Assessing the environmental performance of circular economy options for biowaste flows at city-region level

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Abstract

The purpose of this work is to analyse the environmental consequences when redirecting biowaste flows from conventional treatment options to more circular management systems and to identify the management option with the best environmental performance. We are particularly interested in understanding the effects of combining green and food waste flows, introducing different types of separate collection and implementing different treatment processes within a city.

In order to determine environmental impacts, we perform a life cycle assessment (LCA) based on local data from waste treatment facilities and waste collection providers. Following the study's purpose to analyse a change in the current system, we apply a consequential LCA approach and compare impacts from processes that are replaced with impacts from alternative biowaste management options. The alternative management options that are studied are co-composting and anaerobic digestion (AD) combined with two types of separate collection.

The LCA results show impacts on human health, ecosystems and resources for the different biowaste processes and indicate that both alternative systems perform better than the conventional one. The AD option can achieve more environmental savings, especially regarding impacts on resources.

The results give a first indication about environmental consequences for new treatment options that are discussed in Brussels, but need to be extended by analyses that include decentralised options and the role of prevention.

Keywords: Biowaste, environmental impacts, life cycle assessment, circular economy, city scale

1. Introduction

Within the Circular Economy Action Plan [1], biomass, biobased materials and food waste are considered priority areas for Europe's transition towards circular economy (CE). To implement CE, a wide range of measures is suggested, from material management to waste prevention. However, the central activity to achieve circularity is waste management because this activity determines whether the cycles of organic matter can be closed and whether nutrients and energy can be recovered.

Cities play an important role in CE because, due to the high population densities, they are the main producers of solid waste, which contains between 20-40% of organic content in Europe [2]. Currently, the collection rates and recovery schemes vary greatly between cities [3], and the potential for the recovery of nutrients and energy has not been fully exploited yet. Thus, it is important to analyse the different options for the management of biowaste in cities.

Knowledge on detailed waste flows is a prerequisite for tracking progress on CE targets and also for analysing environmental impacts of waste management scenarios. However, determining bio-waste flows is often challenging due to uncertainties in waste statistics [4], [5]. A specific challenge for the city scale is to cover the whole supply chain, including food processing, retail, hotels and restaurants etc. By combining waste statistics and IO-data, detailed inventories can be created, also at city level, which support the analysis of CE options [6].

To select a specific valorisation option, the hierarchy proposed by the EU Waste Framework Directive (WFD) can be used for a first screening. However, it represents a generalised environmental ranking that should be verified with life cycle assessment (LCA) based on local data [7]. Some LCA case studies have demonstrated that the most circular solution is not necessarily the most environmentally preferable option [8]. Jensen, Møller, and Scheutz (2016) [9] confirmed this for biowaste management systems. Their case study showed a better performance of incineration in most impact categories, but not all, compared to a more circular bioresource management system with combined anaerobic digestion and composting, and mechanical and biological treatment.

Other comparative LCAs [10–12] found more favourable environmental performances for circular bioresource systems.

While the range of biowaste technologies is generally well studied, research is often limited regarding the investigated sources and fractions of biowaste. Most studies consider the organic fraction of household waste (i.e. in most cases food or kitchen waste from households), and not biowaste as defined in the WFD including 'biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants'. Furthermore, the specific challenges for waste collection and treatment infrastructure in the urban context are not sufficiently represented in case studies.

With the goal to implement a more circular management system in Brussels, researchers, policy-makers and citizens discuss the different management options for biowaste. Key questions are: How much waste is exploitable in the future, which type of (separate) collection should be introduced, which type of waste treatment facility (composting/AD) should be installed and which management system should be prioritised (decentral/ centralized system)? An inter-project collaboration between different research teams and projects on biowaste is ongoing to develop and study CE scenarios for 2025 [13]. In the present study we focus on industrial management options and their transport requirements and evaluate the environmental impacts of different circular bioresource management systems. Based on the definition of biowaste in the WFD, we include green waste from urban gardens or parks, and food waste from households and from professional activities. This extended scope allows us to analyse different CE options and to study the impacts from different management combinations that can be particularly relevant for cities.

2. Data and method

2.1. Case study description

The case study is conducted in Brussels, Belgium, a densely populated European city (7,384 inhab./km^2) with around 1.2 million inhabitants. In the current waste management system in Brussels (2019), the main part of the generated *food waste* is managed as part of the residual municipal solid waste (MSW), i.e. the MSW fraction that is supposed to be not recyclable. In Brussels, the residual MSW is collected mainly in bags by a public agency and treated in Brussels' waste to energy facility (WtE). Since 2018 food waste is also collected separately in all municipalities of Brussels. Thus, the collection is only recently introduced and not obligatory which explains that only small amounts are currently collected. Due to the absence of a treatment facility for food waste in Brussels, the separately collected food waste is exported to an AD facility located 115 km outside of Brussels.

Green waste generated by households is separately collected since 2002 and treated in Brussels' composting plant. Green waste collected by private enterprises, for example from professional gardening and landscaping companies is also treated in the green waste composting facility or exported to composting and AD facilities outside of Brussels.

2.2. Data on waste flows and composition

In order to determine the *potential for a more circular management* of waste flows, it is necessary to quantify them. This has been done recently for all waste flows in Brussels [6]. In this previous research an approach based on waste statistics was applied. For biowaste, these statistics include only the amount of biowaste that are *collected* and exclude, for example, green waste from parks or gardens that is managed on-site. Available waste statistics provide the amounts of *separately collected* food and green waste. The amount of biowaste which is *part of the residual MSW* is not directly available and needs to be calculated. This estimation is difficult, because different sources contribute to the residual MSW stream (household and economic activities), different collection systems are established (bags and bins) and different actors perform the collection (public and private). Not for all of these streams waste *composition data* is available and the composition needs to be approximated. Composition data is available for residual bags from households collected by the public authority, and for residual waste from economic activities collected by private companies. Based on the amounts of collected residual MSW and the existing and estimated composition data, a total food and green waste amount 160 kt was estimated for 2014. This represents an average share of 36% of the total collected mixed residual waste.

2.3. Circular economy scenarios for biowaste

Circular economy scenarios for biowaste are currently under development by a group of collaborating research groups that are active around biowaste in Brussels [13]. The research teams agreed on three scenarios:

A. a baseline scenario that extrapolates current trends in urban biowaste management until 2025
B. a scenario that foresees investment in regional industrial infrastructures and
C. a scenario with larger implication of local decentralised initiatives.

In this study, we focus on the industrial management options and their implication on transport and perform an environmental assessment for scenarios A& B. For the decentralised options a multitude of decentralised treatment processes [14] and prevention options need to be parametrised.

The *baseline scenario* assumes that the current collection and treatment modes will continue to evolve according to previous trends, so the main treatment options for biowaste will be maintained.

This scenario will be compared with *alternative scenarios* that assume a higher share of separately collected waste and a more circular bioresource management system. This scenario assumes that by 2025, 50 kt of green and food waste will be collected separately and that new treatment facilities, either a composting or AD facility, will be operated in Brussels.

