Comparison of local and centralized biowaste management strategies – a spatially-sensitive approach for the region of Porto

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Abstract. The increasing concern with greenhouse gas emissions and nutrients cycling creates a need for cost-effective, practical and environmentally sensible biowaste management strategies. Centralized systems have struggled to comply with those needs. Decentralized systems, treating waste at source, promise local nutrient circularity and increased resource sovereignty. The large-scale performance of decentralized systems remains unclear, especially concerning the local sink capacity to assimilate the treatment products. This study aimed to compare centralized and decentralized systems for the region of Porto and assess whether creating additional urban farms could reduce costs and environmental impacts. Spatial analysis was used to assess waste generation, potential compost bin locations, peri-urban and potential urban farmland available, and collection and transport requirements. The carbon footprint of different scenarios was determined using life-cycle assessment. The results show that local composting led to cost savings over centralized systems. However, this system encompassed positive carbon emissions and most districts evidenced limited sink capacity for compost application. Additional urban

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farms added significant sink capacity, however, their impact on cost and carbon footprint was insignificant. The carbon footprint of centralized systems was heavily dependent on factors influencing collection such as population density, and affected by the renewable content of the electricity grid. Anaerobic digestion was the most climate-friendly option in the urban center and local composting in remote and less dense districts. Municipalities may benefit from tailoring the treatment systems to specific districts, creating additional jobs while reducing cost and climate impacts overall.

Keywords: biowaste management; community composting; spatial analysis; nutrient circularity; urban agriculture

1. Introduction

In many countries, expanding urban areas face great challenges in biowaste management and resource recovery. From 2024, all household biowaste in the EU must be treated at source or collected separately (Council of the European Union, 2018). In preparation for this, many municipalities are currently facing the task of restructuring their waste management systems. While this fundamental change presents opportunities, it also raises questions as to which treatment systems best address climate change mitigation and circular resource flows for different types of municipalities, among other desirable outcomes.

Many studies have compared different centralized food waste treatment systems, reaching mainly similar but sometimes contrary conclusions due to different system boundaries for substituted products and different weighting of environmental factors (Vieira and Matheus, 2019). For example, while most studies rated separate collection with anaerobic digestion (AD) as having the lowest impacts, in-vessel composting performed either worse (Kibler et al., 2018; Lundie and Peters, 2005; Slorach et al., 2020) or better (Edwards et al., 2018; Parry, 2016; Righi et al., 2013) than landfill or incineration of mixed waste. A potential trade-off between nutrient recovery and GHG emissions is noted in all studies and some studies point out the strong dependency of the results on transport distance (Mayer et al., 2020), bin size (Purkayastha et al., 2015), collection frequency (Jaunich et al., 2016) and efficiency (Teixeira et al., 2014) of separate biowaste collection. However, these studies do not consider in detail the local sink capacity for waste products and how the impact of inner-city logistics for collection and compost distribution changes for different urban layouts. Moreover, some of these studies omit the potentially significant emissions from land

60 application of the biowaste treatment products (Boldrin et al., 2009). Besides the relatively
61 high cost of biowaste collection and centralized treatment (Forkes, 2007), centralized
62 facilities are often located outside city boundaries, making it difficult to engage communities
63 in the circular economy and utilize resource flows locally. Decentralized or local biowaste
64 treatment with utilization in peri-urban or urban farming is an alternative that has the
65 potential to close these resource loops and deliver a host of positive social outcomes, such
66 as community cohesion and more varied and healthy diets (Aubry et al., 2017). This practice
67 can also be seen as increasing resource sovereignty, effectively empowering citizens to be
68 less dependent on global supply chains, promoting environmental stewardship and creating
69 employment opportunities (Dehaene et al., 2014).

70 Several challenges of community or decentralized composting and their potential solutions
71 have been studied. For example, paid and locally engaged technical personnel are
72 recommended to overcome issues of low participation (Comesaña et al., 2017; Pai et al.,
73 2019), odor and public acceptance (Keng et al., 2020; Parry, 2016; Purkayastha et al., 2015),
74 correct segregation and poor process performance (Comesaña et al., 2017). Furthermore,
75 implementing compost islands in the neighborhood close to residents (as opposed to e.g.
76 only in public parks) could overcome limited processing capacity (Pai et al., 2019),
77 unfavourable drop-off distances and low acceptance of decentralized solutions (Deswal and
78 Laura, 2018; Lunag et al., 2020), increase quantities of bulking material for home
79 composters (Keng et al., 2020) and ensure high quality of compost and low maintenance
80 cost (Bruni et al., 2020). The need for personnel and thus limited revenue and financial self-
81 sufficiency can be addressed through active management by local authorities (Bruni et al.,
82 2020; Comesaña et al., 2017; González-Sierra et al., 2019). Investment costs for auxiliary

equipment, such as wood-chippers and scales, can also be reduced by semi-central processing stations sharing such equipment (Keng et al., 2020). The limitations of local composting studies include missing system-level considerations, such as the potential of local compost application (Vázquez and Soto, 2017) and the difference in GHG emissions between large- and small-scale composting (Parry, 2016; Vázquez and Soto, 2017).

