Cleaner Waste Systems 6 (2023) 100111

Contents lists available at ScienceDirect

Cleaner Waste Systems

journal homepage: www.journals.elsevier.com/cleaner-waste-systems

Emissions associated with the management of household organic waste, from collection to recovery and disposal: A bottom-up approach for Sydney and surrounding areas, Australia

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ARTICLE INFO

Keywords:
Municipal solid waste
Organic waste
Carbon emissions
Carbon footprint
Emissions modelling
Low carbon waste management

ABSTRACT

Recent advances in waste management policies and initiatives world-wide have placed greater focus on the potential greenhouse gas emissions-avoidance that can be achieved via sustainable waste management practices. In New South Wales, Australia, household organic waste has been identified as a problematic stream that through better management, could lead to better environmental outcomes and reduced emissions. However, emissions associated with waste management are poorly characterised in Australia, obscuring decision making around optimal pathways that can maximise landfill diversion and minimise emissions. This study addresses this data limitation by estimating and analysing the emissions associated with household organic waste management. The approach applied route optimisation to estimate emissions from points of collection (weekly and fortnightly) to recovery at composting facilities and disposal at landfills, as well as mass balance modelling to estimate direct and indirect emissions associated with windrow composting and mechanical biological treatment. Landfill gas modelling was also used to estimate lifetime emissions from disposal, as well as potential avoided emissions through recovery. Results for the Greater Sydney and surrounding area show total gross greenhouse gas emissions of approximately 390,100 tCO_2-e, and balanced by approximately 145,600 tCO_2-e of emissions avoidance through landfill diversion. The average net emissions intensity of jurisdictions in the study area was approximately 133 $kgCO_2$-e/t of waste diverted; or 423 $kgCO_2$-e/t of waste managed. Emissions intensity was highest for the mixed waste collection stream, where diversion pathways are limited; and lowest where separate food collection and mechanical biological treatment was employed. Findings indicate that greater separation of food waste from the mixed stream to dedicated food waste collection will result in the greatest improvements in both emissions intensity and landfill diversion.

1. Introduction

The impacts of anthropogenic greenhouse gas (GHG) emissions must be curtailed across all sectors of the economy to limit the impacts of climate change. Although small compared to the electricity sector, waste management is an important contributor to overall GHG emissions, with landfilling alone contributing approximately 3 % to global emissions annually (IPCC, 2021). Due to the continuing use of fossil fuels, significant emissions also occur from the consumption of fuel in machinery and for transportation, plus electricity over the entire waste management chain. While being a source of emissions, waste management systems can also deliver emission reductions, including through offsetting emissions intensive primary material consumption via recycled material utilisation; generating energy from waste materials to replace fossil-fuel derived energy sources; and diverting organic waste from landfill thus avoiding future landfill emissions. Addressing emissions from the waste sector is therefore important, and many recent waste management policies and initiatives, especially in Europe, have been connected with strategies addressing the threats of climate change (Gavrilescu, 2022).

In Australia, the need for sustainable waste management aligned with addressing GHG emissions has been reinforced by recent government action. The *NSW Waste and Sustainable Materials Strategy 2041* (DPIE, 2021) endorses emissions reduction through improved waste management and recovery in the state of New South Wales (NSW). The transition to more sustainable and circular waste management

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https://doi.org/10.1016/j.clwas.2023.100111
Received 23 January 2023; Received in revised form 28 June 2023; Accepted 13 July 2023
Available online 16 July 2023

encourages greater diversion from landfill, and prioritises the recovery of resources including energy and materials from waste streams.

In the case of household organic waste, the need for significant new infrastructure investment has been identified (DPIE, 2021). Currently, the majority of household organic waste is collected via the mixed waste stream where recovery options are limited, resulting in more than half of all organic waste generated by households being disposed to landfill each year. Planned expansions in organic collection and recovery infrastructure are aimed at addressing landfill diversion for organics, through for example mandatory collection of household food waste via comingled food and garden waste collections, and anaerobic digestion as a recovery pathway. Presently, baseline levels of emissions from waste management in NSW are unknown and data is limited, for example only aggregated landfill emissions are reported in national greenhouse accounts (DISER, 2022). Thus, the impact of emissions associated with expanded kerbside collection and management systems is uncertain. This limitation makes prioritising management pathways, and evaluating the impact of system changes aligned with GHG reduction strategies, difficult.

The aim of this study is to examine the waste recovery and GHG emissions potential of the household organic waste stream in the Greater Sydney and surrounding areas in NSW, Australia. The study will inform future organic management pathways aligned with GHG reduction and landfill diversion objectives. The examination of emissions associated with the management of the organic fraction of municipal solid waste (OFMSW) is widespread in the literature, for example in Babu et al. (2021), where several technologies and pathways for resource recovery from the OFMSW stream are comprehensively reviewed. System wide examinations of OFMSW are also common. For example, Paes et al. (2020) examined the transition towards eco-efficient management of municipal waste across regions in Brazil, by estimating emissions generation and mitigation for several organic waste pathways, including composting and energy recovery via landfill gas capture and conversion. Stunzenas and Kliopova (2018) assessed a number of household organic waste management options for regions in Lithuania in terms of organics (nutrient) recovery and biogas output. The authors found that improved source separation of organics at the household, coupled with treatment via anaerobic digestion (AD) at mechanical biological treatment (MBT) facilities, could result in improved nutrient recovery yields and quality, compared to composting. Thanh et al. (2015) evaluated the potential environmental benefits from the introduction of composting of OFMSW on indicators including organic fertiliser production, landfill life extension, and GHG emission reduction, finding that composting of OFMSW in Hanoi can lead to landfill life extension from 0.5 to 8.7 years; and estimated GHG emission reduction between 15% and 98%.

Studies analysing OFMSW management pathways in detail for Australia and NSW are however limited and energy recovery and advanced OFMSW recovery, beyond composting, remains underdeveloped. Lou et al. (2013) for example examined the theoretical maximum benefit of the digestion of food waste in Australia in terms of potential energy recovery. Their study found that multiple decentralised AD facilities across Australia could generate approximately 20.3 PJ of heating potential, or 1915 GWe in electricity generation annually from OFMSW—equivalent to ~3.5 % of Australian energy supply in 2013. Considering Australia's current reliance on fossil fuel for electricity as well as prevalence of landfilling of organic wastes, OFMSW could contribute to important GHG emissions reductions in Australia as a source of renewable energy. The study in Lou et al. (2013) however is limited for evaluating AD and other OFMSW management pathways aligned with recent NSW circular economy strategy, as that study was Australian-wide, focusing on theoretical potential of AD of food waste from all sectors, including household and commercial sources. Dastjerdi et al. (2019) in their study of municipal residual waste energy recovery potential, found that AD of municipal food waste in the mixed waste stream could have an emissions reduction potential of up to 634,000 tonnes [t] of CO_2-e in NSW, from landfill diversion and mitigation of fossil fuels. The study however was focused only on the mixed waste (or residual) collection fraction, and did not consider separately collected organic waste, or the emissions associated with waste collection and transportation.

For this study, we estimate the emissions associated with household organic waste management over the entire waste management chain—from kerbside collection, to recovery and disposal. A route optimisation model developed in Madden et al. (2022) was used to estimate the emissions associated with kerbside collection and transportation of collected organic waste to recovery and disposal facilities. A mass balance model was also utilised to estimate recovery facility throughput and emissions from the recovery processes themselves (e.g., from the consumption of electricity and fuel during recovery). Finally, a landfill emissions model based on the IPCC landfill gas model (IPCC, 2007) was utilised to estimate emissions from the disposal of organic waste, and the emissions avoidance potential from landfill diversion.

Findings from this study can make a number of contributions for informing decision making towards sustainable and low-carbon waste management for household organics in NSW, which could also be broadly applied to other jurisdictions and waste streams. For example, data generated from our study can help inform optimal waste collection and recovery pathways for achieving emissions reduction and landfill diversion objectives, aligned with state waste policies. Moreover, emissions associated with waste management in the study area are poorly characterised in state and national greenhouse gas accounts. Data generated in this study, can help fill this knowledge gap, and enable further evaluation of local waste systems from a low carbon resource recovery perspective.

