electricity for its operation [23]. Another MRF was designed to recover materials from bulky waste, street waste and residual waste. Diesel and electricity consumption in this MRF were 2 kg/t and 44 kWh/t, respectively [23, 24].

Production and Incineration of RDF with Energy Recovery. 40 kWh/t electricity was consumed to produce RDF [35] with standard LHV of 25 MJ/kg and fossil carbon content of 32% by weight [26, 36]. RDF was assumed to be incinerated to only generate electricity with an efficiency of 25% based on the thermal energy production estimated using corresponding LHV of RDF [35]. GHG emission from the incineration of RDF could be calculated based on the mass and fossil carbon content of RDF.

2.5 Life Cycle Impact Assessment

The life cycle impact assessment was characterized by GWP at a 100-year time period, with characterization factors taken from IPCC. The GHGs calculated in this study covered carbon dioxide (CO₂), methane (CH₄) (GWP factor: 25) and nitrous oxide (N₂O) (GWP factor: 298). The total GWP of the MSW management was the sum of GWPs of all GHGs, and expressed as GWP₁₀₀.

3 Results and Discussions

3.1 Results of MFA

Comprehensive material flow diagrams for MSW management situations are presented in Fig. 2 – Fig 4. Residual waste was the dominant waste stream for all situations, but the disposal of it varied in situations. Majority of residual waste (67,617 t) was landfilled in S1 but it was incinerated for energy recovery in S2 and S3. Due to the implementation of kerbside collection and MRF, the recycling (and composting) rate was significantly increased from 3.4% (3.6%) in S1 to 31.4% (44.9%) in S3 (Table 5). But there is still a big gap to the 2020 and 2025 targets. Even though, Nottingham has big achievements on waste prevention, energy recovery from waste and prevention of landfilled waste. The reduction target to 390 kg per person per year of household waste had been achieved in the latest situation (Table 5). In S3, majority of waste (61.9%) was incinerated for energy recovery and the landfill rate reduced to as low as 7.3% (Table 5). As such, MSW management in Nottingham transformed from a relatively simple model (S1) combining landfilling and incineration with energy recovery in to a more complex model (S3) integrating source separation, recycling, composting, pre-treating landfilled waste and incineration with energy recovery.

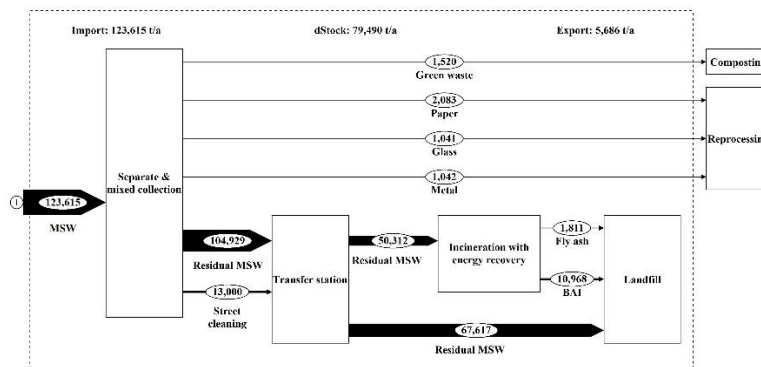


Fig. 2. Material flow diagram for S1.