On local nutrient recovery, first assessments have been carried out to understand the impact of composting with urban farming, which is shown to perform better than landfill systems (Trlica, 2016). It was found that a significant share of farmers on the fringe of the city would accept compost from urban waste as soil amendments (Nigussie et al., 2015). However, a city-wide assessment has identified that local sink capacity may be limited when decentralized schemes are scaled up (Weidner and Yang, 2019), thus being a potential barrier for implementation which would not be encountered by isolated community composting projects. Excessive land application of nutrients in urban environments (beyond their assimilation capacity) may cause pollution of groundwater (Hart et al., 2004) while collecting compost locally for long-distance transport outside city boundaries could potentially incur considerable costs and GHG emissions. We posit that increasing local sink capacity through the conversion of urban land to organic community farms may mitigate these impacts while ensuring that nutrients are recovered locally.

In this work, we present the design of a realistic system for full decentralization of biowaste management, i.e. treatment at source via home and community composting with local land application of compost. This design is compared with conventional practices for centralized biowaste treatment in terms of costs and environmental implications. Addressing local biowaste utilization, the assessment has also included the effects of creating additional

urban farms on compost assimilation, cost, and emissions of the decentralized system. Furthermore, this assessment aims to offer a reliable comparison between local and centralized treatment systems for different urban typologies (represented by districts), which requires the incorporation of spatial details such as population density and distance between waste sources, treatment facilities and application areas. To the authors' knowledge, this work is the first study that compares cost and climate impact metrics of centralized and decentralized treatment strategies considering both (1) the spatially sensitive sink potential for biowaste treatment products and (2) the required logistics for a specific district type (e.g. for bulking material and surplus compost).

2. Methodology

The metropolitan region of Porto, Portugal, has been chosen as a case study. The diverse typology of the municipalities of this region provides an interesting range of settings in terms of availability of peri-urban land, population density and distance to central treatment facilities. Furthermore, the public waste management company for the region, LIPOR, operates an incineration plant for mixed waste, a tunnel composting plant for biowaste (mainly commercial food waste and green waste), and has established local composting and organic urban farming programs (LIPOR, n.d.).

This work focuses on household biowaste and excludes biowaste from commercial sources. Five different systems for biowaste management are compared, including three centralized (with household collection and remote treatment) and two local (with treatment at source and local land application) approaches (see Table 1). Additionally, an LCA was also carried out for landfilling to confirm its well-known detrimental impacts on global warming. The

area assessed in this study consists of 7 of the 8 municipalities covered by LIPOR (1 municipality was not included as no suitable geographical information data was available). These 7 municipalities comprise 76 districts. The spatially sensitive data source used, at the level of residential blocks, assumed a total population of 834,853 people. The models included in this study consider the locations of LIPOR's existing incineration and composting plants (the latter being also considered as the potential site for the AD plant).

The LCA was carried out employing both EASETECH software (v.3.17, <http://www.easetech.dk/>) and Excel using the parameters described below and in the SI (supplementary information). Biogenic CO₂ emissions were excluded. The comparison between different systems was based on the global warming impact, which is a pressing concern both globally and of the case study locale. The project duration was considered to be 25 years and the substitution method was applied where biowaste products or electricity was generated and the use of equivalent products was considered to be avoided. The system boundaries of the five systems and related assumptions are described in the SI (1); further assumptions used in this study are provided in the SI (12) and the scenarios are described in Section 2.5.

Table 1: Details of the five biowaste management systems

SYSTEM	CENTRAL INCINERATION (CENT.- INCINERATION)	CENTRAL ANAEROBIC DIGESTION (CENT. AD)	CENTRAL COMPOSTING (CENT. COMPOSTING)	LOCAL COMPOSTING (LC)	LOCAL COMPOSTING + URBAN FARMING (LC+UA)
TREATMENT	Energy recovery	Biogas production and upgrading, digestate separation	Tunnel composting	Composting islands and home composting	Same as LC
FACILITIES	1 per region	1 per region	1 per region	Multiple within residential areas and 1 semi-central per municipality	Same as LC
HOUSEHOLD COLLECTION	3 x week, mixed	3x week biowaste only, 1x week mixed waste	3x week biowaste only, 1x week mixed waste	1x week mixed waste	Same as LC

OTHER LOGISTICS				Surplus compost and bulking material	Same as LC
LOCAL LAND APPLICATION		Considered in surplus land application	Considered in surplus land application	Peri-urban farmland (except in “no peri-urban farming” scenario)	Same as LC and on urban farms
SURPLUS LAND APPLICATION	Bottom ash landfill	Composted digestate: 50% for farming outside region, 120 km average transport distance. (100% in “external land application” scenario) Liquid digestate: 100% in “external land application” scenario	50% for farming in- and outside of region, 120 km average transport distance (100% in “external land application” scenario)	Only non-farming, 120 km average distance (100% for farming in “external land application” scenario)	Same as LC
STORAGE (SEASONAL)		Liquid digestate (in “external land application” scenario)		Short-term (semi-) central	Same as LC