2. Background – Household organic waste management in NSW

Household organic waste (food waste and garden organic waste) is typically managed via kerbside waste collection services in NSW, with some organics managed through household 'drop-offs' at specified organic collection points, including transfer stations, and landfills. Note that while paper, wood and textiles are also organic in nature, they are not considered in the organic fraction of household waste (DPIE, 2021). Separately collected organic waste is collected at the kerbside via garden organics (GO) fortnightly bin collection, or for some council areas, food organics and garden organics (FOGO) weekly bin collection (mutually exclusive with GO), where food and garden waste are comingled. The number of council areas employing FOGO collection has increased in recent years, however this expansion in services has mostly been in regional areas of NSW, with a slow uptake in Sydney and other metropolitan areas (Surdo and Gupta, 2021). Despite this, expanded FOGO collection to cover all households in NSW has been identified as a key part of future organic waste management in the *NSW Waste and Sustainable Materials Strategy* (DPIE, 2021). Table 1 gives a summary of the number of households with each kerbside collection service, and overall volumes collected across all of NSW for 2019–20.

Generally for FOGO bins in NSW, food makes up approximately 12 % of what is collected (Rawtec, 2020a). Each council area across NSW also has a mixed waste weekly bin collection service which is typically disposed to landfill, or for a few councils in NSW (23 out of 129 councils in 2019–20), is sent to alternate waste treatment (AWT) facilities for

Table 1
Summary of number of households and quantities of waste collected for waste streams containing organic wastes across all of NSW, from NSW EPA (2021).

Waste collection service	Households serviced in NSW, 2019–20	Quantities of waste collected at kerbside in 2019–20 [t]
Garden organics (GO)	1,514,948	405,717
Food and garden organics (FOGO)	550,435	215,899
Mixed waste	2,952,576	1,718,474

recovery (NSW EPA, 2021). Note that councils with FOGO services typically collect mixed waste bins at fortnightly instead of weekly intervals. Fig. 1 shows the composition of the mixed waste, GO and FOGO collection streams for all of NSW. The proportion of organic waste in the mixed waste bin is high, and typically consists of food waste (e.g., kitchen scraps), and is thus the main source of household organic waste that is disposed to landfill. The proportion of food waste in the mixed waste stream is on average between 23 % and 38 % (Rawtec, 2020b); and councils with FOGO services typically seeing smaller proportions of food waste in the mixed waste bin. As such, council areas with FOGO services have average food waste diversion rates of up to 44 % Rawtec (2020a).

Separately collected household organic waste (i.e., GO and FOGO wastes) is typically managed via composting. Windrow composting is utilised for large scale compost processing for the majority of collected household organics, with in-vessel composting and aerated static pile composting also employed at smaller scales (DEC, 2007). AD is currently not utilised at large scale for household organics in NSW, however is identified as an important future recovery pathway in the *NSW Waste and Sustainable Materials Strategy* (DPIE, 2021). Table 2 gives a summary of recovered quantities of organic waste and recovery rates by waste stream for all of NSW in 2019–20. Recovery rates for the GO and FOGO collection streams are high, at approximately 99 % and 96 % respectively. Differences in recovery rates for these streams can mostly be attributed to higher levels of non-organic or non-compliant organic material (e.g., meat) in the FOGO stream compared to the GO stream (Rawtec, 2020a). Organic waste recovered from the mixed waste stream is done so via AWT, however recovery rates are low. Approximately 123, 000 t of mixed waste (organic and non-organic waste) was recovered at AWT facilities in 2019–20, with an average AWT recovery rate of approximately 27 % of incoming waste (NSW EPA, 2021). An important consideration with AWT is the quality of the recovered material stream. The NSW Environment Protection Authority recently restricted the application of AWT derived secondary organics to land, due to problems with contamination in the recovered stream (NSW EPA, 2019; Wilkinson et al., 2021). Despite this, AWT is still seen to be an important part of the municipal waste management system moving towards 2030 and beyond, at least for contributing towards landfill diversion and mitigating the need for future landfill expansions, and subsequent emissions reductions (DPIE, 2021). As a pathway for organics waste recovery however, system intervention is needed beyond AWT recovery for the mixed waste stream, where the majority of household organics waste is found.

3. Methodology

The aim of this research was to examine the emissions associated with household organic waste management in the Greater Sydney and surrounding areas in NSW, Australia. GHG emissions as CO_2-equivalent associated with the management of household organic waste were estimated, along with the emissions reduction potential in terms of avoided landfill gas emissions.

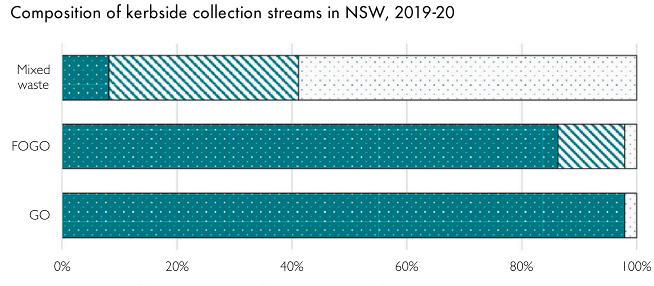

Fig. 1. Composition of the mixed waste, GO and FOGO collection streams for all of NSW, derived from Rawtec (2020b) and Rawtec (2020a).

Table 2
Summary of number of households and quantities of waste collected for waste streams containing organic wastes across all of NSW in 2019–20, from NSW EPA (2021).

Waste collection service	Total waste recovered in 2019/20 [t]	Recovery rate [%]
Garden organics (GO)	400,334	98.67 %
Food and garden organics (FOGO)	208,101	96.39 %
Mixed waste (organics and non-organics)	122,855	7.15 %

Fig. 2 shows the modelling framework developed for this study. The *waste collection and transport model* is based on the modelling described in Madden et al. (2022), which estimated transport-related emissions from the kerbside collection of household organic waste in the study area. The model developed in Madden et al. (2022) was updated with waste generation data at the municipality, or local government area (LGA) level, for the 2019–20 financial year (NSW EPA, 2021).

Data on organic waste throughputs at recovery facilities and landfills were integrated with energy requirements and emissions factors from the literature in an *organic waste recovery model*, to estimate net emissions associated with recovery of household organic waste at dedicated recovery facilities. For this component, a mass-balance model was developed based on Ng et al. (2021) and Pressley et al. (2015), whose work involved material flow analysis of various organic and non-organic waste sorting and recovery processes. The mass balance model was used to estimate the energy requirements of mixed waste sorting at AWT facilities, and associated emissions (scope 2 and 3). Literature data was utilised to estimate direct and indirect emissions for the organic waste recovery process at AWTs, and for recovery at dedicated composting facilities for the GO and FOGO streams. Avoided emissions were estimated based on quantities of waste diverted from landfill. A final modelling step, the *landfill emissions model* was used to estimate the lifetime emissions from organic waste disposed to landfill. For this, the accounting method employed in the Australian National Greenhouse Accounts (DISER, 2021b) was used. Finally, estimates of waste collection, transport, recovery, and disposal emissions from the described modelling steps were combined, to give the overall net waste-related emissions for organic waste management in the study area. Sections 3.2 to 3.4 describe these modelling components in further detail.

3.1. Study area and scope of analysis

Fig. 3 shows the study area, representing the Greater Sydney and surrounding areas of NSW. Within the study area are 43 local government areas (LGAs), comprising the Sydney Metropolitan Area, Greater Western Sydney, Central Coast & Hunter, and the Illawarra & Shoalhaven areas, and is home to a combined population of approximately 6.3 million residents (ABS, 2021), representing approximately 77 % of the NSW state population. With approximately 2.3 million households, the study area is a significant generation source of organic waste, with approximately 1.8 million tonnes of waste collected in 2019–20 across the mixed waste, GO and FOGO streams (NSW EPA, 2021).

Waste treatment pathways in scope of this analysis were broadly described in Section 2 and include windrow composting of GO and FOGO collected organics; AWT for mixed waste collections; and landfill disposal for non-AWT directed mixed waste and residual wastes from the compost and AWT processes.

In terms of GHG emissions accounted for, Fig. 4 includes an overview of the primary emissions and material flows in scope from the management and recovery of organic wastes in the study area. Biogenic CO_2 emissions through the decomposition of organic emissions at landfills and through the aerobic composting process were not considered in scope of this analysis, following guidance from DISER (2021b).

