Food Waste Management Alternatives for New South Wales:
A Life Cycle Assessment Approach

by

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EXECUTIVE SUMMARY

With an increased understanding of the role that atmospheric emissions from anthropogenic activities are playing in climate change, and the rise of net zero carbon emissions targets and policies, virtually no industry has escaped the scrutiny of governments and societies world-wide. Motivated by this, and driven by the New South Wales Government's recently-released Waste and Sustainable Materials Strategy 2041[1], this thesis seeks to add to the rich repository of literature aiding decision-makers and authorities to advance net zero policy directions, and to support industries and technologies that seek to reduce global emissions.

This thesis' focus is centred on the issue of how best to address the treatment of household food waste, which is wasted in the order of millions of tonnes per year in New South Wales. Specifically, it sets out to scope the current state of play. Then it will assess the validity of the premise that diversion of food waste from landfill can offset greenhouse gasses from the solid waste management sector. Finally, it will propose and quantify the benefits of several alternative food waste management strategies that could be scaled to offset Greater Metropolitan Sydney's emissions from food waste in landfill.

In this report's initial section, we investigate a number of pre-existing and pre-eminent technologies used internationally to manage food waste, including open windrow composting with garden organics and anaerobic digestion. Not only are emissions from landfill and the waste management sector more broadly reduced but useful by-products are also produced which can further offset the environmental impacts of the industry. Continuing from this assessment of current technologies, this paper then investigates what technologies are employed within the Australian, New South Wales, and Greater Metropolitan Sydney contexts.

Next, a survey of key decision makers in Sydney's waste management industry was conducted, and its design and methodology are discussed, followed by presentation of its results. The survey uncovers the rapid transition that must be achieved in order to divert food waste from landfill and reduce emissions from the solid waste management sector. It also highlights uncertainty amongst decision-makers as to which food waste diversion strategy is best.

A review of the literature then seeks to develop a quantitative environmental assessment framework to aid in the comparison of different food waste diversion strategies. The finding from this process is that a Life Cycle Assessment of the base case scenario, and two others would be relevant.

Subsequently, this study plans and undertakes a detailed Life Cycle Assessment of the Municipal Solid Waste Management industry in Greater Metropolitan Sydney, comparing the following three scenarios: 1) combined collection and landfilling of residual waste and food organics, with garden organics sent to an open windrow composting facility (Scenario 0, the base case); 2) landfilling of residual waste only, and open windrow composting of combined food organics and garden organics (Scenario 1); and, 3) landfilling of residual waste only, open windrow composting of garden organics only, and the separate collection and anaerobic digestion of food organics (Scenario 2).

The results of this Life Cycle Assessment show that proposed Strategies 1 and 2 lead to an at least 84% reduction in emissions from landfilling of household waste, a 99% net reduction in ecotoxicity, and a 27% net reduction in ozone formation, as opposed to the base case.

The results reveal that Global warming potential emissions from landfill total 797.4 kg CO2 eq per 1 Mg kerbside waste collected, whilst in Scenario 1 the value is 129.6 kg CO2 eq, and for Scenario 2 it is 22.49 kg CO2 eq.

These significant results lead to the conclusion that diversion of food waste from landfill certainly yields improved environmental benefits, not only with respect to reduction in greenhouse emissions. It also suggests that of the alternatives proposed, Scenario 2 appears to yield better long-term environmental outcomes.

A key recommendation arising from the study is further work should be done to further quantify processes within the system boundary considered through utilising first-hand data collection, and to perform a technoeconomic analysis to understand the viability of the different Strategies proposed.

STATEMENT OF ORIGINALITY

I hereby declare that, to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purpose.

I certify that the intellectual content of this thesis is the product of my own work and that all assistance received in preparing this thesis and sources have been acknowledged.

[redacted]

Hunter John Wardman

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
AD	Anaerobic digestion
DQS	Data Quality System
EIA	Environmental Impact Assessment
EPA	Environment(al) Protection Agency
FO	Food Organics waste stream
FOGO	Food Organics and Garden Organics
FU	Functional Unit
GMS	Greater Metropolitan Sydney
GO	Garden Organics waste stream
GWP	Greenhouse warming potential
ISO	International Standards Organisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LGA	Local Government Area
Mg	Tonnes
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
NOX	Nitrogen oxides
NSW	New South Wales, Australia
OECD	Organisation for Economic Co-operation and Development
PFD	Process Flow Diagram
RES	Residual waste stream
SWM	see MSWM
UNEP	United Nations Environment Program

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1. Introduction & Background

With increased socio-political awareness about the impact of emissions on climate change, governments throughout the world have been progressively introducing emissions reduction targets and so-called "net zero" strategies across a wide range of industries. This changing regulatory environment often means that businesses and regional administrations are having to decide between competing technologies and strategies with little scope to transition once a decision has been made due to economic, environmental and/or political pressures. Therefore, it is essential that such decisions are well informed by quantitative evidence.