145

146 2.1 Waste collection

147 To ensure consistency between the scenarios, the same amount of household biowaste was
148 considered for treatment for each system, including food and garden waste (see SI). Also,
149 for each biowaste treatment system, a similar waste collection process was assumed for all
150 the municipalities. For the incineration system, mixed waste is collected three times a week
151 to prevent excessive biowaste degradation. For all the other systems the biowaste is either
152 collected separately or treated at source, thus allowing the mixed waste to be collected only
153 once a week. Since the analysis focuses on the organic part, the collection cost and
154 environmental impact attributable to the organic portion of the mixed waste in the current
155 collection scheme was quantified by the difference between (i) the actual cost and global
156 warming impacts of the current mixed waste collection and (ii) those of a mixed waste
157 collection where only non-bio waste is collected at a reduced frequency of once a week
158 (further visualization in the SI (2.1)).

For centrally collected waste, it was assumed that every municipality carries out the collection for their districts and delivers the waste (without backhauling) to the central treatment facility. The methodology used was inspired by Boskovic et al. (2016) and the calculations accounted for collection parameters (i.e. the collection frequency, pick-up rate [tonne/hr] adjusted for population density, the non-collection driving time, driving distance and fuel use, and unloading and preparation time) and cost information (i.e. working hours and shift length, required amount of trucks and personnel per municipality, kitchen and collection bins required, annualized capital and maintenance cost of trucks). The less frequent mixed waste collection benefited from an increased pick-up rate as described in the SI (2.2). Since the collection routes are intra-municipal, the total municipal cost and emissions were attributed to each district according to its required collection time (calculations and details in the SI (2.3-2.6)). The calculated average cost per collection shift was in the range of the real costs reported by LIPOR (+/-5%).

2.2 Centralized waste treatment

The district-specific amount of household biowaste was used to calculate treatment costs and emissions. Capital costs were included in the total annualized cost, together with the annual maintenance and operational costs. An LCA was conducted by modeling the systems in EASETECH by selecting appropriate modules and end-uses. The GHG emissions from capital goods were excluded from the LCA, mainly due to the lack of data for the decentralized systems and because the contribution of capital goods in waste management systems is usually negligible (Brogaard and Christensen, 2016). The contributions of electricity to GHG emissions were assessed separately and as a function of different carbon intensity scenarios of the grid. For energy recovery in the incineration system, the electricity

Figure 1: Design of local compost system and resource flows with (peri-)urban sinks

generation was adapted to the lower heating value of biowaste compared with the values from mixed waste. In the anaerobic digestion system, the digestate was assumed to be subjected to phase separation with the solid part composted and the liquid part undergoing nitrogen removal to allow sewage discharge. One scenario ('External land application') considered the liquid fraction to be stored on-site for an average of 2 months in appropriate vessels with subsequent transport and land application. Biogas was assumed to be upgraded via membrane separation and compressed for grid-injection. All relevant parameters and calculations for centralized waste treatment, information about the EASETECH model (including some changes to the composting nitrogen balance) and a mass balance for the centralized anaerobic digestion can be found in the SI (3.1-3.5, 4).

2.3 Local waste treatment

The model developed for the present study includes operational learnings and considerations from the community composting systems implemented in Pontevedra and

195 Itsasondo in Spain (González-Sierra et al., 2019). Figure 1 provides an overview of the design
196 with the following considerations:

197 *Compost islands:* Professional and active monitoring and use of sufficient bulking material
198 are crucial for providing pest- and odor-free urban operations, ensuring optimum aerobic
199 conditions, and creating public awareness. Every compost island consists of 3-12
200 composting cubes each with 1000 liter capacity. Each composting cube should cover a
201 maximum of 60 residents to ensure adequate maturation. One technician was assumed to
202 be responsible for churning and monitoring 30 cubes. The numbers of islands and cubes per
203 district were determined via a location-allocation algorithm in ArcGIS Pro, ensuring a
204 maximum walking distance of 250m (further described in the SI (5.3)).

205 *Home composting:* Home composting was considered for residential blocks classified as
206 semi-rural and semi-urban according to their built-up and population density (further
207 described in the SI (5.3)). Households involved in home composting were considered to
208 apply the compost in their garden, and were not associated with compost islands.

209 *Bulking material and compost:* The existing municipal recycling centers (*Ecocentros*) were
210 considered to be semi-central locations for intermediate storage of surplus compost and for
211 preparation (shredding) and delivery of bulking material. The transport of bulking material
212 to each composting island was carried out with small electric vehicles. A deficit in bulking
213 material was compensated for and collected from the central composting facility.

214 *Compost usage:* It was considered that the technicians would inform farmers and citizens
215 when the compost in a cube is matured and ready for collection (for free). Surplus compost
216 not utilized locally (see below for local sinks) was considered to be picked up by small

electric vehicles for monthly storage at the respective recycling center, which could send the compost either to other districts within the municipality, if there is local demand, or to the central treatment facility.