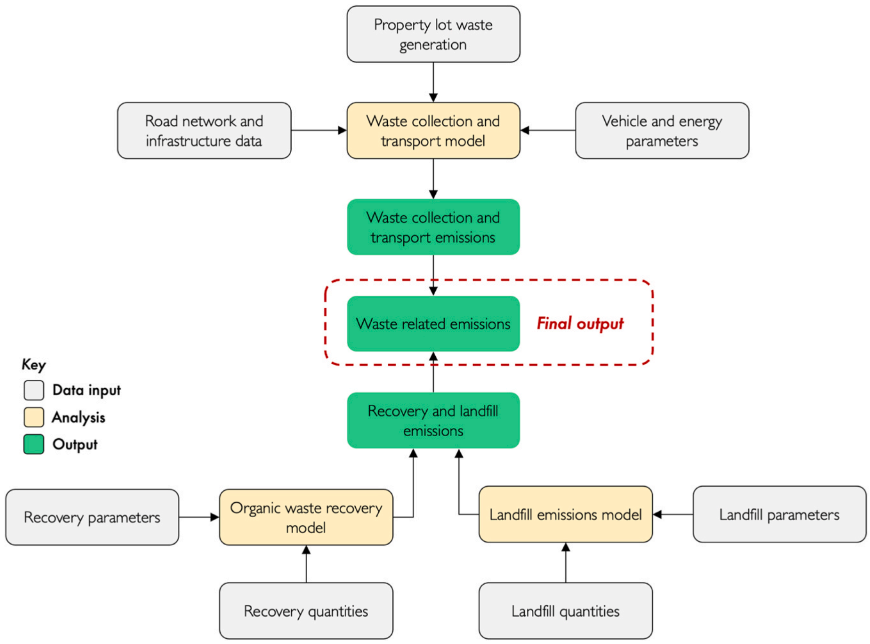

Fig. 2. Methodological overview for this study.

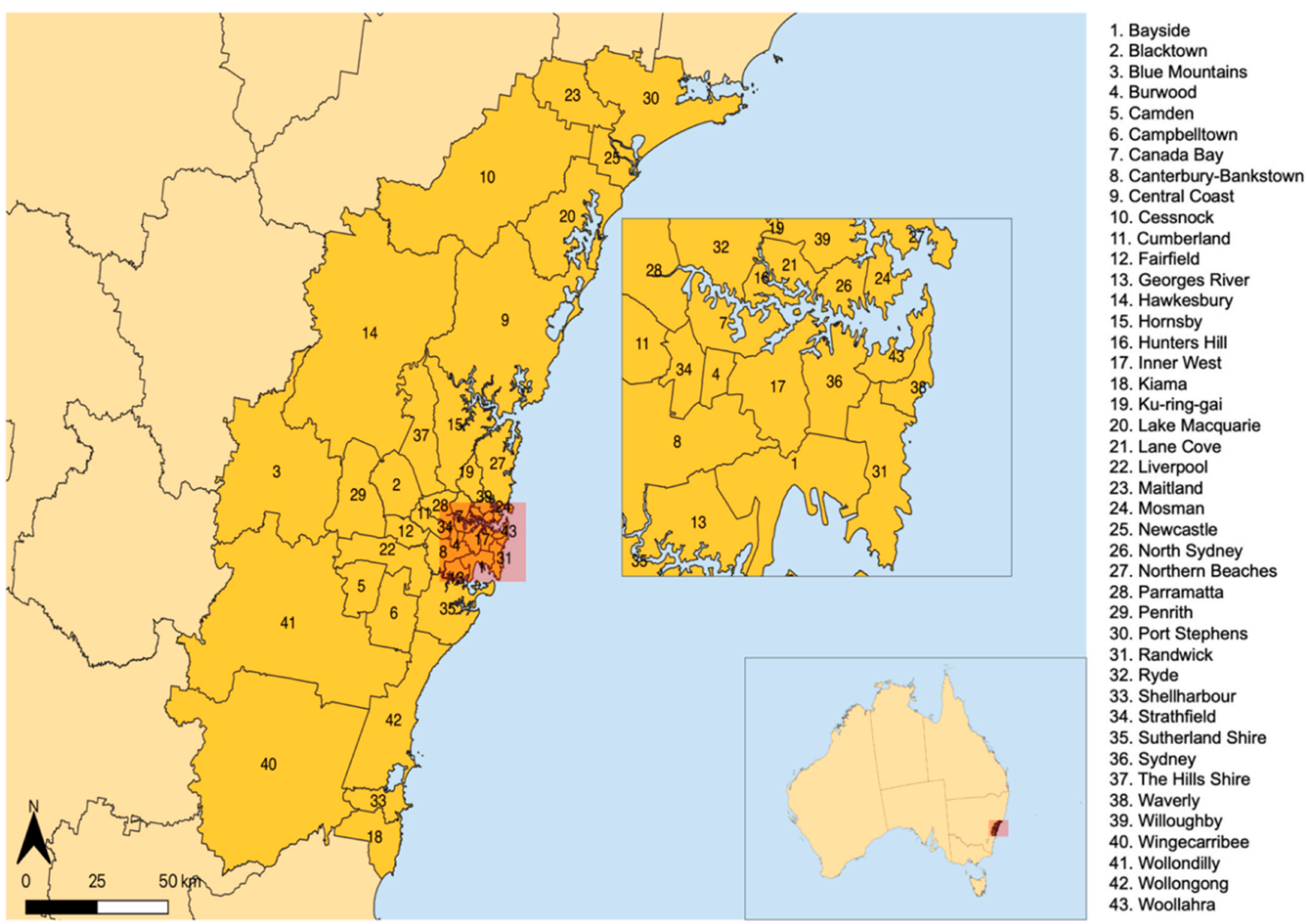

Fig. 3. Study area for this analysis.

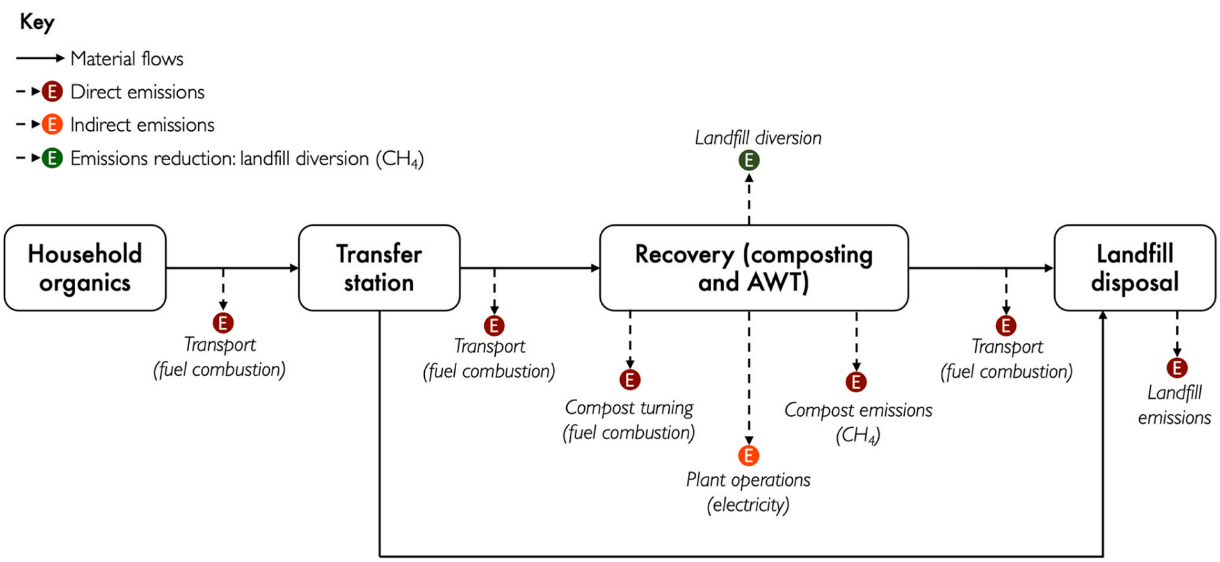

Fig. 4. Overview of emissions and major material flows in scope for this analysis.

However, emissions of methane and nitrous oxide (both converted to CO_2-equivalent) were considered. Furthermore, emissions avoided from material being diverted from landfill due to recovery is considered in this analysis. Emissions avoided from the application of recovered compost to land as substitution for mineral-based fertilisers were not considered in scope, as data for this relevant to the study area is limited. In addition, for the study time period, recovered organics from the municipal stream (specifically from AWT recovery of the mixed stream) is restricted from application to land, due to contamination fears NSW EPA (2019).