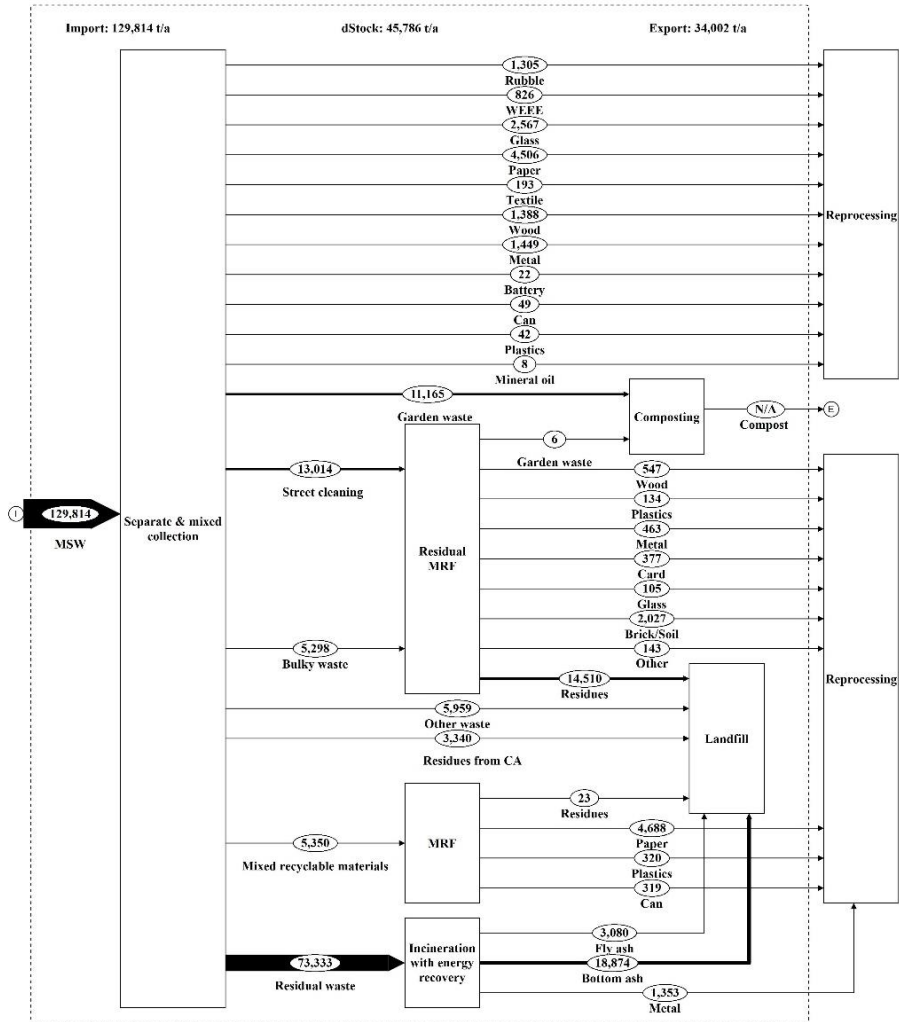


Fig. 3. Material flow diagram for S2.

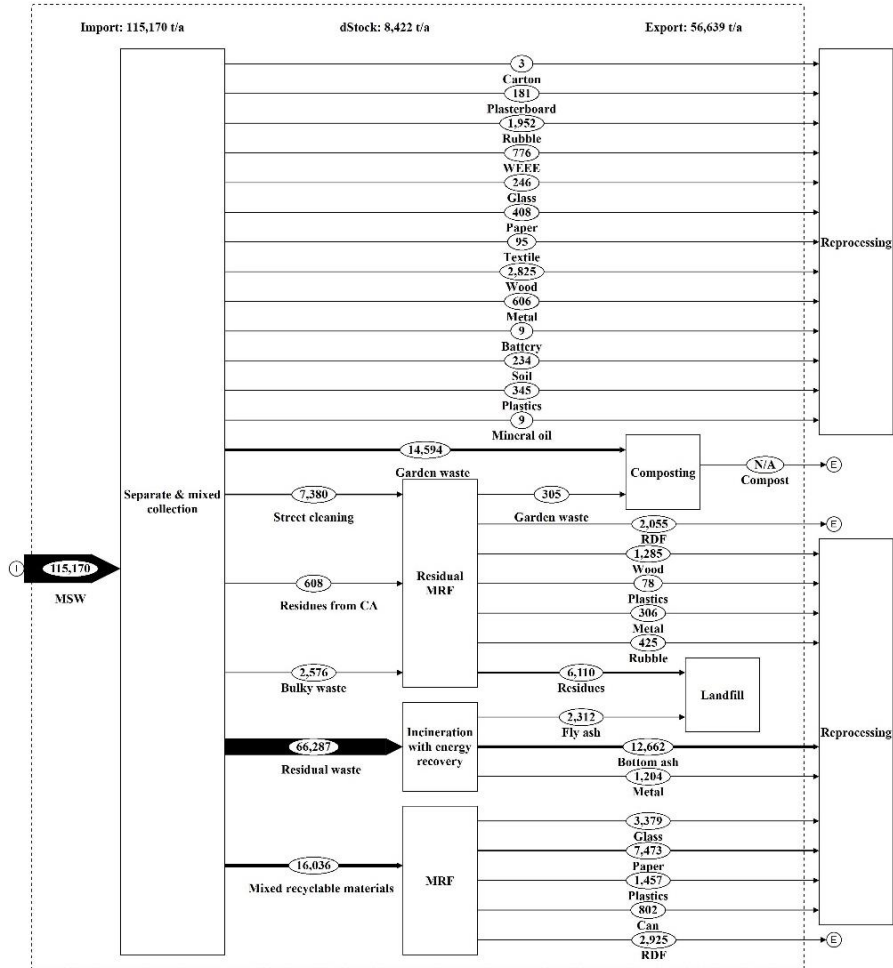


Fig. 4. Material flow diagram for S3.