The assessment for bulking material and surplus compost was carried out for each season, as the volume of green waste and the potential for land application differs throughout the year. Similar to the waste collection, the capital investment (cubes, shredder, bins, trucks), labor, fuel costs, distances and driving times were considered in the total annualized cost. Emissions were modeled in EASETECH, using the methodology and adjustments to account for the different composting processes described in the SI (4.4). Further information related to the local waste treatment can be found in the SI: relevant parameters (SI 6), more information on emissions for compost and digestate (SI 7), and calculations (SI 8.1-8.6).

2.4 Local sinks and land application

The local application of compost from compost islands on peri-urban fields and organic urban farms (i.e. local sinks) was assessed via spatial analysis in ArcGIS Pro, the impacts were assessed in EASETECH. To evaluate the effect on cost and GHG emissions of increased local sink area, one of the local systems considered assumed that vacant land and greenspaces would have been partially converted to urban organic farms. The term “productive” application in this work means compost is used where it substitutes synthetic fertilizer, e.g. for growing food or public gardens.

The following assessments were carried out for the two systems with local waste treatment for each district: (1) area of peri-urban farmland, employing different data sources (see SI, 5.1-5.2); (2) existing urban farms and their size; (3) area convertible to urban farms (green

spaces and vacant land); (4) seasonal productive compost application on peri-urban fields and urban farms, depending on the seasonal share of the annual application rate; (5) seasonal productive compost application in household gardens, depending on garden size (determined via linear interpolation as a function of population density); (6) productive compost uses indoor, e.g. for potting (with replacement of peat); (7) surplus compost from districts was considered to be distributed via recycling centers if productive land was still available in other districts from the same municipality; (8) surplus compost not used up within a municipality would be delivered to the central treatment facility once a month and applied to land without productive use (e.g. not replacing fertilizer); (9) the economic potential of the applied compost product (the compost generates no direct revenue as it is provided for free to the citizens); (10) emissions related to productive and non-productive land application. Transport emissions were neglected for the local sinks because: a) collection by citizens would be non-motorized, b) farmers would normally drive to collect their synthetic fertilizer and soil conditioner anyway and c) a rough assessment resulted in negligible GHG emissions.

GHG emissions of productive land application were assessed according to EASETECH, which included plant nutrient uptake and run-off, fertilizer substitution rates, tractor fuel (fields only), gaseous emissions, soil carbon storage (100-year horizon) and other soil benefits (i.e. effects of increased water retention and reduced soil erosion (details in SI (6., 7.)). The impacts of land application (e.g. fertilizer substitution) of compost generated in a different district in the same municipality were accounted for in the district where the compost was applied. Although this work focuses on compost application for food production, any public use could also be represented in the greenspace conversion in the LC+UA system.

For the centralized treatment system (tunnel composting and anaerobic digestion with composting of the solid fraction), it was assumed that a share of compost product is distributed in the wider region (120 km return) and sold as a soil amendment for crop production. For the municipal surplus compost in the local system, non-productive land application was considered (accounting only for soil carbon storage, with no other positive effects of compost application). This reveals any differences in cost and GHG emissions (i) between the districts (in LC and LC+UA) and (ii) incurred by increased urban farming (by comparing LC and LC+UA). To allow a fair comparison with the centralized systems, one scenario (for sensitivity analysis, described below) considers 100% productive use of the surplus compost produced in the local system, equal to the centralized systems in that scenario. Details of all related calculations can be found in the SI (8.4-8.5).

2.5 Base scenario and parametric sensitivity

Parametric sensitivity was evaluated for several key parameters that can have a strong impact on the results of the assessment, especially concerning GHG emissions.

The parameters for the base scenario were selected to represent a plausible implementation towards the middle of the project duration: (1) the electricity grid features 80% of total power consumption from low-carbon sources such as solar, as pledged by the Portuguese government in their Carbon Neutrality Roadmap (<https://descarbonizar2050.pt>) for 2030 (roughly the middle of the project duration); (2) 0%/50%/50% productive application of compost outside the region for the local composting systems, centralized composting and composted digestate solids, respectively; liquid digestate is treated for sewage disposal; (3) peri-urban farmers with 75% compost adoption rate for commercial

food growing; (4) 50% of vacant land and 25% of urban green spaces converted to urban farms; (5) 25% of the population was assumed to maintain their compost well, modeled as compost islands in EASETECH, the rest was modeled as non-turned tumble composters.

Further scenarios deviating from the base scenario were evaluated to assess the sensitivities: (1) no changes to the grid: the carbon intensity of electricity reflects the power consumption pattern in 2018; (2) external land application: 100% productive application of all biowaste products (surplus outside of region, 120 km), including liquid digestate; (3) no peri-urban farming: commercial peri-urban farmers would not adopt compost application (adoption rate 0%) and compost would be applied non-productively; (4) maximum urban farming: 75% of vacant land and 50% of urban green spaces converted to urban farms; (5) optimized home composting: 100% of the population was assumed to maintain their compost well, leading to reduced CH₄ and N₂O emissions (emissions, mass balance and application impacts chosen from compost island process).