3.2. Waste collection and transport model

The *waste collection and transport model* is a route-optimisation model integrated with GIS, used to estimate the collection of household waste from the kerbside for the 1.8 million property lots in the study area. Described in detail in Madden et al. (2022), the model is based on a solution to a capacitated vehicle routing problem (CVRP), solved via a nearest-neighbour search algorithm. The model estimates the emission associated with kerbside collection of household waste, and the transport of collected waste between waste management infrastructure. The components of transport considered in the *waste collection and transport model* are: (1) kerbside collection, from households to transfer stations; (2) recovery transfer from transfer stations to waste recovery facilities, and; (3) disposal transfer: including transport of residues from recovery processes to landfill sites, and transport of mixed waste not directed to AWT facilities from transfer stations to landfill. See Madden et al. (2022) for a full description of this approach.

3.3. Organic waste recovery model

Emissions from industrial composting of organic waste, and sorting and recovery of organics in the mixed waste stream at AWTs were considered in the *organic waste recovery model*, and apportioned to LGAs from where the waste was originally derived. Direct and indirect emissions were estimated for the consumption of fuel and grid-supplied electricity at recovery facilities, and methane and nitrous oxide emitted during the composting process, as per Fig. 4. Direct emissions of CO_2 from the composting process were not considered, due to these emissions being biogenic, and not considered in the National Greenhouse Accounts.

For industrial composting, windrow composting with a 16 week composting time was assumed, based on ROU (2006). Electricity consumption for operational activities (e.g., offices, lighting, etc.), and diesel consumption for feedstock loading, shredding and windrow turning were considered, based on factors in ten Hoeve et al. (2019) and ROU (2006). Emissions intensity factors (scope 2 and 3) were used to estimate the emissions associated with electricity consumption, based on intensity factors published in the National Greenhouse Accounts (DISER, 2021a), specific to the NSW energy supply mix in the study time period. It was assumed that all organic waste composting facilities had sufficient capacity to treat all incoming organic waste during the study timeframe. Recovery rates for garden waste and food waste recovery were based on GO and FOGO waste recovery rates in NSW EPA (2021). Mature compost and residual waste were the assumed outputs of the composting process, with residual waste transferred to landfills for disposal (transport for which was considered in the *waste collection and transport model*). For landfill diversion, the *landfill emissions model* described in the following section was utilised, to estimate the landfill gas (methane and nitrous oxide) emissions avoided from waste recovery. Table S1 in the Supporting information includes parameters from the literature utilised in the *organic waste recovery model* for composting.

For AWT facilities, electricity consumption for mechanical sorting of the incoming mixed waste stream was estimated. This was achieved using a mass-balance model, based on the work in Ng et al. (2021) and Pressley et al. (2015). This approach estimated the energy consumption of the equipment in use at AWTs during sorting and recovery operations individually (e.g., conveyers, trommel screens, etc.). Fig. 5 shows the assumed system diagram of AWT sorting. While the focus of this study is on organic waste recovery, the electricity requirements for both organic and non-organic waste at AWTs were estimated. This was done as accounting for only the organic processing electricity consumption would underestimate the total electricity requirements for treating the incoming mixed waste stream, considering that organics and non-organics are comingled. Separation efficiencies for each sorting equipment (i.e., the proportion of material moving from one equipment to the next in the figure) were estimated based on efficiencies in Ng et al. (2021), adjusted via optimisation for each LGA such that overall AWT separation is consistent with AWT recovery rates in NSW EPA (2021).

Average equipment sorting rates used are summarised in Table S2 in the Supporting Information. Note that sorting rates estimated are for material entering a process step, and are averaged over LGAs sending waste to AWT facilities. Overall AWT recovery rates (i.e., the proportion of total AWT throughput recovered) in the study area and timeframe are low, ranging from no recovery (i.e., 0% recovery rate), to approximately 60%.

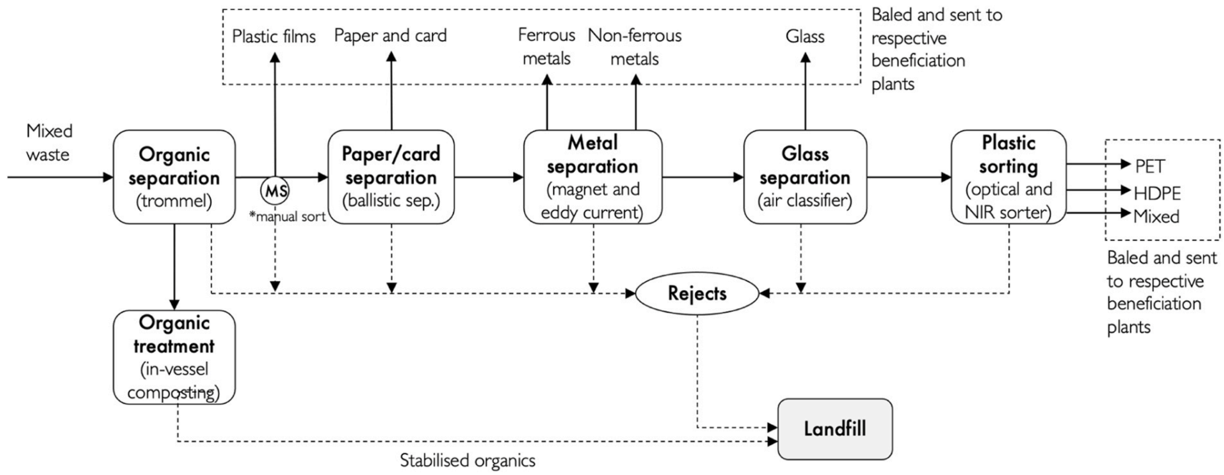

Fig. 5. Assumed system scope of AWT sorting.

Energy intensity factors from Ng et al. (2021) and Pressley et al. (2015) were applied to estimate the energy consumed by each piece of sorting equipment. Overall energy consumption for each facility was then estimated as the sum of electricity consumption estimated for all sorting equipment. Sorted organic waste was assumed to be composted on site via in-vessel composting following Połomka and Jędrczak (2019), Ng et al. (2021), and described in Jacobs (2019). Emissions of methane and nitrous oxide (again assuming all CO_2 emissions are biogenic) from the in-vessel composting process due to leakage were based on windrow composting emissions factors in US EPA (2010). The same assumptions around shredding and feedstock loading fuel requirements for windrow composting were used, based on intensities in ROU (2006) and ten Hoeve et al. (2019). As the application of organic products from AWT to land have been restricted by the NSW waste authority NSW EPA (2019), the final destination of recovered organics from AWT was assumed to be as bio-stabilised material sent to landfill for the purpose of this study. As such, emissions savings from landfill diversion are assumed to still apply. Note that primary data collection from AWT operators were not in scope for this work, which relied on desktop data only. As the scope of emissions savings in this study are confined to landfill diversion, the destination of bio-stabilised material is arbitrary and has no impact on in-scope emissions reductions. Parameters used to estimate AWT emissions are summarised in Table S3 in the Supporting information.

3.4. Landfill emissions model

Emissions from waste degrading in landfills are estimated in the *landfill emissions model*. For this, the method and parameters from the Australian National Greenhouse Accounts (DISER, 2021b) were utilised. With this method, expected lifetime emissions from the decay of materials disposed to landfill were estimated as tonnes CO_2-equivalent for GO and FOGO waste disposed (i.e., residual waste from composting); and from mixed waste disposed (i.e., direct to landfill disposal; and organic and non-organic residues from AWT recovery). Material disposed to landfill decays over decades, therefore the emissions estimated for waste disposed in the study timeframe are the assumed lifetime emissions, given by Eq. 1:

$$\text{Lifetime GHG } (tCO_2e) = \left\{ \left[\left(Q \bullet DOC \bullet DOC_f \bullet F_1 \bullet C_{CH_4} \right) - R \right] \times (1 - OX) \right\} \times GWP \quad (1)$$

Where Q is the quantity of municipal solid waste disposed to landfill in a given timeframe; DOC is the proportion of degradable organic carbon; DOC_f is the fraction of degradable organic carbon dissimilated; F_1 is the methane fraction of landfill gas; C_{CH_4} is the conversion rate of carbon to methane; R is the amount of landfill gas recovered or flared in the given year; OX is the oxidation factor; and GWP is the global warming potential used to estimate CO2-e from methane. Parameter values from DISER (2021b) are summarised in Table S4 in the Supporting information. Estimates for landfill gas capture rates were based on LMS Energy (2021), where 85 % of landfill gas is estimated to be captured across landfills in Australia. Note that for methane gas captured and flared at landfills, the CO2 emissions are not counted as emissions, but considered as part of the natural carbon cycle (DISER, 2021b).