2.4. Scenario assessment with Life Cycle Assessment

In order to compare environmental impacts of the different scenarios, we perform a comparative life cycle assessment (LCA). LCA is a method to quantify environmental impacts of goods and services from ‘cradle to grave’. Through its holistic perspective LCA is particularly suited to support decision-making in waste management [15]. LCA results help to identify the management option that creates the lowest environmental impacts.

The LCA performed in the present study is a *consequential LCA*, i.e. a study that aims to identify environmental impacts as a result of a change in a system. The change that is studied in the alternative scenarios is the redirection of food waste from the incinerator and the redirection of green waste from the existing compost process to alternative treatments. This change also influences the amount and types of by-products that are created during the waste treatment (compost, electricity) and a change in the collection system (increased separate collection).

The system that is studied in the consequential LCA is only the part of the biowaste flows in Brussels that is supposed to be changed, and not the entire biowaste flows. The composition of this LCA product system is shown in Figure 1. We study the treatment of 50kt of biowaste (composed of food and green waste) that are redirected from their current treatment modes to a new composting (Scenario S1) or AD facility (Scenario S2). This implies to model the avoided impacts of the processes that are replaced (grey boxes, flows indicated by a minus) and to model the impacts of the new transport and waste treatment processes (blue boxes).

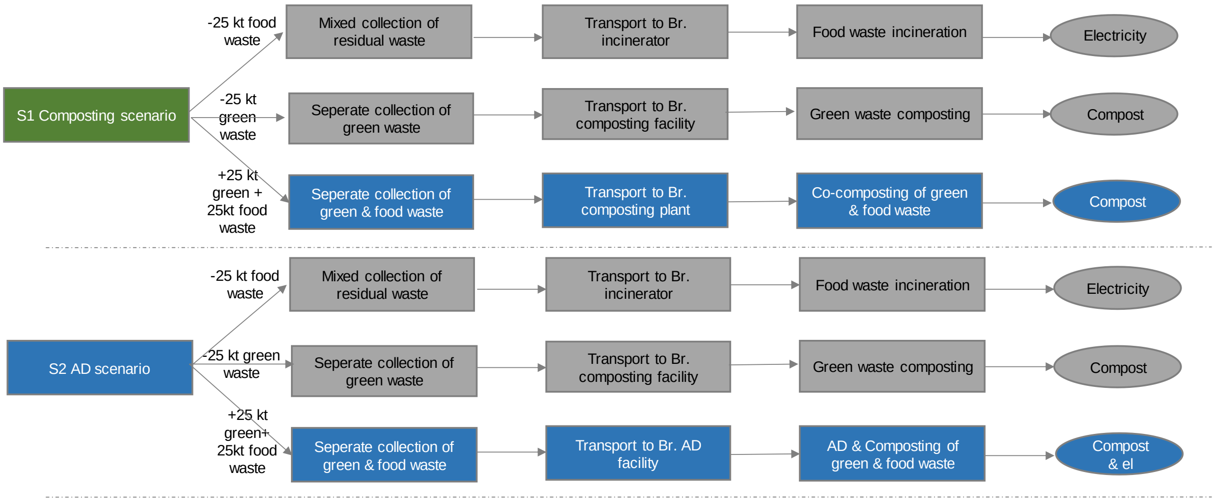


Figure 1: LCA product system

As shown in Figure 2, the *system boundary* is a bin-to-cradle boundary, starting from waste generation until the final residual treatment. The main process steps are the collection of waste, transport to the waste treatment facility, the waste treatment processes and the final residual treatment. For the *by-products* of the waste treatment service, such as compost or electricity, we apply the substitution approach in which the waste treatment system receives credits for the avoided production of alternative products.

The *functional unit* is the treatment of the separately collected biowaste fraction generated in Brussels in 2025. The reference flow is the treatment of 50.000 tons of separately collected biowaste.

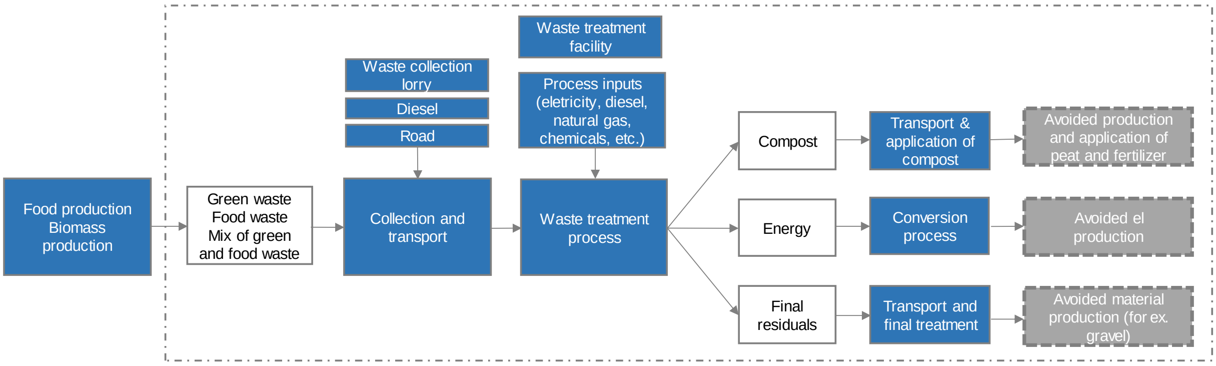


Figure 2: System boundary for the LCA

2.5. Life cycle inventory data

For each scenario, we chose a representative collection and treatment process, for example a representative composting process, although in reality several composting systems and a multitude of decentralized processes are used. The life cycle inventory data for these collection and treatment processes was collected from the local waste collectors and treatment facilities. For the new treatment facilities, data was taken from the feasibility study conducted for Brussels [16].

In order to compile a complete emission inventory and not only to use data for emissions that are monitored by the facilities, we used environmental models based on transfer coefficients and default data on the physico-chemical composition. The modelling of the physico-chemical composition and substance transfer was implemented with EASETECH software and its integrated database [17]. Due to its capacity to handle heterogeneous material flows it is specifically suited for modelling waste treatment processes. The whole LCA model including the modelling of the process inputs and substitution effects was modelled with SimaPro and ecoinvent (v. 3.5, consequential model).

2.5.1. Physico-chemical waste composition

In the present LCA study, we take into account a specific *fractional composition* for each biowaste mix entering a waste treatment process. For example, a specific food waste mix sent to incineration, a specific green waste mix for green composting, etc. However, due to absence of measurements of physico-chemical composition of Brussels' waste, we calculate the *physico-chemical composition* for each biowaste mix based on composition data available in the EASETECH database ([17], [18]).

The two principal fractions of biowaste that are studied, food waste and green waste, are composed of different subfractions. We estimate that the fractional composition in Brussels of food waste is 70% vegetable and 30% animal food waste and that the composition of green waste is 31% plants, 35% grass and leaves, 17% branches, 17% tree. The detailed fractional composition of each mix is indicated in Table A 1. The waste mix that enters a treatment facility has also a small share of plastic bags. For the green waste composting, the co-composting and AD we assume that by 2025 plastic bags are completely substituted by biodegradable bags. Table A 1shows the physico-chemical composition of each principal fraction (food waste, green waste mix and plastic) and the mixture that is treated in a certain facility.