Solid waste management (SWM) has been, and continues to be, a persistent issue of global concern. Globally, the waste management sector is estimated to be responsible for about 2.8% of total greenhouse emissions[2, 3]. A significant proportion of this is attributable to the emission of methane from landfills, the most common practice for MSW management[3], most of which is derived from the decay of organic waste[4]. Acknowledging that landfilling is not a net zero practice, therefore, authorities are choosing to process organic waste streams via alternative manners. These can include composting of organics to repurpose it into soil and fertiliser products, anaerobic digestion of food waste to repurpose both the biogas to supplement gas and electricity grids and the nutrient-rich digestate, or other processes involving heat treatment, for instance gasification and pyrolysis.

In addition to the competing technologies available for managing food organics, authorities must also decide on optimal kerbside waste collection strategy, including the number of service streams offered and collection frequency. This quickly becomes an economic, logistic, and environmental challenge to balance.

As stated above, food waste is a large contributor to the SWM industry's overall environmental impacts, particularly to its GHG emissions. This is because the decay of food organics releases quantities of methane, which has a global warming potential (GWP) of 28-36[5] (relative to carbon dioxide which has a GWP of 1). Undoubtedly, a new approach to managing food waste can help to improve the environmental impact of the SWM industry. Whilst there are attempts to reduce the net amount of food waste that Australia, and indeed the world, produce[6], there will continue to remain a component of the domestic waste stream which comprises of food waste.

1.1. Thesis Aim

This Thesis seeks to quantitatively benchmark competing municipal solid waste management strategies with respect to food waste by performing a Life Cycle Assessment. The study models a range of processes involved in the kerbside collection, transport, and treatment of solid waste with a particular focus on residual, food organics, and garden organics waste streams. It is intended that the results from this Thesis will help to inform key decision-makers in Local Government Areas (i.e., Councils' waste management officers), and other interested bodies of the environmental merits of the competing strategies proposed.

1.2. Food waste management strategies

The Waste Hierarchy[7] (Figure 1.1) is a well-known strategy which outlines a set of priorities to minimise the environmental impact of waste generation and treatment. Its principles can be applied to a broad range of consumer products and their respective waste management strategies.

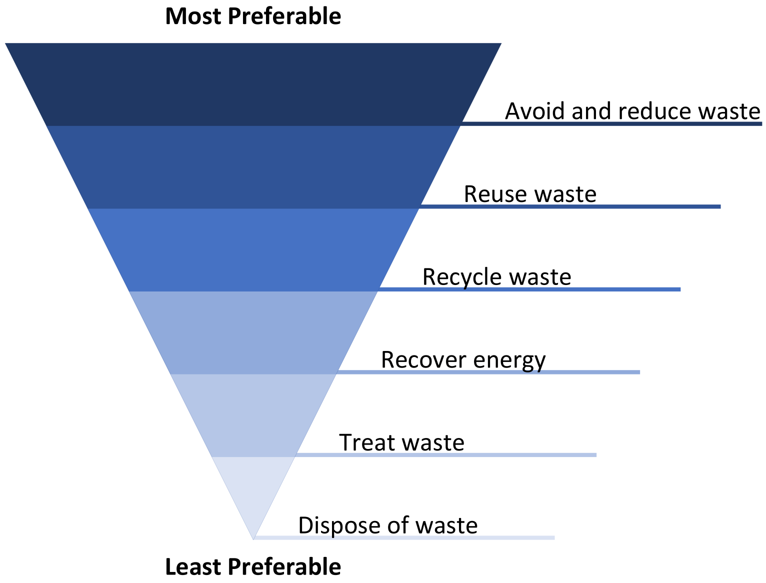

Figure 1.1: The Waste Hierarchy, based off NSW EPA[7], incorporating competing management strategies for food waste.