3.5. Sensitivity analysis and model validation

A sensitivity analysis was performed to test the robustness of emissions estimates given variation in key model variables, including: the methane gas capture rate (R in Eq. 1), where data on this is limited for the study area; AWT sorting equipment energy requirements, where some variation between technology selection between Ng et al. (2021) and technology in Australia may exist; and composting parameters. For composting parameters, fuel requirements for feedstock preparation and pile turning, and operations energy requirements varied considerably in the literature. Methane and nitrous oxide emissions from the composting process were also considered uncertain, based on remarks in US EPA (2010) indicating that these parameters are uncertain owing to measurement uncertainty, and large variation in compost pile composition. Sensitivity in parameters for the estimation of kerbside collection and transport emissions were taken from Madden et al. (2022), where variation in estimated emissions were reported.

For this analysis, the sensitivity of overall net emissions to parameter uncertainty were evaluated following a combined Latin hypercube sampling-Monte Carlo simulation approach. Latin hypercube sampling (LHS) makes sensitivity analysis with a large number of parameters practical, providing a convenient approach for dimension reduction by generating random samples of multiple parameters from known probability distributions, spaced evenly over a sample space (McKay et al., 1979). In this approach, parameter values are drawn randomly from the LHS, and net emissions are computed. This was performed 10,000 times for this analysis, to generate a distribution of estimated net emissions from which sensitivity could be evaluated. A similar method was employed for analysing uncertainty in aluminium material flows in China (Li et al., 2021). Value ranges for uncertain parameters were assumed to be uniformly distributed in a range ± 10 % of the baseline parameter value. Outputs from the sensitivity analysis is a distribution of estimated net emissions for the study area. Sensitivity of emissions estimates to variation in uncertain parameters was evaluated by comparing the percentage change in emissions given percentage change in parameter value using regression analysis, after Acevedo (2013). Finally, emissions estimates with uncertainty were compared to related values found in the literature.

4. Results and discussion

4.1. Overall organic waste recovery and emissions for 2019–20

Table 3 shows the total amount of waste generated, recovered and landfilled by waste collection stream. This data forms the basis of the emissions footprint performance indicators reported later in this section. Over 1.8 million tonnes of OFMSW was generated by households in the study area in 2019–20, at an overall per-household generation rate of 956 kg per household. Approximately 579,100 t of organic waste was recovered from the GO, FOGO and mixed waste streams, at an overall recovery rate of 31.4 % of waste generated. Together, waste collected via GO and FOGO streams accounted for approximately 25 % of all waste generated in the study area in 2019–20.

Overall emissions and their sources are summarised for each waste stream in Fig. 6. Gross emissions across all waste streams in 2019–20 were estimated at approximately 391,000 tCO_2-e. This was balanced by an approximate 146,000 tCO_2-e of emissions avoidance, resulting in overall net emissions of approximately 245,000 tCO_2-e. The mixed waste stream was the largest contributor to overall emissions. Some emissions avoidance occurring from the mixed waste stream, equal to approximately 35,800 t, which is attributed to landfill diversion from existing AWT recovery. Landfilling of mixed waste alone was responsible for approximately 55 % of total gross emissions. This is expected given the poor waste recovery rates for this stream, as indicated in Table 3. The GO stream was responsible for approximately 64 % of all recovery emissions, and approximately 60 % of all emissions avoidance. This is also expected, given the large quantities of waste recovered via this collection stream, thereby avoiding lifetime landfill emissions. The contribution of the FOGO stream to overall emissions is low, with the stream responsible for only 5 % of waste collected in the study area.

Fig. 7 shows the breakdown of estimated gross emissions by source and waste stream. Lifetime landfill emissions were the largest contributor to overall gross emissions, accounting for approximately 56 % of all OFMSW management emissions in 2019–20. For the mixed stream, lifetime landfill emissions accounted for 79 % of emissions for that stream. Such large emissions from landfill disposal again is owing to the large quantities of mixed waste disposed to landfill. Conversely, landfill emissions contributed only 1 % and 2 % to GO and FOGO stream emissions respectively, consistent with the relatively small quantities of these streams disposed to landfill. Transport emissions were consistent across the streams, ranging between 12 % and 17 % of emissions. Overall, transport emissions contributed 13 % to gross emissions, consistent with total transport emission estimates in Madden et al. (2022). Although small, the contribution of transport emissions should not be ignored in holistic evaluations of the emissions intensities of OFMSW management. This is especially true for the mixed waste stream, where transport emissions were approximately a third higher than emissions associated with the AWT recovery process. This is expected, given the large quantities of mixed waste collected compared to the small quantities of mixed waste sent to AWT for recovery.

Table 3
Summary of waste generation and recovery by waste collection stream for 2019–20 in the Greater Sydney and surrounds study area.

Waste stream	Waste generated, 2019–20 [t]	Waste recovered, 2019–20 [t]	Waste landfilled, 2019–20 [t]	Waste recovery rate
GO stream	377,465	373,873	3592	99.0 %
FOGO stream	90,047	88,273	1773	98.0 %
Mixed waste stream	1,374,096	119,377	1254,718	8.7 %
Overall	1,841,607	579,140	1262,467	31.4 %

Table 4 summarises emissions intensity for each waste stream and overall. The net emissions per tonne of waste diverted is the chosen emissions intensity performance indicator. This is an important metric used for accounting and evaluating emissions of different resource recovery systems (Gavrilescu, 2022; Iacovidou et al., 2017). Compared to a gross emissions intensity metric, net emissions better characterise the emissions balance by considering avoided emissions. Compared to net emissions on a per tonne managed basis, the chosen metric also factors in resource recovery efficiency. This means that emissions intensity performance is impacted both by the quantity of waste recovered, and the balancing of emissions and avoided emissions, thereby better reflecting the principles of low carbon resource recovery than net emissions on a per tonne managed basis. Overall, net emissions were approximately 423 $kgCO_2$-e/t of organic waste diverted in the study area. Emissions intensity was lowest for the GO stream, at approximately 8.5 $kgCO_2$-e/t of waste diverted from landfill. As indicated in Fig. 7, avoided emissions were significant, which mostly offset gross emissions. FOGO stream intensity was higher than GO stream intensity, due to greater transport emissions intensity for FOGO collections, and lower stream recovery compared to the GO stream. Mixed waste stream emissions intensity was very high, at approximately 2 tCO_2-e/t of waste diverted. This can be attributed to poor stream recovery rates leading to significant quantities of waste disposed to landfill. Improving mixed waste recovery and reducing the quantities of waste collected via mixed waste (e.g., via FOGO collections) would likely have significant impacts on reducing overall emissions intensity, based on these findings.

4.2. Emissions from composting

Approximately 467,500 t of household organics were treated through composting in 2019–20 in the study area. Table 5 summarises estimated composting emissions for GO and FOGO waste streams. Total gross emissions for composting were approximately 96,500 tCO_2-e, and avoided emissions from landfill diversion were estimated at 109,800 tCO_2-e, making composting a negative net emissions process at − 13,300 tCO_2-e. When considering emissions associated with collection and transportation, overall net emissions becomes positive, at 3500 tCO_2-e. Of the emissions occurring from the compost process itself, approximately 93 % were attributed to direct emissions of methane and nitrous oxide. Compost turning, using diesel fuel, contributed approximately 7 % to composting emissions, and facility operations (e.g., lighting and office equipment), less than 1 %. GO stream composting contributed 81 % to overall composting emissions—expected given the larger quantities of GO stream waste collected for composting.