Table 5. Comparison of MFA indicators for the three situations.

Indicator	Description	Situation		
		S1	S2	S3
Waste generation per capita (kg/y)	The MSW generated by each resident in a specific place (in this case is Nottingham) in a statistical year.	463.0	465.8	361.2
Recycling rate (%)	The ratio between the amount of waste prepared for recycling and the total amount of waste generated.	3.4	17.6	31.9
Recycling and composting rate (%)	The ratio between the amount of waste prepared for recycling and composting and the total amount of waste generated.	4.6	26.2	44.9
Recovery rate (%)	The ratio between the amounts of waste used for recovery options and the total amount of waste generated.	40.7	56.5	61.9
Landfill rate (%)	The ratio between the amount of waste disposed in landfill and the total amount of waste generated.	54.7	35.3	7.3

3.2 Life Cycle Interpretation

Based on the results of MFA, LCA has been performed for all MSW management situations. The LCA results are presented in Fig. 5. GWP_{100} of MSW management in Nottingham significantly decreased from 1,076.0 kg CO₂-eq./t of MSW in S1 to 487.9 kg CO₂-eq./t of MSW in S2, and further to 211.3 kg CO₂-eq./t of MSW in S3. This is mainly due to the diversion of waste from landfill to more sustainable management options such as recycling, composting and incineration with energy recovery. Followed by incineration, landfills were the main source of GHG in S1 and S2, but their roles were reversed in S3. GHG emission from landfills kept falling during the study period because of the reduction of landfilled waste. GHG emission from incineration increased from 210.3 kg CO₂-eq./t of MSW in S1 to 294.7 kg CO₂-eq./t of MSW in S2, and then decreased to 174.5 kg CO₂-eq./t of MSW in S3 even though the share of incinerated waste kept increasing. The main reason of decreased GHG emission from incineration from S2 to S3 is the change of composition of incinerated waste. The shares of materials having high content of carbon, such as plastic film and dense plastics, were lower in S3 than that in S2. Due to the improvement of separation of garden waste, GHG produced by composting kept growing from 1.3 kg CO₂-eq./t of MSW in S1 to 13.2 kg CO₂-eq./t of MSW in S3.

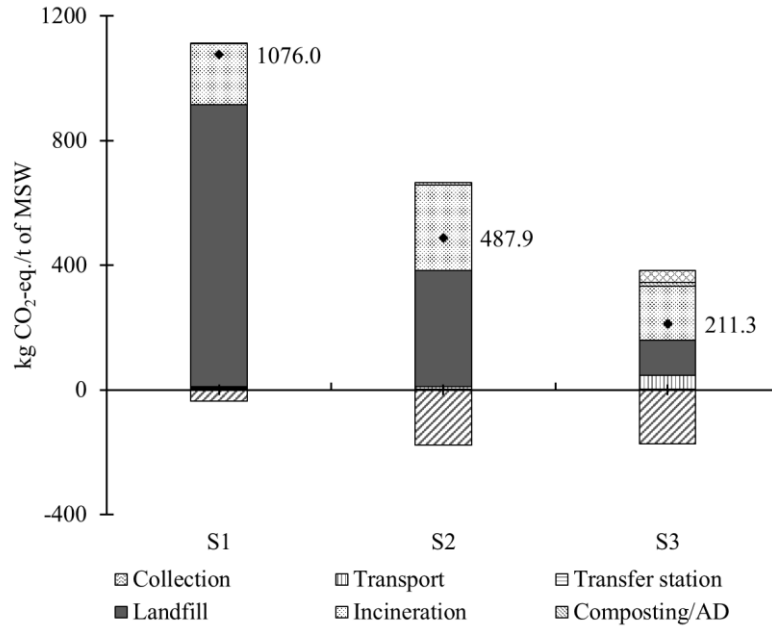


Fig. 5. Change of total GWP₁₀₀ and GWP₁₀₀ added by MSW management processes.