2.5.2. Waste collection

When studying the impact of waste management scenarios in a setting with bin-to-cradle system boundaries, proper estimations of the transportation requirements of each scenario are vital. The introduction of an additional waste fraction to be collected separately will create additional transportation and therefore both additional costs and negative externalities. Our estimations are based on transport data provided by the responsible authority in the Brussels Capital Region (BCR) for the door-to-door waste collection. The data provides information on how much waste was collected in which areas of the BCR during 5 months in 2018 for the different municipal waste streams collected separately. A summary of the 2018 data can be found in Appendix 2. Note that we only look into the door-to-door collection provided by the public service in the BCR. Part of the green waste (10,500 ton) is transported by private actors and part (500 ton) is collected in civic amenity sites where residents can drop off all sorts of waste in dedicated containers. As the scenarios do not alter the quantity of separately collected green waste, this will not impact our results.

The transportation distances were calculated for the baseline case, and the two scenarios presented earlier. For scenarios 1 and 2 the same type of waste collection is required. We therefore discuss them together. Two options are available for collecting food waste:

- option 1: 25 kt food waste is taken out of the residual waste fraction and collected together with green waste;

- option 2: 25 kt food waste is taken out of the residual waste fraction and collected separately from green waste;

The distance driven for a newly separately collected waste stream depends on the area serviced (e.g. green waste is only collected in some areas of the BCR) and on how often trucks have to drive from the area being serviced to a treatment facility. The latter is largely determined by the amount of waste to be collected and the density of the waste stream as this affects how quickly a truck fills up. To estimate the transportation distance in each scenario, we make a distinction between the collection distance and the non-collection distance. The former comprises of the distance travelled during the actual collection, i.e. while bags and bin contents are deposited in the collection truck. The latter contains the distance travelled from the truck depot to the service area, between service areas, from the service area to the treatment facility, from the treatment facility to the service area and from the treatment facility back to the depot. For the estimation of the collection and non-collection distances for each waste stream in each scenario we refer to Appendix 2.

Combining the collection and non-collection distances and the waste quantities per waste stream enables us to calculate a km/ton ratio which will be used in the LCA analysis. The waste quantities, distances, ratios and densities calculated are provided in Appendix 2. Table 1 presents the total transportation distance, the collected weight and the km/ton per waste stream in each scenario. The last column in Table 1 clearly shows that Scenarios 1&2 will create additional waste transportation in the BCR. However, the reduced externalities associated with treating food waste separately could balance out or even surpass these added negative transportation externalities, which is analysed in the LCA study.

Table 1: Yearly collected weight, transportation distance and km/ton for each waste stream under the baseline case and the two transportation scenarios; total scenario distance under the baseline case and the three transportation scenarios

			Weight (ton)	Transportation distance (km)	km/ton	Scenario distance (km)
Baseline case		Residual	340,007	1,702,103	5.01	1,917,511
		Green	14,000	215,408	15.39	
Scenario 1&2	Option 1	Residual	315,006	1,686,464	5.35	2,078,639
		Food + Green	39,000	392,175	10.06	
	Option 2	Residual	315,007	1,686,464	5.35	2,261,729
		Food	14,000	215,408	15.39	
		Green	25,000	359,857	14.39	

Emissions from the collection of waste are modelled based on a representative collection and hydraulic compression vehicle for MSW collection as inventoried in ecoinvent 3.5 (21 ton lorry, gross load capacity 8.2 ton, load factor 50%). Included activities are diesel fuel consumption (0.4 kg/tkm driven), air emissions from fuel combustion for stop and go drying, abrasion (tyre, brake lining, road), the vehicle and road construction.

2.5.3. Incineration facility

Brussels' incineration plant is a waste to energy (WtE) facility for the treatment of municipal solid waste (MSW). The facility produces steam which is used in the neighbour power plant to generate electricity. In 2018, 490 kt of MSW have been incinerated to produce 280 GWh electricity. The combustion technology is a grate-based incineration. The facility is equipped with an air pollution prevention system (electrofilter and wet scrubber) and a DeNOx unit.

To model the environmental impacts of the incineration process, the facility provided data on energy use and generation, process inputs, emission data and data on the treatment of final residuals such as bottom and fly ash etc. This data represents a multi-input process for the incineration of residual MSW, including organic and in-organic fractions. In order to develop a model showing only process inputs and outputs related to the incineration of food waste, several methodological decisions need to be taken regarding the distribution of inputs and emissions and the consideration of credits. In the present study, we distributed process inputs (such as natural gas, caustic soda, activated carbon, ammonia, etc.) and process emissions (such as NOx, SO_2, HCl, etc.) over the multiple waste fractions proportional to their wet weight. Thus, food waste received, for example, 33% of the ammonia input used in the DeNOx process and 33% of NOx emissions. This decision is justified by the fact, that these emissions are driven by the conditions of the process and not by the type of waste input. In contrast, input-specific emissions such as CO_2 and heavy metals are calculated based on the physico-chemical composition of the food waste mix entering the incinerator (see Table A 1) and based on the transfer coefficients specified in Easetech's incineration model ([19],[18]). Based on these coefficients, the final residuals of the incineration process for food waste mix result in 1.5 kg of fly ash and 134 kg of bottom ash per ton of food waste input. The fly ash from this facility is transported by lorry to Germany where it is disposed in salt mines. The bottom ash is transported by boat to the Netherlands and used in road constructions. Environmental burdens for these transport requirements are modelled with ecoinvent datasets. For the final deposit of fly ash in salt mines we assume that no environmental impact occurs. For the application of bottom ash in road construction we include leaching of heavy metals according to [20] and give a credit for the substitution of gravel production. Impacts from infrastructure are approximated with the MSW facility modelled in ecoinvent.

An important methodological decision concerns the treatment of the by-product electricity for which a credit is given according to the substitution method in c-LCA. In previous waste-type specific incineration models ([11], ecoinvent consequential model) the amount of electricity from a specific fraction is calculated based on its energy content. This seems a correct approach under the assumption that the relative composition of the mix entering the facility remains stable. However, if a specific fraction is diverted from the incinerator, the change in composition and the associated change of the average heating value needs to be taken into account. Based on plant-specific information on heating values, food waste content and electricity output, we calculate an electricity surplus of 2.62 MJ/kg if 25kt of food waste is redirected from the incinerator.

2.5.4. Green waste composting

Brussels' composting facility is an open (partially enclosed) windrow composting for green waste that is collected from gardens and parks by the public service, municipalities and professional garden enterprises. In 2018, 14.800 tons of green waste was treated and around of 7.400 tons of compost were produced (compost yield: 0.5; density 410 kg/m³). The produced compost is mainly sold unpacked to professional enterprises and private clients.

The composting process is an aerobic process with temperatures between 60 and 70°C and has a duration of 5-6 months. In the first two weeks of the process, the green waste is placed under the dome where the air is aspirated and passes a biofilter. The process steps are chopping, composting under the dome, maturation of the compost (outside in compost heaps), sieving and separation of plastic waste with a windsifter.

To model the environmental impacts of the green waste composting process, data on green waste inputs, process inputs (electricity and diesel), compost yield (50%) and quality was collected from the facility. Until 2018 green waste was collected in plastic bags and the plastic fraction was separated with a windsifter at the end of the composting process. Since 2018 green waste is collected in biodegradable plastic bags which are degraded during the composting process. We assume that in 2025 the old plastic bags do not occur any more at the facility.