The sensitivity analysis was carried out by changing the relevant parameter (see Tables S1, S3, S5, S6) in the calculations (see SI 3.2 to 3.5 and 8.2 to 8.6).

3. Results and discussion

3.1 Regional economic assessment for the base scenario

The result of the economic assessment of the five waste treatment systems (base scenario) for the Porto metropolitan area are shown in Figure 2. This assessment considers the annualized cost per tonne of waste treated (69,241 tonnes in total), including capital and operational cost, and the revenues from the sale of electricity, biomethane, and compost. The cost of waste treatment was significantly different between the five systems assessed.

Local composting systems encompass the lowest total cost of all systems. The surplus compost logistics cost is significantly lower than the labor costs for the technicians looking after the compost islands. They therefore constitute only a small portion of the total costs and increasing the local sink capacity through urban farming only reduces these costs marginally.

Figure 2: The economic balance (in EUR per tonne of treated waste) and share of labour cost for the five systems. Biowaste collection logistics, surplus compost logistics and biowaste treatment costs include labor and non-labor (infrastructure, material and fuel) components, all other costs compromise only non-labor components. The farm input value from fertilizer in the local composting systems is not included in the net total cost.

For centralized biowaste treatment, collection logistics represent the fraction with the highest share of costs; from 64% to 86% of the total costs for the municipalities, depending on the system and urban setting. Waste collection costs were more affected by the population density (which impacts on the pick-up rates) than by the distance to treatment facilities. Centralized composting and AD have the highest logistics cost because these systems require separate collection of biowaste. Nevertheless, collection costs are also

significant for the incineration system as the collection frequency of mixed waste is higher and the pick-up rate lower when no separate collection or local treatment option is implemented. It must be noted that the waste collection frequency in Porto is quite high compared with other municipalities in Europe, partly due to safety and odor concerns in warmer environments; collection costs might thus be substantially lower in regions with less frequent collection (Bianchi-Aguiar et al., 2011).

The share of labor in total costs varies significantly in the different systems. For local composting, labor represents most of the annualized costs (98%, equivalent to 433 full-time equivalent jobs or FTE). For centralized composting and AD, labor also represents the largest share of the total costs (61-62%, equivalent to 758 and 760 FTE), since the separate collection scheme involves high labor costs. Incineration involves a significantly lower share of labor in total costs (31% or 387 FTE).

a. Regional emissions comparison for the base scenario

The contribution to global warming of the different waste treatment systems, estimated by LCA on the base scenario, is displayed in Figure 3. The emissions estimated for all the assessed systems were considerably lower than the emissions estimated for landfilling in a similar scenario (374.2 kg CO₂e/tonne, see SI (10.6)).

AD showed the best performance regarding GHG emissions (-21.9 kg CO₂e/tonne) with biomethane, the product of AD, replacing natural gas from fossil sources. The high share of low-carbon electricity assumed in the base scenario results in modest credits for avoided electricity production from energy recovery in incineration. Despite this, incineration

exhibits lower emissions (27.4 kg CO₂e/tonne) than centralized composting (89.3 kg CO₂e/tonne) and the local composting systems with and without urban farms (53.0 and 63.9 kg CO₂e/tonne, respectively).

Figure 3: Annual GHG emissions for the base case per tonne of household biowaste processed for the five systems, excluding the impact of capital goods. Biowaste treatment includes inputs (e.g. electricity) and gaseous emissions. Land application, use and logistics includes gaseous emissions after application, carbon storage, mechanized compost application and 120 km transport. Avoided emissions include fertilizer replacement, soil erosion, and water retention benefits.

Collection logistics is the main source of GHG emissions in centralized systems, especially for separate biowaste collection in the centralized AD and composting systems. Population density and distance to central treatment facilities were found to influence the environmental impact of collection, with closer and denser districts performing better. This reflects the importance of efficient route planning and multi-household collection strategies with their respective trade-offs (Gallardo et al., 2010). The outcome, however, could be

altered if future waste collection trucks are powered by renewable electricity, which has the potential to reduce transport-related emissions by up to 93% (see SI 10.7).

Despite having no collection associated emissions, local composting systems entailed high GHG emissions from treatment and use of compost, which could not be compensated for by the avoided emissions through productive land application of compost. The reason for this is that CH₄ and N₂O are emitted in the composting process and after land application, especially when it is not well managed, as it is frequently the case in home composting (further discussed in the SI (4.4)). The environmental performance of home composting schemes could be improved if composting technicians are actively involved in educating, monitoring and providing feedback and if suitable bulking material can be sourced, particularly in winter (González-Sierra et al., 2019). Moreover, the benefits of compost on GHG emissions considered in this study may be underestimated as some of its long-term effects are less well studied (discussed in the SI (7)). Further limitations of the study are described in section 13 in the SI.

Regarding the potential of UA, creating additional urban farms provided a moderate reduction in emissions, mainly due to reduced surplus compost logistics and increased avoided emissions from land application. The transferability of the insights by district typology to other cases is described in section 12 in the SI. The nutrient recovery potential for the region is discussed in SI 14.