Table 6 summarises estimated emissions intensities for composting, including emissions associated with transport to composting facilities. Approximately 8 $kgCO_2$-e was emitted per tonne of waste diverted from landfill via composting of GO and FOGO. Differences in intensities between the organic streams were minor, with differences owing to the greater transport requirements for the FOGO stream. Focusing on the compost process itself by excluding transport emissions, overall net

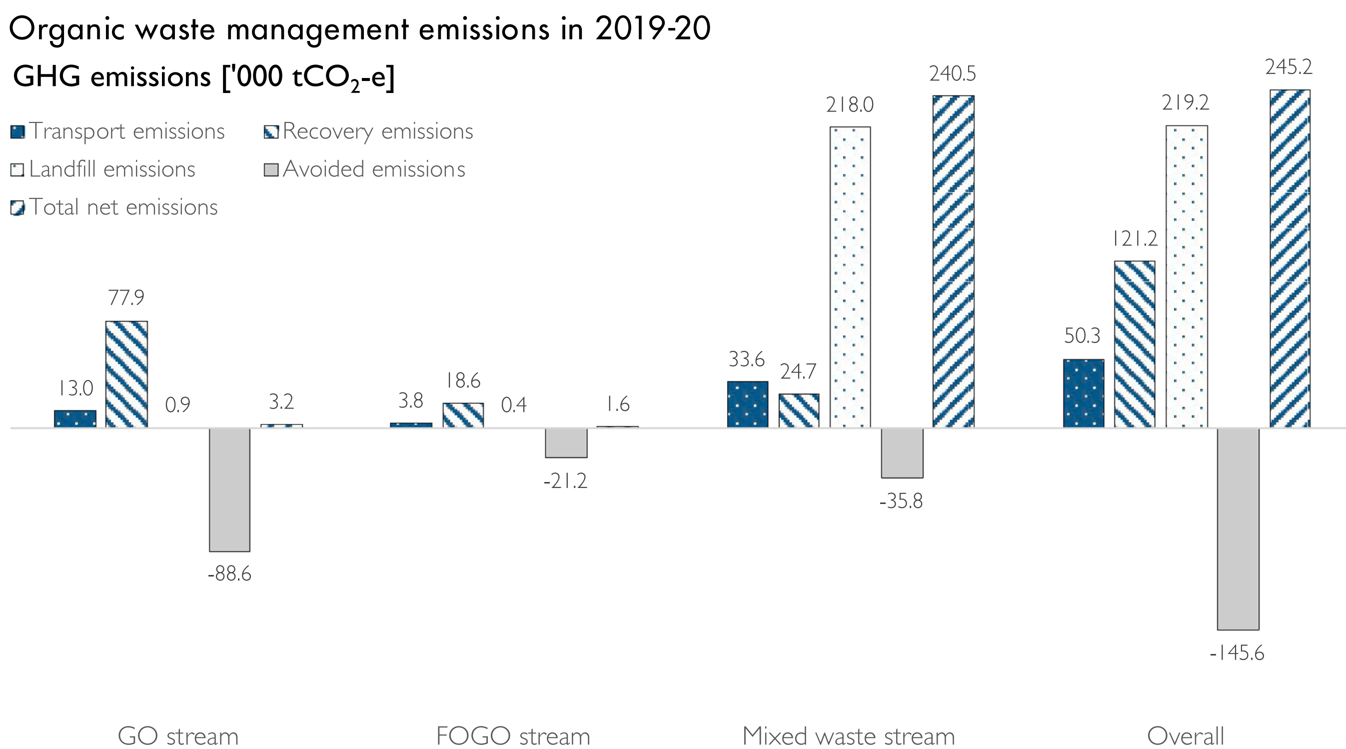

Fig. 6. Estimated emissions by waste stream in the study area for 2019–20.

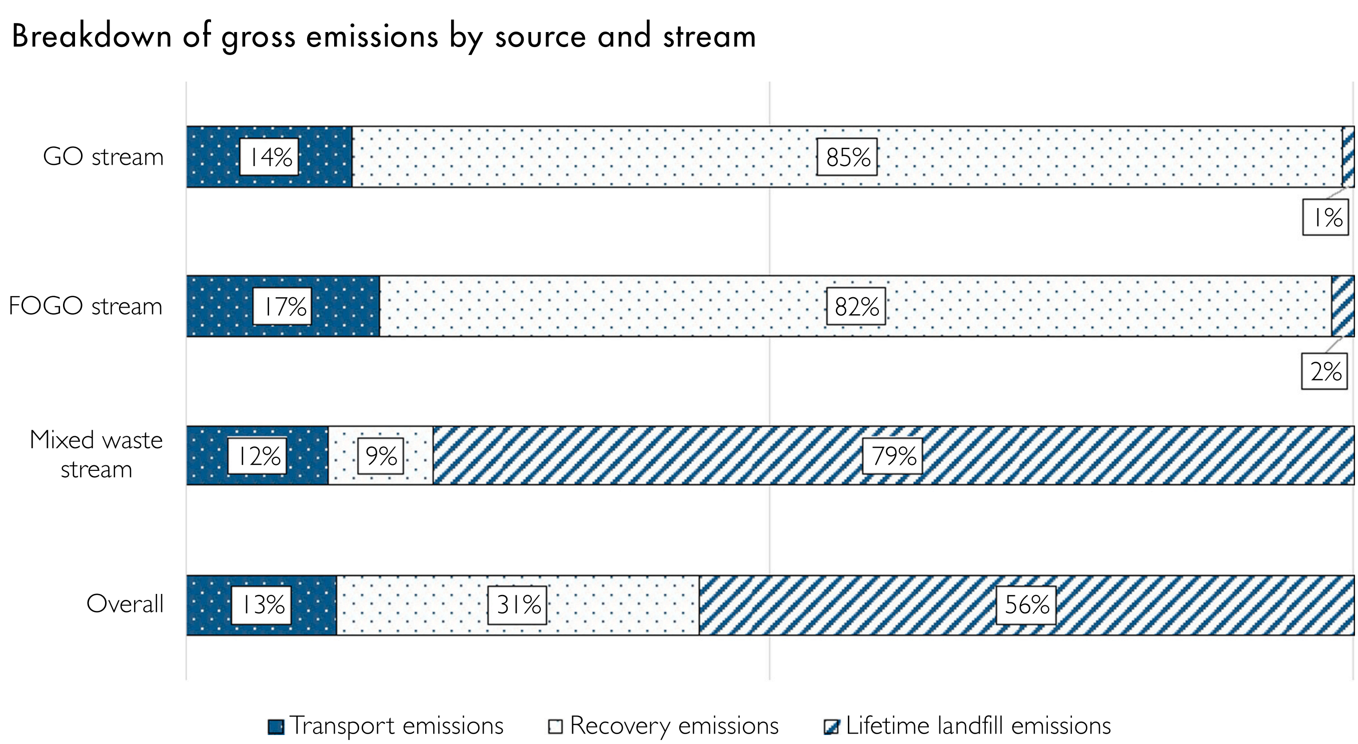

Fig. 7. Breakdown of emissions by source and stream for 2019–20.

emission intensity was approximately − 29 $kgCO_2$-e/t waste diverted from landfill.

These estimates of composting emissions do not include downstream emissions associated with the final utilisation of mature compost. As noted in the literature (e.g., Boldrin et al. (2009); Fernández-Delgado et al. (2020); Friedrich and Trois (2013)), mature compost can offset the use of mineral based fertilisers, which can have considerable life-cycle emission considerations. Boldrin et al. (2009) and Friedrich and Trois (2013) for example assume the 3.76 kg of nitrogen in OFMSW derived compost would offset 1.88 kg of nitrogen from mineral sources

Table 4
Summary of net emissions intensity for each waste stream for 2019–20.

Waste stream	Net emissions intensity per tonne diverted [kgCO_2-e/t]
GO stream	8.5
FOGO stream	17.7
Mixed waste stream	2055.6
Overall	423.4

(assuming a substitution of mineral fertiliser at a rate of 50 %), resulting in approximately 24 kgCO_2-e savings per tonne of compost produced. Moreover, as noted in ROU (2006) and Friedrich and Trois (2013), the application of mature compost to land also carries and emissions burden, mainly from the consumption of fuel required by transporting of compost and from farm equipment applying it to land, as well as emissions savings from carbon bound to soil (Friedrich and Trois, 2013). These emissions were not considered in this analysis for several reasons. Firstly, as indicated in NSW EPA (2019), the application of municipally derived compost is restricted in its application to land for food crops, due to contamination concerns. The rate of substitution of mineral based fertilisers for OFMSW compost is also an unknown, and is wide ranging in the literature, making estimation difficult. Boldrin et al. (2009) for example assumes a substitution rate of 20–60 %. The level of potential substitution however would likely be dependent on the application to land, with food and other high value crops likely having lower substitution rates, as fertiliser inputs must be consistent to guarantee crop yields. This point however does require further analysis to verify. Future applications of this modelling could incorporate an expanded system scope, to include the emissions savings from mineral-based fertiliser substitution. Data on the existing rates of fertiliser consumption would be needed, as well as current utilisation levels of secondary organics, to accurately assess the potential of emissions avoidance.