Since emission data is not measured at the facility, degradation models are used to determine emissions from the composting process. Due to its ability to take a specific biowaste composition into account, the model for biological treatment of organic municipal waste in EASEWASTE is used [21]. The composting model estimates the amount of C-containing (CO_2 and CH_4) and N-containing gaseous emissions (NH_3, N_2O and N_2) as a function of the degradation of C- and N-containing compounds in the biowaste. We used the degradation values and conversion ratios to gaseous emissions as specified for an open-air windrow composting facility [22], [23]. For N-compounds the model determines a degradation ratio of 8% of the total N input, which are converted to 15% N_2O, 83% NH_3 and 2% N_2. The C degradation ratio for the green waste mix modelled is 56% of the Cbio input. It is distributed over 97.8% CO_2 and 2.2% CH_4. For the biofilter we assume that 60% of emissions passes the biofilter during the 2 weeks composting process under the dome according to measurements of VS degradation in a closed tunnel facility [24]. The removal efficiency as specified in EASETECH for a biofilter in a closed tunnel facility is 99% for ammonia and 95% for methane [18].

The compost produced in the facility is currently used in gardens and parks in Brussels. Thus, it is mainly used as growth media and substitutes conventional growth media based on peat. We model C-sequestration, emissions into air, water and soil from the application of the compost based on degradation values for compost application and based on measurements from leaching tests as specified in the LCA inventory for compost and peat [25]. We also take into account the avoided emissions from the production of the conventional growth media (volume based substitution of peat; density peat: 200kg/m³) including mineral fertilizer (mineral fertiliser equivalents of 20% for nitrogen and 100% for P and K) and the avoided emissions from the degradation and leaching of peat based on LCA inventory data in [25].

2.5.5. Co-composting

Possible designs of a future composting facility in Brussels, including its location, mass flows and process inputs have been recently studied in a feasibility analysis [16]. The proposed technology is a closed-building tunnel composting facility for the composting of a mix of green and food waste (40% green waste, 60% food waste). Due to its modular design different capacities are possible. For this case study we consider the yearly treatment of 25 kt of food waste and 17 kt of green waste.

The composting process operates in a temperature range of 60 and 70°C, and has a duration of only 6 weeks. The process steps are chopping, sieving and separation of the biowaste, composting in the tunnel (2 weeks with automatic aeration and hydration), maturation of the compost (4 weeks in the maturation zone in the building) and final sieving. As in the previous installation, we assume the use of biodegradable bags, so a separation process is not necessary. The air of the complete building is aspirated and passes a biofilter. The tunnel composting has a similar demand on diesel as the previous installation (3l/ton of waste), but a higher consumption on electricity (111 kWh/ ton of waste) and water (190l/ton of waste). The compost yield is lower compared to the green waste composting process (0.31), but the nutrient content is higher for some macronutrients, for example for P.

In order to estimate direct process emissions for this composting process, we used the same approach as described above based on the specific biowaste composition and a degradation model to determine gaseous emissions (CO_2, CH_4, NH_3, N_2O and N_2). We used the degradation values as specified in Easetech for a closed tunnel composting facility which are 71% of the N and 66% of the C-content of the waste. Degraded N is further converted into 1.4% N_2O, 98.5% NH_3 and 0.1% N_2; C is converted to 99.8% CO_2 and 0.2% CH_4 (without biofilter). [24]. For the biofilter we use the efficiencies as specified in EASETECH for a biofilter in a closed tunnel facility (99% removal efficiency of ammonia and 95% of methane).

Emissions from the use of the compost and the credits from the substitution of growing media and fertiliser are modelled according to the approach described for the green waste composting facility. The density of the produced compost is 600kg/m³.

2.5.6. Anaerobic digestion plant

Possible designs of a future AD facility in Brussels, including its location, mass flows and process inputs have been studied in a feasibility assessment [16]. The proposed technology is combination of AD of (mainly) food waste and a subsequent composting of the digestate together with the green waste. The proposed capacity of the facility is 50 kt in the feasibility study (40% green waste, 60% food waste) which we scale to a yearly treatment of 25 kt of food waste and 17 kt of green waste in this study.

The proposed AD process is a dry, one step process. The food waste is pretreated (sieving, chopping, metal separation) and then sent to the digester (AD stage of 3 weeks). The produced biogas can be used for electricity generation or upgraded to biomethane. The digestate is mixed and composted with green waste which was previously chopped and sieved. The composting process takes place in a closed hall which is equipped with a biofilter. After 2 weeks of composting, the precompost is sieved and the small fractions are sent to maturation in the maturation hall (2 weeks). Process inputs are electricity for the pumps, ventilation, etc. (77 kWh/ton of waste, internally provided), diesel for the machinery (2.4 l/ton of waste), heat to heat up the digester (9.6 kWh /ton of waste, internally provided) and tap water (0.017m³/ton of waste).

The biogas yields determined in the feasibility study are between 95-128 Nm³ for the different biowaste fractions. The overall methane content is estimated to be 55%. When relating the annual biomethane production to the total biomass input of the facility the plant specific biomethane yield is 38.2 m³/ton.

In order to estimate direct process emissions for this AD process, we take into account fugitive CH_4 emissions (2% of generated methane [18] and emissions from the biogas combustion in stationary engines in case of electricity generation (el efficiency: 0.37). We also take into account the avoided impacts from the substitution of the electricity (net electricity 71 kWh/ton). In addition to electricity, compost is one of the final co-products of the process. As in the previous description, we consider emissions and sequestration of carbon from its application on land as well as the avoided impacts from the production of fertilizers and peat.

2.5.7. Overall environmental balance/ comparative scenarios

The results for the comparative scenarios are calculated as follows: The total impact of scenario S1 is the sum of

- the avoided impacts from redirecting 25kt food waste from the incinerator (-25kt food waste* impact per kt food waste incineration)
- the avoided impacts from redirecting 25kt green waste from the green waste composting (-25kt green waste* impact per kt green waste composting with biofilter)
- the impacts from directing 50kt of biowaste into the co-composting (+42kt biowaste*impact per kt of biowaste co-composting, joint collection + 8kt of green waste* impact per kt of green waste composting, without biofilter).

Total impact of scenario S2 is the sum of

- the avoided impacts from redirecting 25kt food waste from the incinerator (-25kt food waste* impact per kt food waste incineration)
- the avoided impacts from redirecting 25kt green waste from the green waste composting (-25kt green waste* impact per kt green waste composting, with biofilter)
- the impacts from directing 50kt of biowaste into the new AD/composting process (+42kt biowaste*impact per kt of AD/composting, joint collection +8kt of green waste* impact per kt of green waste composting, without biofilter).