3.3 District level differences for the base scenario

The regional results shown above were obtained by aggregating the economic and environmental impacts of individual districts. The results at the district level (base scenario)

are shown in Figure 4. The districts of the Porto metropolitan area exhibit considerable differences in population density (Figure 4-A), distance to the central treatment facilities (indicated in Figure 4-A, listed in section 9.2 in the SI), and amount of peri-urban farmland (Figure 4-C, SI 9.1), all with a strong influence on the outcomes. Population density directly affects the potential for home composting implementation (Figure 4-B and SI 10.1).

The main factor influencing the cost of waste management in the different districts for the local composting system (Figure 4-D) was the potential for home composting (29.4% overall, details in SI 10.2). Home composters require less infrastructure, maintenance, and monitoring than composting islands, and therefore encompass lower costs to operate (see SI (6.)). A study of different biowaste management options in Canada reported similar cost differences between home composting (\$42/tonne) and community composting (\$118/tonne)(Adhikari et al., 2010). The highest cost of treatment per capita was observed in districts with a low population density and low potential for home composting. These areas are mostly constituted by distant semi-urban houses without gardens and therefore its composting islands are used by a lower number of citizens than the islands in urban areas (SI 10.3). These results suggest that the design of a new biowaste management system should consider such local peculiarities. The cost per capita in this system in general was not significantly influenced by the amount of surplus compost (SI 10.4). The main factor influencing the cost of waste management in the different districts for the Cent. AD system (Figure 4-E) was population density. Remote districts with lower population densities had the highest costs essentially due to the lower waste pick-up rates and larger transport distances to the central waste treatment facility (SI 10.5). For comparison, the annual cost

per person for centralized incineration and composting ranged from 24.53 to 61.85 €/tonne
and from 201.77 to 652.75 €/tonne, respectively (not shown in the figure).

Figure 4: Particularities of the districts (4-A and 4-B), potential for home composting implementation (4-C) and district-level outcomes for annualized cost (4-D to 4-F) and GHG emissions per tonne (4-G to 4-I) for the local composting + urban agriculture, the centralized

AD system and comparisons between the two systems. The indicator for the biowaste plants (4-A) describes the location for the industrial composting and the anaerobic digestion plant.

A district comparison of the waste management cost of local composting and Cent. AD is shown in Figure 4-F. Local composting allows savings between 17% in urban areas closer to the central treatment plants to 97% in more rural areas further from the central treatment plants.

District comparisons of the annual GHG emissions per capita are displayed for the LC+UA system (Figure 4-G) and the Cent. AD system (Figure 4-H). The main factor influencing GHG emissions in the local composting system was the home composting potential. Home composting would produce more emissions than composting islands since it would not be continuously monitored by a technician. Another key factor influencing GHG emissions in this system per capita was the sink area available to mitigate the negative emissions through productive land application.

The main factors influencing GHG emissions in the different districts for the Cent. AD system were population density and distance to the treatment facilities. The GHG emissions were highest (195.52 kg CO₂e/tonne) in the more remote districts with a low population density. The main reason for this is the increased emissions from collection and transport.

A district comparison of GHG emissions between the local composting system and the centralized AD system is shown in Figure 4-I. AD has a better environmental performance than local composting in districts with a higher population density and closer to the treatment units (shown in purple). Conversely, local composting has a better environmental performance than AD in districts with lower population densities and more distant to treatment facilities (shown in cyan). Similar findings were observed for the district

comparison of local composting with centralized composting and incineration (data not shown).

A district-level comparison was also carried out to estimate the effect of increasing the sink potential in waste treatment costs and GHG emissions of the local composting systems (LC vs LC+UA, SI 9.3 and 9.4). The effect of increasing the sink potential on cost savings was small, only up to 6.3% in denser urban areas with a high potential for urban land conversion. Conversely, the effect of increasing the sink potential on GHG emissions was more pronounced, with emissions savings of up to 60% in dense urban areas with a high potential for urban farms.

3.4 Implications of urban farming and surplus compost

Although the compost produced in the local composting systems is primarily destined for the citizens using the composting islands and for the local farmers, surplus compost, which has to be transported out of the region, might be generated. The concept of increased urban sink area with productive use (e.g. through increased urban agriculture) allows more compost to be used locally, especially when it can easily be shared between districts through short-term storage at recycling centers.

The implications of the available local sink area on annualized cost and GHG emissions for the different municipalities were assessed for two different scenarios (Figure 5).

Municipalities differed in the amount of existing peri-urban farmland (excluding any private garden land), land potentially convertible to urban agriculture and the potential for home composting implementation (reducing the amount of compost generated in compost islands).

In the base scenario, the main sink for compost was the peri-urban farmland and sufficient productive sink area is available in most municipalities to assimilate the compost produced by the local composting systems. In both scenarios, creating additional urban farms would only marginally reduce costs since surplus compost logistics (transporting compost from islands to semi-central short-term storage and central long-term storage) have little weight on the annualized cost.