However, materials recycling was the only waste management practice that consistently saved GHG emission in all scenarios, while composting of garden waste and incineration with energy recovery added GWP₁₀₀ because of the limitations of outdated technologies and low efficiencies of the facilities. Technology adopted for composting was open windrow composting which had high potential of methane generation. Production of organic fertilizer from each ton of garden waste avoided 20.4 kg CO₂-eq./t GHG emission, but the GHG emissions (122.5 kg CO₂-eq./t of garden waste) from decomposition of garden waste and facility operation were much more than the emission saved by avoiding landfilling. The energy recovery efficiency of Eastcroft EfW appeared to be lower than other cases reported in the literature, e.g. 26.1% of electricity production, 77.2% of heat production and 52.1% of combined heat and power reported by Reimann [37], and 28% for electricity and 85% for heat reported by Habib et al. [38].

GHG emissions from collection and transport were usually ignored when performing the life cycle impact of MSW management because it only took a small part of the overall GHG emission. However, we noticed that the quantity and share of GWP₁₀₀ contributed by transport of recyclable materials to reprocessing facilities showed an increasing trend. It increased from 1.1 kg CO₂-eq./t of MSW in S1 to 42.2 kg CO₂-eq./t of MSW in S3 (Table 6). This growth was the result of the combination of growing recycling rate and the distant locations of reprocessing facilities. Some of them were located in overseas.

Table 6. Comparison of GHG emissions (unit: kg CO₂-eq.) from collection and transport.

	S1	S2	S3
Collection	3.4	3.1	2.8
Transport to of recyclable materials to reprocessing facilities	1.1	4.7	42.2
Transport between treatment facilities	3.5	2.5	2.0
Total	8.0	10.3	47.0

3.3 Recommendations for Future Improvements

According to the results of MFA and LCA, some recommendations have been made for the future improvement of MSW management in Nottingham.

Separating food waste at source and applying biological treatment for it are recommended. First, this measure could help the local authority to meet the recycling and composting target. Second, separating food waste improves the LHV of incinerated waste, thus improves efficiency of incineration and reduces the potentials of toxic gas generation resulted from incomplete combustion. Third, applying biological treatment on separately collected food waste provides additional organic fertilizer and/or renewable energy. Furthermore, separating food waste at source could reduce the potential of contamination of recyclable materials.

The results of MFA show that textile waste has been used more for the energy recovery. Textile was excluded by kerbside collection. Studies indicates that recycling textile generates less environmental burden compared to using virgin materials [39]. Therefore, we recommend to take textile into the scope of kerbside collection and recycling textile materials rather than incinerating it. In this way, the recycling rate in Nottingham could be further improved.

We also recommend the local authority to use advanced biological treatment technology, such as anaerobic digestion, to treat BMW (garden waste and food waste in this case) and to upgrade the EfW facility to improve the energy recovery efficiency. As food waste is recommended to be separately collected and treated, more methane will be produced from it. Adopting anaerobic digestion can not only reduce GHG emission but also improve the energy recovery ability of the MSW management system.

Furthermore, the significantly increased GHG emission from transport indicates that improving domestic reprocessing of secondary materials also need to be enhanced in the future. Improving energy consumption of vehicles also helps to reduce the GHG emission from transport.

4 Conclusions

The enforcement of EU waste directives and the associated targets have stimulated the update of national and local waste management regulations, plans and strategies. To assess the transition of MSW management under the guidance of these waste directives, this study assessed the performance of three historical MSW management situations at different transitional stage in Nottingham using the combined MFA and

LCA. Both the MFA and LCA result confirmed the improved performance of the MSW management in Nottingham which changed from a simple model of combined landfilling and incineration with energy recovery to a combination of source separation, recycling, pre-treatment before landfilling, production of RDF, composting, incineration with energy recovery and landfilling with complex waste flows. The transition resulted in a constant reduction of GWP₁₀₀. All these improvements contribute to the development of circular economy in the UK by providing renewable material and energy resources from waste. However, more efforts need to be made to meet national and local management targets. The future improvements can be made by separating food waste and textile waste at sources, replacing open windrow composting by anaerobic digestion, updating the EfW facility and enhancing domestic reprocessing of secondary materials.

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