2.6. Impact assessment

For the impact assessment, we apply the state-of the art impact assessment method ReCiPe2016 that converts life cycle inventories into 17 midpoint and 3 endpoint impact categories [26]. The endpoint results indicate potential environmental impacts on human health, on ecosystems and on resources. Impacts on human health are expressed in DALY which stands for disability adjusted life years and represents 'the years that are lost or that a person is disabled due to a disease or accident'. Damages on ecosystems are expressed as potentially disappeared fraction of species$\cdot$m$^2\cdot$year or potentially disappeared fraction of species$\cdot$m$^3\cdot$ year. This damage category describes the 'local relative species loss in terrestrial, freshwater and marine ecosystems, respectively, integrated over space and time'. Impacts on the availability of resources are measured in US dollars ($), which represents the extra costs involved for future mineral and fossil resource extraction. This impact category aggregates mineral and fossil resource scarcity.

From the three sets of midpoint and endpoint characterisation factors, we chose the hierarchist scenario. It refers to a set of values that consider a 100-year time horizon and integrates effects accepted by international bodies such as the World Health Organisation.

For the processes that are evaluated in this study, the counting of biogenic carbon is of particular importance, since, for example, the main gaseous emissions from incineration and composting is biogenic CO_2, the main emission from AD is biogenic CH_4. In the chosen impact assessment method for global warming (that refers the IPCC 2013 method), biogenic CO_2 is not accounted, biogenic methane has a characterisation factor of 34 kg CO_2 eq./kg.

3. Results and discussion

3.1. Biowaste treatment processes

Figure 3 shows the LCA results for the different management options related to the treatment of 1 ton biowaste. These endpoint results indicate potential environmental impacts on human health (DALY), on ecosystems (potentially disappeared species per year) and on resources (USD). The figure shows the contribution of processes to the total impact. Processes are grouped into transport processes (blue), infrastructure (green), process inputs (grey) and direct emissions from the waste treatment process (red). The absolute results for the different waste treatment processes cannot be directly compared, because different waste fractions with different compositions are analysed (food waste, green waste and biowaste mix). The figure shows positive values indicating environmental impacts, negative values indicating environmental credits and the net balance (sum of impacts and credits).

Impacts on human health and ecosystems from the food *waste incineration process* are mainly dominated by process inputs, for example by sodium hydroxide with a contribution of 34 and 30%. Impacts on resource uses are mainly caused by the potential loss of electricity through the combustion of food waste in the MSW mix (49.5%) and the use of natural gas in the incineration process (28%). Regarding environmental credits, the results show only a small credit for the substitution of gravel by bottom ash.

Impacts on human health and ecosystems from the *green waste composting process* are mainly driven by direct emissions of the composting process (N_2O, CH_4, NH_3). Equipped with a biofilter (as in Brussels' facility) the contribution of direct emission is between 43 to 52%. Without biofilter the contribution of direct emissions to human health and ecosystems impacts can increase to 60-68%. Impacts on resource availability are mainly caused by the waste collection service and by the diesel used in the composting facility. In addition to impacts, the results show environmental credits (negative values) from the avoided production of fertiliser and peat. The net balance indicates that the credits offset impacts for the impact categories human health and ecosystems, but not for resource use.

For the alternative biowaste scenarios, the results show two options for the separate collection (see 2.5.2). For the *co-composting process*, the waste collection service has a contribution between 16 and 31% of the impacts. The lower contribution occurs for the joint collection of food and green waste. The impacts on human health and ecosystems are mainly driven by process inputs (42-49%) and direct emissions of the composting process (31-40%). Compared to the previous process, the contribution of process inputs is higher, because electricity consumption is much higher and also the biofilter efficiency is increased. The credit for avoided peat production and application is lower compared to the green waste composting, because the compost yield is lower and density is higher. Impacts on resource use are mainly caused by electricity consumption (around 50%). The net results for the co-composting process show for the three damages categories environmental impacts.

The final biowaste treatment option that is studied is *anaerobic digestion with post composting*. Impacts on human health and ecosystems from this are mainly driven by direct emissions of the composting process that takes place after the AD phase (39-48%). Resource use is mainly caused by waste collection (57-66%) and by diesel use (37-29%). Process inputs such as electricity and heat do not affect the balance because they are internally provided. The internal use, however, reduces the net output of the facility and the net credit for substituted electricity. The net results for this process show for the three damage categories environmental savings, except for resource use where the balance could turn into a net impact if waste collection is implemented with a two bags system.