A number of competing technologies for managing food waste are known to yield differing socioenvironmental benefits. With respect to the food waste stream, avoiding, reducing, and reusing food waste focuses on changing households' behaviours to support more efficient consumption of waste, donating excess food to food banks, and repurposing food waste into animal feed. The recycling of waste is associated with composting, the use of worm farms, and biotechnological reprocessing of food waste into commercial animal feeds. Pham et al.[8] detail a number of energy recovery processes available for food waste, including biological technology such as anaerobic digestion and fermentation, and thermal and thermochemical technology such as incineration, pyrolysis, gasification, and hydrothermal carbonisation. Treatment and disposal of food waste involves the sending of waste to landfill.

Each processing technology for food waste yields differing benefits, downsides, and challenges to implementation. Avoiding, reducing, reusing and recycling of waste requires behavioural changes amongst consumers, and each community exhibits different abilities to conform to public messaging campaigns surrounding improved food waste management[9]. Energy recovery is a promising alternative to food waste management and can be integrated into the kerbside waste collection scheduling. It illustrates how an economically viable process can be developed from the processing of waste.

Landfilling is relatively inexpensive in Australia compared to other countries[10] due to an abundance of land. This means it can be difficult to make alternative food waste stream management technologies economically viable. To incentivise more efficient waste management practice, states and territories have introduced levies or fees to avoid the landfilling of organic waste.

In recent decades in Australia, there has been increased investment into dedicated food waste management facilities, as well as an improvement in emissions from open-cut landfills. EarthPower[11] is an example of a Sydney-based SWM organisation which specialises in the anaerobic digestion of organic waste streams. This is a promising technology which has a proven track record both in Australia, as well as globally, which accelerates the decomposition of food waste through microbial activity, collecting the methane produced and supplement the energy grid, as well as producing a nutrient-rich sludge which is dried and pelletised into high-nutrient fertiliser. However, it is documented in the literature that the uptake of food waste anaerobic digestion in Australia has been scarce[12].

1.3. Food Waste in Australia and New South Wales

Australians are estimated to generate 7.3 million tonnes (Mg) of food waste yearly across our entire supply and consumption streams[13]. The United Nations Environment Programme[14] (UNEP) reports a high confidence estimate of Australia's yearly per capita household food waste production rate to be 102 kg/capita/year. The predominant strategy of managing food waste until now has been to incorporate it into the residual waste stream, and to send it to landfill. Minimal amounts of organics are sorted via advanced waste recovery (AWT) and decomposed, capturing methane emissions, however the vast majority continues to be sent to landfill[15]. In New South Wales, it is estimated that food waste accounts for 38%[16] to 45%[17] of the total rubbish in household garbage bins.

Bearing in mind the impacts of food waste on the waste management industry's overall greenhouse gas emissions (as discussed above), the New South Wales Government[1] released in mid-2021 its Sustainable Materials Strategy 2041 which outlines a strategy to achieve net zero emissions from organics in landfill by 2030. The Strategy mandates all Local Government Areas (LGAs) in NSW (which are responsible for kerbside collection of MSW) to separately collect food organics from the general waste stream by 2030. This means that households will receive an additional bin for the collection of food scraps[18]. Whilst a positive step towards reducing methane emissions from landfill, quantification of the impacts of this strategy on the environment has not yet been conducted. This is confirmed by the findings of the survey outlined in Section 2.

1.4. Treatment facility types

1.4.1. Residual waste

Residual waste is almost exclusively landfilled in Australia. As discussed previously, this is because land is inexpensive, and there are few alternative treatment facilities available. The NSW Department of Planning[19] has confirmed that energy-from-waste alternatives are "new to New South Wales." In other States, Western Australia and Victoria have several waste-to-energy incineration projects for residual waste in either the planning, commissioning, or pre-operational stages. There have been proposals for residual waste to energy facilities in New South Wales[19], some for a number of years, however key members of the NSW Government, and LGAs within Sydney remain opposed to the idea[20]. It is also worth noting that incineration of waste sits lower in the Waste Hierarchy (Figure 1.1) than the recycling/repurposing of waste into other materials, and it is an end-of-life process.

The typical model for metropolitan collection and disposal of residual waste is collection via a 21-tonne lorry, transport to a centralised transfer facility, of which there are a number serving larger cities, and then transport via rail to the final destination (i.e., landfill). Kerbside collection of residual waste occurs every 1 to 2 weeks.