Aspect	Farmland per person (excl. HC)	Land to UA conversion possible	Potential for home composting	Compost surplus (LC)	Compost surplus (LC+UA)	Difference LC+UA vs LC	Difference LC+UA vs LC	
Municipalities	m2/cap	%	%	%	%	Cost	Emissions	
Base scenario	Espinho	<div><div></div></div> 32.0	<div><div></div></div> 2.7%	<div><div></div></div> 48.2%	<div><div></div></div> 29.4%	<div><div></div></div> 0.0%	<div><div></div></div> -2.4%	<div><div></div></div> -19.0%
	Gondomar	<div><div></div></div> 47.5	<div><div></div></div> 0.4%	<div><div></div></div> 41.4%	<div><div></div></div> 18.7%	<div><div></div></div> 3.6%	<div><div></div></div> -0.9%	<div><div></div></div> -12.7%
	Maia	<div><div></div></div> 78.8	<div><div></div></div> 0.5%	<div><div></div></div> 38.3%	<div><div></div></div> 0.0%	<div><div></div></div> 0.0%	<div><div></div></div> -0.5%	<div><div></div></div> 0.1%
	Matosinhos	<div><div></div></div> 26.7	<div><div></div></div> 0.6%	<div><div></div></div> 19.0%	<div><div></div></div> 34.9%	<div><div></div></div> 26.3%	<div><div></div></div> -1.1%	<div><div></div></div> -21.8%
	Porto	<div><div></div></div> 0.1	<div><div></div></div> 1.5%	<div><div></div></div> 13.9%	<div><div></div></div> 93.1%	<div><div></div></div> 64.2%	<div><div></div></div> -2.5%	<div><div></div></div> -39.9%
	Povoa de Varzim	<div><div></div></div> 267.2	<div><div></div></div> 0.4%	<div><div></div></div> 48.9%	<div><div></div></div> 0.0%	<div><div></div></div> 0.0%	<div><div></div></div> -1.1%	<div><div></div></div> -0.1%
	Valongo	<div><div></div></div> 33.1	<div><div></div></div> 0.4%	<div><div></div></div> 36.6%	<div><div></div></div> 28.0%	<div><div></div></div> 12.9%	<div><div></div></div> -1.1%	<div><div></div></div> -17.5%
Scenario 'no peri-urban farming'	Espinho	Same as above			<div><div></div></div> 91.3%	<div><div></div></div> 0.0%	<div><div></div></div> -5.5%	<div><div></div></div> -42.1%
	Gondomar	Same as above			<div><div></div></div> 92.4%	<div><div></div></div> 39.2%	<div><div></div></div> -3.0%	<div><div></div></div> -34.8%
	Maia	Same as above			<div><div></div></div> 91.2%	<div><div></div></div> 37.1%	<div><div></div></div> -3.2%	<div><div></div></div> -37.5%
	Matosinhos	Same as above			<div><div></div></div> 94.2%	<div><div></div></div> 65.6%	<div><div></div></div> -2.3%	<div><div></div></div> -38.1%
	Porto	Same as above			<div><div></div></div> 93.9%	<div><div></div></div> 65.0%	<div><div></div></div> -2.5%	<div><div></div></div> -40.0%
	Povoa de Varzim	Same as above			<div><div></div></div> 90.7%	<div><div></div></div> 20.1%	<div><div></div></div> -5.4%	<div><div></div></div> -37.8%
	Valongo	Same as above			<div><div></div></div> 93.5%	<div><div></div></div> 43.2%	<div><div></div></div> -2.9%	<div><div></div></div> -38.1%

Figure 5: The influence of increased urban agriculture in the local composting systems on surplus compost, annualized cost, and GHG emissions. The alternative scenario considers that compost from compost islands is not used for food production on existing peri-urban fields. Any surplus compost is considered to be applied to land non-productively

For GHG emissions, converting land for urban agriculture would be more beneficial, especially in the denser municipalities of Matosinhos and Porto. Nevertheless, more urban farms would not be able to assimilate all compost generated in such areas. In the scenario where none of the compost is applied on peri-urban farms, there is a higher impact of creating additional urban farms in the reduction of emissions (37.5-42.1%). The full results from the spatially sensitive regional overview can be found in the SI (9.1-9.4). The outcome of this analysis suggests that city planners would need to consider whether the benefits of

local composting and urban farms justify the land footprint they require, particularly in denser neighborhoods. Nevertheless, the positive experiences from urban farming and community composting trials with face-to-face interactions across Spain (Comesaña et al., 2017) and the Horta à Porta urban farm program in Porto have shown that the engagement of citizens in waste and farming practices could bring a range of other benefits, including facilitated education and awareness about food waste reduction, resource circularity, and changes in diet (Benis and Ferrão, 2017; Slater and Aiken, 2015).