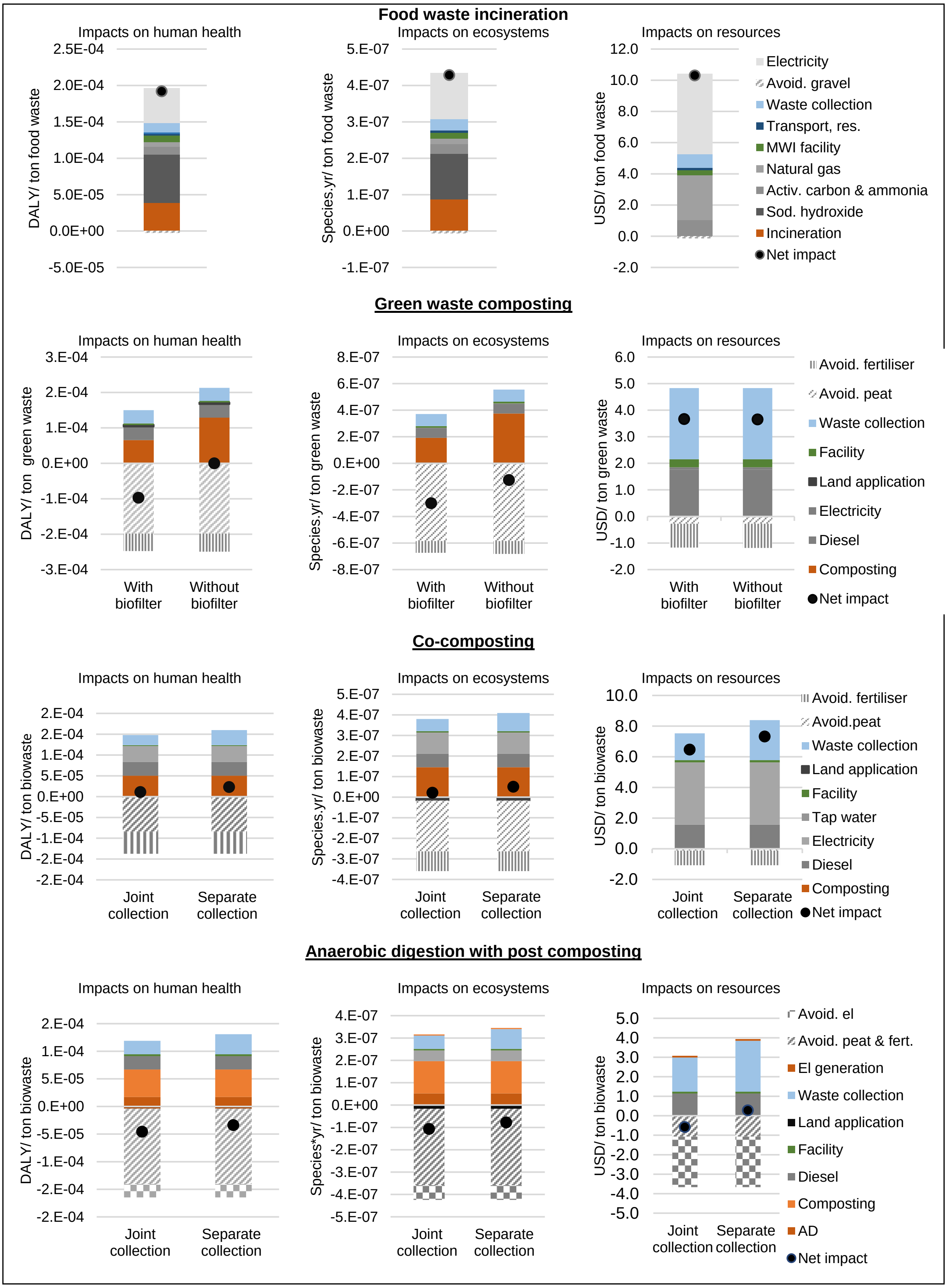


Figure 3: LCA results per waste treatment process

3.1.1. **Comparative scenario results**

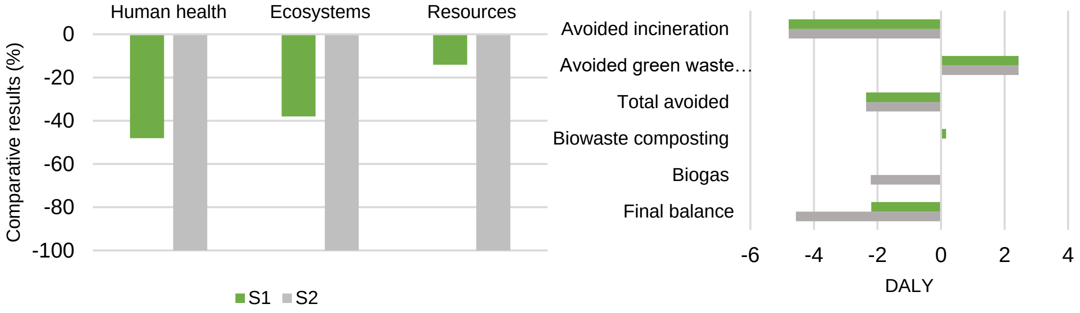
The comparative scenario results show the environmental balance for the processes that will be replaced in the future and the impacts from the new treatment processes. Figure 4 a shows the final balance for the two alternative scenarios. The key messages from this figure are that both alternative systems perform better than the biowaste system that is currently in place and that the AD option (S2) can achieve more environmental savings, especially in the impact category resources.

Figures 4b-d show the balances per impact category, composed of the net results from replaced incineration and composting and the net results from the alternative treatments (co-composting and anaerobic digestion).

The balances for impacts on *human health and ecosystem* follow a similar structure: Through the reduction of incineration, damages on human health and ecosystems can be prevented. However, through the reduction of green waste composting, a potential environmental credit is lost (indicated by a positive value in the graph, for example +2.5 DALY). The sum of replaced incineration and green waste composting gives the total avoided impact which is the benchmark for the new processes. As presented previously, for impacts on human health and ecosystems, the net result of the new processes shows very little impact or even a net reduction (AD). Therefore, the final balance shows a net reduction for co-composting and AD. Regarding *resource use* the results for co-composting show comparatively high impacts. However, compared to the sum of avoided incineration and composting, the total balance still indicates a net reduction. The final balance for AD indicates a potentially significant reduction in terms of resource uses.

A. Scenario results-overview

B. Impacts on human health



C. Impacts on ecosystems

D. Impacts on resources

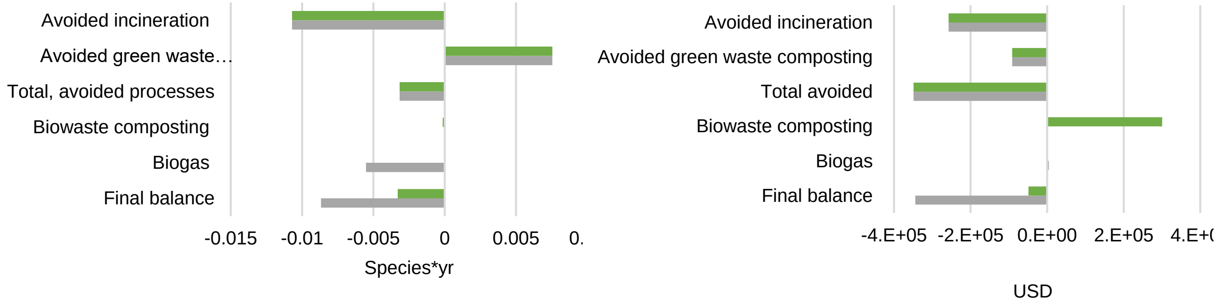


Figure 4: Overview of scenario results and balances per impact category

3.1.2. **Sensitivity analysis**

In order to discuss the robustness of results, we perform a sensitivity analysis by changing parameters that have significantly determined the overall balance. We will first discuss the sensitivity of the first result that indicated a better performance of the alternative scenarios compared to incineration and green waste composting. As shown in the contribution analyses (Figure 3), this result is mainly determined by the substitution effects of compost and by the energy credit for not-incinerating food waste.

- The assumption that the future compost produced in Brussels is used as a growth media in gardens and parks is based on observations of the current use. However, depending on the price of the compost an agricultural application without peat substitution could also occur in the future. Thus, we change the credit for peat substitution to zero. As shown in (Table 2; column V1), the results without credits for peat substitution still show an environmental benefit for the alternative scenarios.
- The integrated modelling of impacts on the MSW incineration process as proposed in this study represents the physical reality of incineration where a reduction of the input of wet food waste into incineration increases the heating value of the remaining MSW mix and increases electricity production. However, the type of electricity that is substituted could be different than the one chosen in this study. The default

electricity chosen in our assessment is the marginal electricity mix for Belgium, as specified in the consequential model in ecoinvent 3.5 which is composed of natural gas (55%) and wind energy (42%). Choosing as alternative process the current Belgian electricity mix changes the impacts on resource use by around 30% (Table 2; column V2), but the general trend is maintained.

The second result that will be critically discussed is the advantage of a combined AD/composting compared to the composting process. First, it has to be mentioned that the same basic model is used for both processes and that the data quality is comparable for both scenarios.

- The change in electricity mix indicates that the advantage for AD may be less in the case that the electivity mix changes, but that the general trend is still maintained.
- Another parameter that is often discussed in LCA studies for AD is the assumption on fugitive methane emissions may vary between 1% to 5% [27]. The increase from 2%, the value chosen in this study, to 5% fugitive methane emissions would change the results for human health and ecosystems significantly.