4.3. Emissions from AWT recovery

Table 7 summarises total AWT throughput and recovered quantities and recovery rates for the study area for 2019–20. Quantities of AWT throughput and waste recovered are derived from NSW EPA (2021). Approximately 464,000 t of mixed waste was diverted to AWTs for recovery in 2019–20, originating from 19 LGAs in the study area. The recovery rate of LGA mixed waste ranged from 0 % to 50 %, with a total recovery rate of approximately 26 % that is predominately associated with the organic fraction. Some LGAs sending mixed waste to AWTs reported recovery rates of 0 % in NSW EPA (2021); namely Georges River, Hunters Hill, Lane Cover, Penrith and Woollahra council areas. Reasons for this 0 % recovery are unclear. Notably, 2 of the listed LGAs had FOGO collection, therefore organic waste in the mixed stream may have been insufficient for AWT recovery processes prioritising organic waste recovery. In total, AWT diversion represented approximately 34 % of total mixed waste generated across the study area.

Table 8 summarises some key statistics from the *organic waste recovery model*. Approximately 43 % of the AWT throughput stream was organic waste, primarily consisting of food waste. Organic waste accounted for an estimated 98 % of total waste recovered from the mixed stream at AWTs. Total gross emissions from AWT recovery including transportation was approximately 36,200 tCO_2-e. Approximately 67 % of these emissions were attributed to the in-vessel composting process. The mechanical sorting component accounted for only 2 % of overall AWT emissions. The energy intensity of mechanical sorting operations was estimated at 1.53 kWh/t of material throughput. This is compared to a value of 1.32 kWh/t in Ng et al. (2021), from which the AWT sorting component of the *organic waste recovery model* waste based. Considering only the organic waste recovered at AWT facilities, AWT outperformed composting in terms of net emissions intensity on a per tonne diverted basis. This can be attributed to the much higher proportion of food waste in the mixed waste stream treated via AWT, than food waste in the FOGO stream. Food waste accounted for approximately 38 % of mixed waste diverted to AWT, compared to approximately 12 % in the FOGO stream. This indicates that better management of the food waste stream might lead to significant impacts on emissions reductions. Expansion of FOGO services to more households and LGAs is planned for NSW, which would lead to greater quantities of food waste diverted from landfill. However considering restrictions on AWT derived compost (NSW EPA, 2019), diverting more of the food waste in the mixed stream to the FOGO stream (i.e., increasing the proportion of food in FOGO) would be more beneficial from a compost utilisation perspective, and the potential downstream

Table 6
Estimated composting emissions intensities.

Waste stream	Net composting emissions per tonne diverted [kgCO_2-e/t]
GO	6.21
FOGO	12.83
Overall composting	7.47

Table 7
AWT throughputs, and recovered quantities.

Mixed waste fraction	AWT throughput, 2019–20 [t]	Waste recovered via AWT, 2019–20 [t]	AWT recovery rate [%]
Organic waste	197,606	116,995	59.2 %
Non-organic waste	266,484	2382	0.9 %
Total	464,090	119,377	25.7 %

Table 8
Summary of key AWT statistics estimated in this study.

Metric	Value
Waste sent to AWTs 2019–20 [t]	464,090
Fraction of input that is organic	42.6 %
Mixed waste recovered at AWTs in 2019–20 [t]	119,377
Fraction of recovered that is organic	98.0 %
Mechanical sorting energy [MWh]	711.4
Mechanical sorting energy intensity [kWh/t]	1.53
Mechanical sorting emissions [tCO_2-e]	604.7
Organic recovery emissions* [tCO_2-e]	36,240
Emissions reductions via diversion [tCO_2-e]	35,774
Net emissions [tCO_2-e]	466
Net emissions intensity (diverted) [kgCO_2-e/t]	3.9
Waste sent to AWTs 2019–20 [t]	464,090

* Includes compost turning, operations and direct emissions

Table 5
Estimated composting emissions.

Waste stream	Compost turning emissions [tCO_2-e]	Compost operations emissions [tCO_2-e]	Direct emissions (CH_4 & N_2O) [tCO_2-e]	Total compost emissions [tCO_2-e]	Emissions reductions via diversion [tCO_2-e]
GO	5594	12.83	72,285	77,892	88,563
FOGO	1335	9.95	17,244	18,588	21,235
Overall composting	6929	22.78	89,529	96,480	109,798

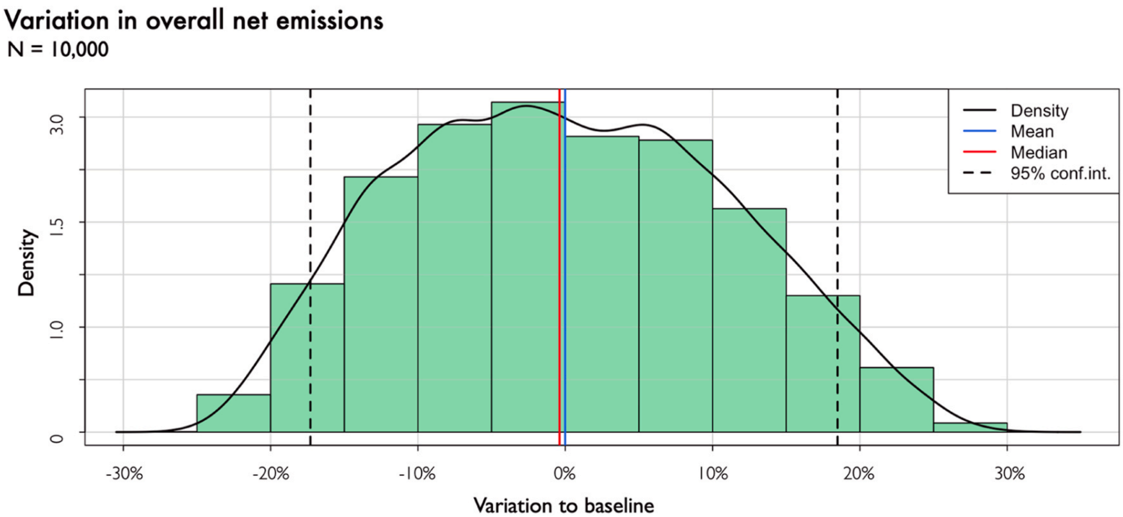

Fig. 8. Distribution of overall net emissions estimates given variable uncertainty, based on a Monte-Carlo simulation with 10,000 iterations.

Table 9
Summary of regression analysis used to evaluate variable sensitivity on overall net emissions.

Variable	β-coefficient	*p*-value
Intercept	-0.0000683	0.240
Waste generation	**0.7946286**	**< 0.005**
Landfill gas capture rate	**-1.7024166**	**< 0.005**
Compost fuel requirements	**0.0353115**	**< 0.005**
Compost energy	0.0008206	0.415
Compost CH_4 emissions	**0.2675333**	**< 0.005**
Compost N_2O emissions	**0.1913701**	**< 0.005**
Trommel energy	0.0013947	0.166
Vacuum sorting energy	0.0001036	0.918
Ballistic sorting energy	0.0010762	0.286
Metal separation energy	-0.0008182	0.417
Air knife separation energy	0.0001406	0.889
Optical sorting energy	0.0006554	0.515
Conveyer belt energy	0.0001219	0.904
R^2 value	0.9972	
Adjusted R^2 value	0.9972	
Model *p*-value	< 0.005	

emissions reductions.

4.4. *Sensitivity analysis and comparison with emissions intensities from the literature*

Fig. 8 shows the distribution of overall net emissions estimates, derived from a Monte-Carlo simulation (10,000 iterations) with random values for selected variables as described in Section 3.5. Variation in overall net emissions was estimated at approximately ± 18 % at the 95 % confidence level. Table 9 summarises results from a regression analysis on the generated outputs of the Monte-Carlo simulation, used to evaluate sensitivity on variation in selected variable values, based on Acevedo (2013). Eq. 2 shows the functional relationship analysed:

$$y = \beta_0 + \beta_n x_n + \epsilon \quad (2)$$

Where y is the estimated percentage variation in net emissions compared to baseline with nominal variable values; β_0 is the estimated model intercept; β_n is the coefficient value for the n^{th} variable; x_n is the variation of the n^{th} variable compared to the nominal value; and ϵ is the error term.