3.5 Sensitivity analysis on the regional level for alternative scenarios

The base scenario, described in the methods section, is based on the most likely development for key parameters such as renewable content of the electric grid, productive application of compost, adoption of compost in peri-urban farms, amount of land convertible to farms, and performance of the composting process. A sensitivity analysis was conducted to assess scenarios reflecting variations of these parameters.

The outcome of the sensitivity analysis had a generally low impact on waste management costs. The biggest impact on costs is the scenario “external land application”, in which the possibility of spreading liquid digestate on land would decrease the cost of the Cent. AD system by 4.3%. Conversely, in the scenario ‘no peri-urban farming’, the cost of local composting would increase by 2.6% and 1.1% in the systems without and with urban farming, respectively.

The outcome of the sensitivity analysis was more significant for GHG emissions (Figure 6). The scenario 'no changes to the grid', which considers the carbon intensity of the electricity grid existing in 2018, results in higher carbon benefits for the electricity generated by the incineration plant and more process emissions for centralized AD and composting. According to this scenario incineration would have a better impact than AD on GHG emissions; similar results have been reported by previous studies (Chiew et al., 2015; Salemdeeb et al., 2018). Further comparison with literature can be found in section 11 in the SI.

Figure 6: The influence of the different scenarios and their parameters on annual GHG emissions for the five biowaste management systems.

If regulations for liquid digestate application favor land use (see scenario 'external land application'), the AD system would become even more attractive in this study while the three composting systems were also shown to reduce slightly their GHG emissions. To realize the benefits, farmers would have to reduce their synthetic fertilizer application to prevent overfertilization. A mixed solution, featuring local composting and a more central

487 AD plant, would provide farmers with a variable choice of organic fertilizer and soil
488 amendments.

489 In the scenario 'no peri-urban farming', where farmers do not use the locally produced
490 compost, emissions would increase for the local composting systems, in particular without
491 additional urban agriculture.

492 In the scenario 'maximum urban farming', by increasing green and vacant land conversion to
493 urban farms, emissions could be reduced slightly for the LC+UA system. This was mainly due
494 to the reduction in emissions attributed to productive land application. The results indicate
495 that the GHG emission benefits of productive land application of compost (e.g. including
496 fertilizer replacement and reduced top-soil run-off) are significantly higher than the
497 emissions related to transport of compost outside of the municipality. This means that
498 prioritising productive over non-productive applications of compost is more critical than
499 choosing the location of compost application; a strong argument for the creation of
500 additional urban farms is their role in ensuring a (local) productive application of compost.

501 Lastly, in the scenario 'optimized home composting', better performance of the home
502 composting would lead to a decrease in process emissions. This could be achieved by
503 educating and enabling households to monitor and churn their compost to prevent
504 anaerobic decomposition.

505 4. Key messages

506 This study investigated the waste management costs and environmental impacts of three
507 centralized and two local biowaste management systems, taking into account different
508 scenarios. The novelty of the study lies in the application of spatially sensitive modeling to

(1) evaluate the influences of local details such as population density and productive sink area available, and (2) design and assess a scaled-up local composting system with urban farms. An overview of benefits is given in table 2. The main learnings derived were:

1. Local composting has lower costs than centralized models.

Considering the region-wide outcome, local systems had significantly lower costs than centralized models, with labor representing 97-98% of the operational costs. This makes biowaste management through local composting an attractive choice for municipalities.

2. The creation of urban farms has a small impact on the reduction of treatment costs and emissions associated with local composting.

The conversion of urban areas to farms can provide a local destination for the surplus compost produced in local composting systems but the cost reduction associated with the creation of urban farms is not significant. A small positive impact on global warming can be achieved when additional urban farms ensure that compost is applied productively (i.e. cycling nutrients by replacing synthetic fertilizer) or in urban municipalities with no or little peri-urban farming.

3. The generation of GHG emissions associated with the different biowaste treatment methods is dependent on the local context. Expected changes to electricity grids and trends in compost and digestate application favor anaerobic digestion.

The renewable content of the electricity grid and the possibilities for the productive utilization of compost and digestate are key factors for influencing the GHG emissions associated with the different treatment methods; increasing the share of low-carbon

sources in electricity generation reduces the benefits of producing electricity from the incineration waste.

4. Local composting can benefit from improved home composting practices.

Home composting with poor monitoring and non-productive land application makes composting less favorable. Better education and capacity building could improve this.

5. Regionally integrated biowaste management plans combining different systems are the best option to achieve cost-effectiveness and emissions reduction.

Municipalities should adopt waste management solutions tailored to their different needs. For instance, separate collection of biowaste and treatment in a centralized AD plant can be implemented in denser and central neighborhoods, and local composting can be implemented in more remote and less dense neighborhoods of the same municipality.

Table 2: Summary of expected economic and environmental impacts of the biowaste management systems. Benefits are displayed as + and ++ according to the relative performance compared with the other systems.

Aspect	Cent. Incineration	Cent. AD	Cent. composting	Local composting	Local composting + urban agriculture
Cost	+			++	++
GHG emissions	+	++		+	+
Nutrient circularity		+	++	+	+
Soil benefits		+	++	++	++
Job creation		++	++	+	+

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