Table 2: Sensitivity analysis indicating the impact on the results when changing key parameters (V1: No credit for peat substitution; V2: Change in electricity; V3: Change in % of fugitive methane emissions)

		Reference result	V1: No peat substitution		V2: Change of electricity mix		V3: Fugitive methane emissions	
S 1 Composting scenario				% change		% change		% change
Human health	DALY	-2.19E+00	-2.04E+00	-7	-2.22E+00	1	-2.19E+00	0
Ecosystems	Spec. yr	-3.30E-03	-2.84E-03	-14	-3.20E-03	-3	-3.30E-03	0
Resources	USD	-4.85E+04	-4.83E+04	0	-6.66E+04	37	-4.85E+04	0
S2 AD scenario								
Human health	DALY	-4.57E+00	-4.41E+00	-3	-4.44E+00	-3	-3.48E+00	-24
Ecosystems	Spec.yr	-8.68E-03	-8.21E-03	-5	-9.28E-03	7	-5.41E-03	-38
Resources	USD	-3.45E+05	-3.44E+05	0	-2.35E+05	-32	-3.45E+05	0

3.2. **Conclusions**

The present research investigated an integrated solution for the management of green and food waste that is particularly interesting for cities. The results determined the key parameters when analysing environmental impacts from a LC perspective, such as: the type of separate collection system, specific process parameters (such as removal efficiencies of biofilters), implications on the MSW incineration process and the fate of the co-products. From this point of view, we can support previous conclusions from waste management studies that emphasized the importance of local data [7].

The results indicate an environmental benefit when changing a part of the current biowaste systems to a more circular system of biowaste management- either a system based on co-composting or a system based on AD/combined composting. When comparing the two alternative systems we find a significant advantage for AD in terms of resource availability. Also in terms of impacts on human health and ecosystems the results support the AD/combined composting option.

The results show only two simplified scenarios of a future biowaste management system in Brussels. We did not include the various possibilities of decentralised management systems which are already in place and the future ones discussed for Brussels. These systems have the additional advantage of avoiding waste collection and transport. We neither included the potential role of prevention, which does not only prevent the impacts of waste treatment, but also avoids the impacts of food production, which can be significant.

Acknowledgments

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Appendix 1:

Table A 1: Physico-chemical composition of the different fractions

	Food waste mix[1]	Green waste mix[2]	Plastic bags[3]	Food waste mix (Incinerator)[4]	Green waste mix (Composting)[5]	Biowaste mix (Co-Composting and AD)[6]
Total Wet Weight (kg)	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00
Water (kg)	710.30	530.20	71.00	706.45	530.20	638.26
Total solids (kg)	289.70	469.80	929.00	293.55	469.80	361.74
Volatile solids (kg)	270.13	297.60	877.91	273.79	297.60	281.12
Ash (kg)	19.57	172.20	51.10	19.76	172.20	80.62
Energy (MJ)	6105.89	5488.97	29690.84	6247.96	5488.97	5859.12
C bio (kg)	147.77	121.76	3.30	146.90	121.76	137.37
C fossil (kg)	1.84	1.22	655.87	5.78	1.22	1.59
H (kg)	20.79	19.18	90.11	21.21	19.18	20.15
O (kg)	87.02	121.73	103.12	87.12	121.73	100.90
N (kg)	12.07	3.71	4.65	12.02	3.71	8.72
S (kg)	0.78	0.35	0.48	0.78	0.35	0.61
P (kg)	1.65	0.54	5.21	1.68	0.54	1.21
S (kg)	7.83E-01	3.54E-01	4.83E-01	7.81E-01	3.54E-01	6.11E-01
Al (kg)	2.03E-01	2.74E+00	5.25E+00	2.33E-01	2.74E+00	1.22E+00
As (kg)	1.28E-04	5.34E-04	1.86E-04	1.28E-04	5.34E-04	2.90E-04
Cd (kg)	2.98E-05	8.54E-05	3.20E-05	2.98E-05	8.54E-05	5.20E-05
Cr (kg)	9.96E-04	5.47E-03	2.67E-03	1.01E-03	5.47E-03	2.78E-03
Cu (kg)	2.80E-03	2.96E-03	8.81E-02	3.31E-03	2.96E-03	2.86E-03
Fe (kg)	5.66E-02	0.00E+00	7.89E-01	6.10E-02	0.00E+00	3.39E-02
Hg (kg)	5.79E-06	7.51E-06	1.84E-05	5.87E-06	7.51E-06	6.48E-06
Mg (kg)	3.27E-01	5.60E-01	4.24E-01	3.28E-01	5.60E-01	4.20E-01
Mn (kg)	1.47E-02	7.40E-02	9.38E-03	1.47E-02	7.40E-02	3.84E-02
Mo (kg)	1.79E-04	7.75E-04	1.21E-03	1.86E-04	7.75E-04	4.17E-04
Ni (kg)	5.03E-04	8.84E-01	4.12E-03	5.25E-04	8.84E-01	3.54E-01
Pb (kg)	1.76E-04	1.69E-03	1.19E-03	1.83E-04	1.69E-03	7.82E-04
Sn (kg)	0.00E+00	2.13E-03	0.00E+00	0.00E+00	2.13E-03	8.51E-04

[1] *Composition food mix: 30% animal-based, 70% vegetable based*

[2] *Composition green waste: 31% plants, 35% grass and leaves, 17% branches, 17% tree*

[3] *Plastic bags: non-recyclable plastic selected*

[4] *Food waste mix (incinerator): 99.4% food waste mix, 0.6% plastic*

[5] *Green waste mix (co-composting): 100% green waste*

[6] *Biowaste mix (composting and AD): 60% food mix, 40% green waste*

Appendix 2:

Calculation of transportation distances

In order to calculate the transportation distances for the different scenarios, several data manipulations were required. This appendix provides a detailed description of the data used and the intermediary results of the calculations. A summary of the data provided by the BCR's waste collection authorities is provided in Table A 2. Note that we only look into the transportation provided by the public service in the BCR. Part of the green waste (10,500 ton) is transported by private actors. As the scenarios do not alter the quantity of separately collected green waste, this will not impact our results.

Residual waste is collected twice a week while green waste and food waste is only collected once a week. Furthermore, residual waste is collected in bags and bins which will also be the case for separately collected food waste. This entails a different collection distance for the two methods as trucks do not need to pass every curb in the case of bin collection. Green waste is only collected in a select number of neighbourhoods while residual waste and food waste is collected throughout the entire region.

Table A 2 shows a summary of the 2018 5 month waste collection data. From June 1 2018 until October 31 2018, 83,330 ton residual waste was collected in bags on the curb while 34,688 ton was collected from apartment buildings, offices, etc. in large bins. The data contains information on where the waste was collected, but only for the bag collection, which is why no distinction between the collection and non-collection distance could be provided. Green waste is only collected in bags. During the same period of time, 4,175 ton green waste was collected. An estimation was provided for the total residual and green waste collection in 2025, which is also presented in Table A 2.

Table A 2: Summary of data provided by the BCR's waste collection authorities

	Transportation distance (km)	Weight (ton)	Non-collection distance (km)	Collection distance (km)
Residual waste bins 5 months 2018	228,978	34,688		
Residual waste bags 5 months 2018	384,557	83,330	248,433	136,124
% bin collection		29%		
% bag collection		71%		
Green waste bags 5 months 2018	74,426	4,175		35,837
			38,589	
Residual waste yearly 2025		340,007		
Green waste yearly 2025 - Household		14,500		
Green waste yearly 2025 - Professional		10,500		
Waste taken out yearly for bio-waste 2025		25,000		

The 2018 5 month collection and non-collection distance for the bag collection of residual and green waste needs to be extrapolated to the 2025 yearly estimate. As mentioned previously, a distinction is made between collection and non-collection distance. The former is the distance travelled during the actual collection, i.e. while bags and bin contents are deposited in the collection truck. The latter is the distance travelled from the truck depot to the service area, between service areas, from the service area to the treatment facility, from the treatment facility to the service area and from the treatment facility back to the depot. Therefore, adjusting the 5 month collection distance to a year by simply multiplying it by 12/5 is sufficient as the length of the curbs to be visited is not affected by the change in waste generation. For the non-collection however, a weight ratio (WR, km/ton) is calculated by dividing the 2018 5 month non-collection distance by the 2018 5 month collected weight. This ratio represents the kilometers a truck needs to drive during non-collection for one ton of waste. It is independent of the total amount of waste to be collected. The 2025 yearly non-collection distance is then the result of multiplying this WR by the 2025 yearly collected weight estimate. The WR and the resulting non-collection and collection distances for the 2025 bag-collection can be found in Table A 3.