Of the variables assessed in the sensitivity analysis, variation in waste generation quantities; landfill gas capture rate; compost turning fuel requirements; and direct methane and nitrous oxide emissions from the composting process were found to have a significant impact on variation in net emissions. Of these variables, the overall net emissions in the study area were most sensitive to variation in the landfill gas capture rate, with a halving of the landfill gas capture resulting in an approximately 80 % increase in net emissions. This is expected, given that lifetime landfill emissions have been shown through this analysis to be the most significant contributor to waste-related emissions. This identifies that better landfill data will help improve model accuracy.

Variability in waste generation had a statistically significant impact on net emissions, with a doubling of waste generation across the study area resulting in an approximately 80 % increase in net emissions. The impact of waste generation variation on transport emissions were explored in Madden et al. (2022), where it was found a 20 % change in waste generation resulted in 2.5 % increase in transportation emissions. Considering that transport emissions make up approximately 13 % of overall gross emissions, the impact of waste generation variability is more significant on recovery and landfill emissions.

The impact of variability in compost emissions variables on net emissions was relatively low, however still significant. Results indicate a doubling of the parameter values for methane and nitrous oxide emissions from windrow composting, would result in an approximate 27 % and 20 % increase in net emissions respectively. The impact of variability in electricity requirements for composting was statistically significant, however very small, with a doubling of parameter value resulting in an approximately 3 % change in net emissions.

The impact of variability on AWT processes emissions was found to not impact the overall net emissions estimates. This is somewhat

Table 10
Comparison of mean value performance metrics from this analysis, compared with some data points from literature sources.

Metric	Value (this analysis)	Value from literature	Reference
Gross compost emissions intensity	206 kg/t	218 kg/t	Dastjerdi et al. (2019)
per tonne managed		402.3 kg/t	Friedrich and Trois (2013)
		170 kg/t	Martínez-Blanco et al. (2009)
		98.4 kg/t	Martínez-Blanco et al. (2009)
		172.2 kg/t	Zhu-Barker et al. (2017)
		75–150 kg/t	Vergara and Silver (2019)
Landfill emissions per tonne disposed	238 kg/t	259.5 kg/t	Liu et al. (2017)
		569.8 kg/t	Thanh et al. (2015)

expected, given that emissions from AWT sorting account for a relatively small proportion of overall emissions from the management of the mixed waste stream.

The sensitivity analysis performed does reveal some limitations with the modelling in this analysis, which can be addressed through targeted data collection, for example, more specific landfill gas capture rates for NSW. Estimating direct methane and nitrous oxide from composting has been noted as being difficult, due to complexities in the composting process, and wide variation in compost technology and feedstock composition (US EPA, 2010). Despite these limitations, comparison with metrics from data generated through this analysis with data from the literature, gives confidence to the baseline estimates described in this section. Table 10 summarises this comparison, showing key indicators calculated from data generated from this analysis, compared to data from the literature. These indicators are gross compost emissions intensity: calculated as the gross emissions from composting (shown in Table 5), divided by the quantity of waste managed via composting (467,512 t); and landfill emissions per tonne disposed: calculated as emissions from landfill, divided by tonnes of waste disposed to landfill. Data was selected from the literature that could be aligned with data generated from this analysis. Metrics from this analysis are generally consistent with values in the literature, illustrating that the emissions intensity of OFMSW management estimated are similar to values reported in the literature. Values in the literature however, especially with respect to emissions intensity per tonne managed, vary widely. This can be attributed to variation in the composition of OFMSW internationally, as well as the different composting and recovery technologies employed. Coupled with the results of the sensitive analysis described above, this gives confidence to the results.

4.5. Summary of 2019–20 emissions intensities

A final summary of estimated emissions intensities is shown in Table 11, calculated by averaging net emissions intensities on a per tonne managed and per tonne diverted basis for each organic management pathway employed by LGAs in the study area. Corresponding average recovery rates for each pathway are also shown. In the table, 'GO only' and 'FOGO only' refer to LGAs that have GO and FOGO composting as the only organic waste recovery pathways, and estimated intensities also includes emissions associated with mixed waste management. 'AWT only' refer to LGAs that do not separately collect organics, but send a proportion of mixed waste to AWTs for recovery. 'GO+AWT' and 'FOGO+AWT' refer to LGAs that separately collect GO and FOGO waste for composting as well mixed waste to AWTs (including also emissions associated with the management of non-AWT mixed waste). One LGA did not separately collect GO or FOGO, or send mixed waste to AWTs for recovery.

Table 11
Average emissions intensity factors for different LGA organic waste pathways. Percentage uncertainty is derived from the standard deviation of LGA level estimates, and should be treated with caution due to small sample sizes.

LGA organic waste pathway	Average waste recovery rates [%]	Net emissions intensity factor, per tonne managed [$kgCO_2$-e/t]	Net emissions intensity factor, per tonne diverted [$kgCO_2$-e/t]
GO only (N = 20)	29.7 %	165.9 ± 19.4 %	557.8 ± 41.1 %
FOGO only (N = 3)	50.2 %	98.8 ± 9.4 %	196.6 ± 9.5 %
AWT only (N = 2)	23.3 %	109.5 ± 16.7 %	470.2 ± 40.5 %
GO + AWT (N = 15)	34.7 %	96.9 ± 52.3%	279.7 ± 54.7 %
FOGO + AWT (N = 2)	45.0 %	75 ± 21.1 %	166.8 ± 65.9 %
No organics (N = 1)	0.0 %	216.8 ± 17.3 %	NA

Of these different organic management pathways, 'FOGO only' and 'FOGO+AWT' LGAs had the lowest net emissions intensities, at approximately 197 $kgCO_2$-e/t and 167 $kgCO_2$-e/t respectively. Interestingly, LGAs that divert mixed waste to AWT as the only recovery pathway, had lower net emissions intensities than 'GO only' LGAs. In addition, 'GO+AWT' LGAs had lower emissions than 'AWT only', but higher than LGAs with FOGO collection. Given that the only pathways for food recovery are via FOGO collections or AWT recovery, these findings support that increasing the diversion of food waste from landfill leads to improved overall emissions performance. Although this finding is useful from a waste management planning perspective, results should be treated with a degree of caution, given that sample sizes for the different LGA pathways are low. Further analysis on state-wide waste related emissions and organic waste recovery, would give greater certainty to these finding and allow further exploration of trends in emissions intensities between the organic management pathways.

5. Conclusion

This paper presented a modelling framework and results on the emissions associated with OFMSW management in the Greater Sydney and surrounding areas for 2019–20. The analysis found that total emissions associated with OFMSW recovery in the study area including upstream and downstream management, was approximately 245,000 tCO_2-e, with emissions from landfill disposal accounting for approximately 56 % of all emissions generated. Management of the mixed waste stream, which also accounts for the majority of organic waste generated by households in the study area, had the largest impact on overall emissions, and the highest emissions intensity on a per tonne diverted basis. The analysis also addressed an important knowledge gap identified in Madden et al. (2022), on the accounting of OFMSW management emissions beyond transportation; finding that emissions from transportation account for approximately 13 % of overall OFMSW management emissions.

The analysis highlighted that landfill diversion of organics, especially food waste in the mixed stream, is crucial in the context of achieving good low carbon resource recovery performance. Simply put, by improving the recovery rate of the household organic waste stream, the overall net emissions can be reduced. Increasing the diversion of food waste from the mixed stream to separate FOGO collections, and increasing quantities of mixed waste treated via AWTs were shown to have a positive impact on landfill diversion and organic waste recovery. These strategies are also aligned with the *NSW Waste and Materials Strategy 2041*, and would likely have significant impacts on transitioning to low carbon resource recovery.

The modelling approach can be further adapted, to investigate other OFMSW management strategies and their impacts on low carbon resource recovery, including for example, the impacts of anaerobic digestion as a recovery pathway, as well as evaluating other household waste streams. The modelling approach performed well from an uncertainty and parameter sensitivity perspective, and analysis identified where improvements could be made to give further confidence in the accuracy of results. Namely, better data on landfill capture rates, and direct emissions of methane and nitrous oxide from the composting process could improve the accuracy and certainty of results. Future analysis may also explore expanding the system boundaries, to include the emissions potential of the utilisation of secondary organics to land, including from carbon capture in soil, and from offsetting mineral based fertiliser consumption.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.clwas.2023.100111.

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