1.4.2. Food & Garden Organics

Hyder Consulting[21] proposes the following seven main processing technologies for organic waste streams (comprising both food organics and garden organics):

- Vermicomposting
- Open windrow composting
- Aerated static pile composting
- In-vessel composting
- Fully enclosed composting

- Anaerobic digestion
- Combustion

Adding to this list, Guo et al.[22] suggest the following technologies and processes used throughout the world:

- Feeding (i.e., for livestock)
- Bioethanol conversion
- Biodiesel conversion
- Integration system-biorefinery

Each technology has its own useful products, including compost, soil, nutrient-rich digestate and biogas, however Figure 1.2 suggests that if one were able to separate general organics into more discrete streams, we may be able to extract greater value from the feed streams and maintain quality of by-products (such as digestate/soil products/compost/etc.). The Figure implies a preference towards treating food waste via the anaerobic digestion technology, which has been confirmed through interviews conducted in the survey as outlined in Section 2, as well as Waste Hierarchy.

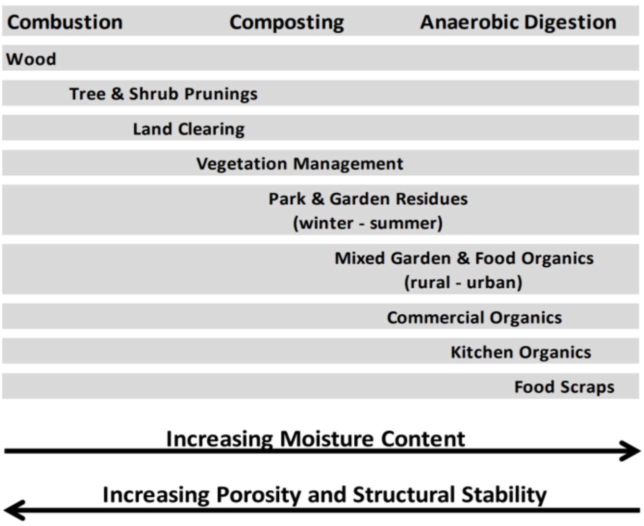

Figure 1.2: Proposed suitable organics types for varying processing technologies relative to moisture content, and porosity and structural stability. From Hyder Consulting[21].

Bernstad & la Cour Jansen[23] assessed four main treatment technologies: incineration, landfill, anaerobic digestion, and compost. These will form the main food waste management technologies compared in the present review, with the exception of incineration as the technology has had little traction in attaining public support in New South Wales[24], and it is expected to continue on this trajectory.

1.4.2.1. Food organics waste

There are a small number of dedicated food organics waste stream treatment facilities in Australia. EarthPower[11] is a Sydney-based facility which anaerobically digests food waste. Whilst the World Biogas Association[25] predicts that there are an estimated 242 digesters operating in Australia, the majority of these are landfill, wastewater, and agricultural plants. As such, the capacity for anaerobic digestion in New South Wales remains small.

A number of initiatives have also been launched in recent years to incentivise households' uptake of worm farms and composting, however the rate of this remains low when considering that around 40% of the residual waste stream is comprised of food organics[15].

1.4.2.2. Garden Organics Waste

In Australia, garden organics is almost exclusively composted or reprocessed into soil products. The Department of Agriculture, Water and the Environment confirms that a substantial quantity of non-core organics wastes is generated and composted[26], with the current national organics recycling rate being 49%. Garden organics are composted in open windrows, which is an effective method of processing large quantities of organic matter, however, is also known to contribute to the release of methane emissions.

2. A Survey of Current Practice in Organics Waste Management in NSW

In order to contextualise the mandates implemented by the NSW Government, a survey of 34 LGAs within Greater Metropolitan Sydney was conducted. The purpose of this survey was to directly engage with key decision makers & managers who oversee municipal solid waste management in each of Sydney's LGAs. Its results enable the forecasting of trends and technology changes required to reach the 2030 net zero emissions from landfill target.

2.1. Survey Design and Method

A series of questions were developed to poll LGAs on their current approaches towards kerbside solid waste management relating to residual, garden organics, and food organics waste streams. These three streams were the focus of the study because it enables a holistic comparison between the business-as-usual scenario (i.e., landfilling residual and food waste streams) and competing strategies for managing food waste (namely whether to combine with garden organics and compost, or to keep separate and process with alternative technologies such as anaerobic digestion). Paper and plastics recycling waste streams were disregarded as their treatment strategies are superfluous to food waste management.