Unfortunately for the bin collection of residual waste, only a total transportation distance was provided. We therefore had to transform the transportation distance proportionally to the weight to be collected in 2025. We acknowledge that this will overestimate the transportation distance for the bin-collection. As the main (we assume only) difference between bin and bag collection lies in the actual collection, i.e. the collection distance, we use the residual waste bag-collection WR to calculate the non-collection distance. The collection distance for the residual waste in bins is then derived by subtracting the non-collection distance from the total distance. The BAU estimates for the collection and non-collection distance for residual waste in bins are presented in Table A 3.

Table A 3: Estimation of the collection and non-collection distances for the Baseline scenario

		Weight (ton)	Transportation distance (km)	Collection distance (km)	Non-collection distance (km)	WR (km/ton)
BAU bins	Residual waste bins	99,936	659,679	361,738	297,940	2.98
BAU bags	Residual waste bags	240,071	1,042,424	326,697	715,728	2.98
	Green waste bags	14,000	215,408	86,009	129,399	9.24

In the two transportation scenarios the residual waste to be collected is reduced by 25 kt food waste. Reducing the residual waste to be collected does not affect the collection distance as all curbs (bags) and apartment buildings, offices, public buildings (bins) have to be serviced regardless of the generated amounts. The collection distance is therefore kept as is. For green waste, the BAU collection distance applies for all transportation scenarios except for Scenario 1&2, option 1 where it is collected simultaneously with food waste. In Scenario 1&2, option 1 and Scenario 1&2, option 2, trucks will drive the same route twice: once to collect residual waste and once to collect respectively food or food + green waste. The collection distance is therefore calculated as the residual waste collection distance divided by two to account for weekly/bi-weekly collection. Table A 6 presents the resulting collection distances per waste stream, collection method (bag/bin) and transportation scenario.

The non-collection distance however is affected by a change in the total waste to be collected and a change in the composition of the waste. A waste stream's non-collection distance (NCD) can be divided into two factors which are multiplied: the total waste quantity to be collected (QTY) in ton and the weight ratio (WR) in km per ton (see formula 1).

$$NCD = QTY \times WR \qquad (1)$$

The weight ratio is the distance a truck driver has to drive during non-collection for collecting one ton of waste. This WR is affected by how quickly a waste truck is full. While assuming truck sizes (in m^3) do not differ across waste streams, the WR is affected by the density (ton/m^3) of each waste stream. The WR can thus be calculated by dividing a volume ratio (VR) (km/m^3), which is the distance a truck has to drive during non-collection for collecting 1 m^3 waste, by the waste stream's density (ton/ m^3) (see formula 2).

$$WR = VR / Density \qquad (2)$$

Using the 2018 data, we find for the baseline residual waste composition a WR of 2.98 km/ton. The composition of this baseline residual waste is 41% food waste, 4% green waste and 55% other residual waste. The densities for the three fractions can be found in Table A 4. By applying these density factors for the three waste fractions, we derive a BAU residual waste density of 0.163 ton/m^3. This results in a VR of 0.48 km/m^3. Taking 25 kt food waste out of the residual waste fraction will result in a lower density, i.e. 0.153 ton/m^3 (for the calculation see Table A 5). Combining the adjusted density with the density-independent VR results in a WR of 3.17 km/ton.

Table A 4: Waste densities

	Residual (kg/m3)	Food (kg/m3)	Green (kg/m^3)
Waste density	101	775	213

Table A 5: Waste stream density calculations

	Weight (ton)	Food part (ton)	Green part (ton)	Residual part (ton)	Density (ton/m^3)
Residual waste BAU	340,007	138,902	14,954	186,150	0.163
% of each fraction (weight)		0.41	0.04	0.55	
Residual waste Scenario 1&2	315,007	113,902	14,954	186,150	0.153
% of each fraction (weight)		0.36	0.05	0.59	
Food & green waste Scenario 1&2: option 1	31,652	17,652	14,000		0.358
% of each fraction (weight)		0.56	0.44		

For separately collected food waste (in Scenario 1&2, option 2), the WR is derived from the density-independent VR for residual waste (0.48 km/ m^3) and the waste density (0.775 ton/m^3). For separately collected green waste (Scenario 1&2, option 2), no additional calculations are required. Note that the VR for green waste is larger than the residual waste VR. This can be explained by the fact that green waste is not collected in all areas of the BCR, and that therefore trucks have to additionally drive between different areas during their collection rounds. In Scenario 1&2, option 1, food waste and green waste are collected simultaneously. Applying the conversion factors allows us to determine a density of 0.358 ton/ m^3 for this combined waste stream. Inserting this density and residual waste’s VR results in a WR of 1.36 km/ton. The non-collection distance for the three transportation scenarios can then be calculated by multiplying the WR by the amount of waste to be collected.

The waste quantities, distances, ratios and densities calculated are provided in Table A 6.

Table A 6: Yearly collected weight, collection, non-collection and total distance, weight ratio, volume ratio, density and km/ton for each waste stream under the baseline case and the three transportation scenarios; total distance travelled under the baseline case and the three transportation scenarios

			Weight (ton)	Collection distance (km)	Non-collection distance (km)	Total distance (km)	WR (km/ton)	VR (m^3/ton)	Density (ton/m^3)	km/ton	Scenario distance (km)
Baseline case	Residual	Bags	240,071	326,697	175,728	1,042,424	2.98	0.48	0.163		1,917,511
		Bins	99,936	361,738	297,940	659,679	2.98	0.48	0.163		
		total	340,007			1,702,103				5.01	
	Green	Bags	14,000	86,009	129,399	215,408	9.24	1.97	0.213	15.39	
Scenario 1&2	Residual	Bags	222,419	326,697	704,685	1,031,382	3.17	0.48	0.153		
		Bins	92,588	361,738	293,343	655,082	3.17	0.48	0.153		
		total	315,007			1,686,464				5.35	
Option 1	Food + Green	Bags	31,652	163,348	42,908	206,256	1.36	0.48	0.358		2,078,186
		Bins	7,348	180,869	4,597	185,466	0.63	0.48	0.775		
		total	39,000			391,722				10.04	
Option 2	Food	Bags	17,652	163,348	11,042	174,391	0.63	0.48	0.775		2,261,729
		Bins	7,348	180,869	4,597	185,466	0.63	0.48	0.775		
		total	25,000			359,857				14.39	
	Green	Bags	14,000	86,009	129,399	215,408	9.24	1.97	0.213	15.39	