An initial email was sent to councils on 9 July 2021 via their generic public email addresses addressed to the "Manager, Waste, Rubbish & Recycling". The questions asked of each LGA were as follows:

1. Which of the following does your LGA/Council offer?
    a. Garbage/General Waste
    b. Green Waste & Garden Organics
    c. Food Waste
    d. FOGO (Food Organics & Garden Organics)
2. Are you aware of where and how the above waste streams are treated/disposed? If so, are you able to detail this?
3. Has your Council considered a separate waste management strategy for household food waste? If so, are you able to briefly detail work to-date, including any specific numbers, and any future developments?

On 3 August 2021, a follow-up email was sent to those councils who had not yet responded to the 9 July 2021 email. In total, 29 of the 34 LGAs polled responded to the survey, equivalent to a response rate of 85.3%. For those LGAs that did not respond in time to the questionnaire, research was conducted on their websites to assess the collection strategies that they employed.

2.2. Survey Results and Discussion

The results highlight that over 85% (29 of 34) of LGAs in Greater Metropolitan Sydney currently have no management strategy for food waste streams, other than landfilling. This is significant when considered in the context that this will be mandated by 2030. Through further discussions and interviews with representatives from certain LGAs, it appears that a considerable number of current waste management contracts within Sydney are due to expire within the next four years. By 2025 it is predicted that a tipping point will be reached with regard to Local Councils addressing food waste. This prompt need for Councils to understand the best management practices from an environmental perspective contextualises this present body of work.

Figure 2.1 presents a choropleth representation of the current state-of-play within the study area. Table 6.3 in Appendix 6.1 presents all detailed feedback to the survey received from each LGA that responded.

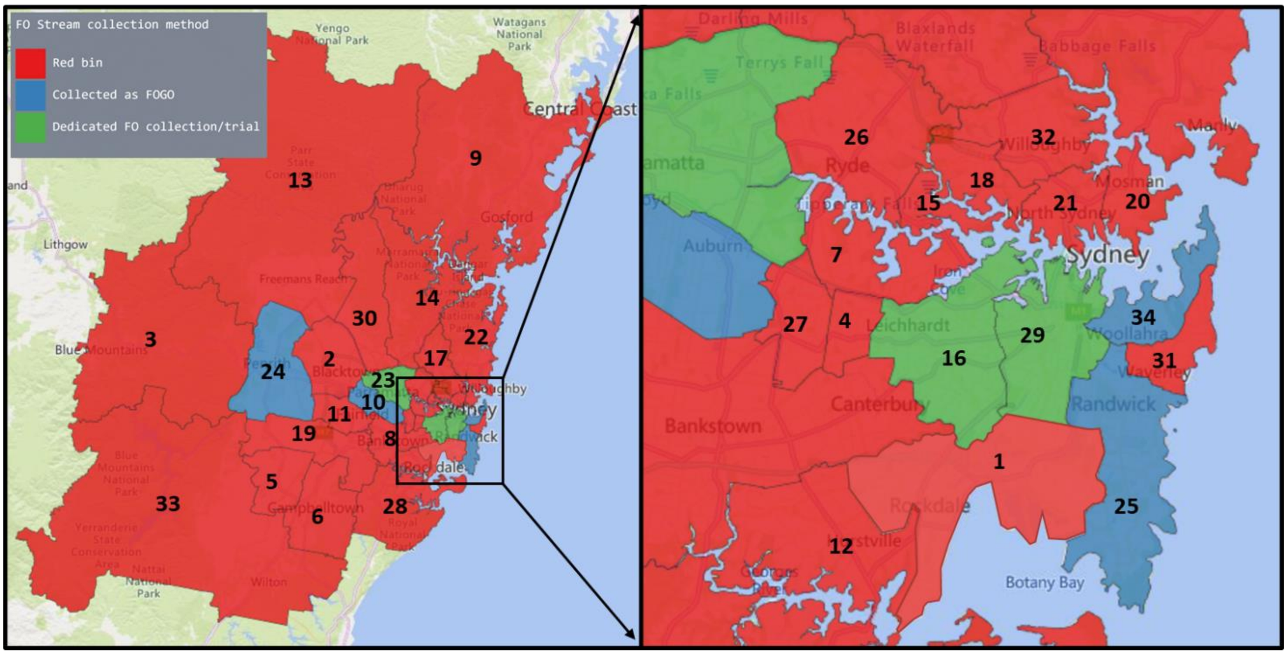

Figure 2.1: Choropleth map of LGAs in Greater Metropolitan Sydney representing current councils' municipal food waste management strategies. For LGAs who did not respond, research was conducted on their websites to assess the collection strategies that they employed. Key: Red = Food waste combined with residual waste and landfilled; Blue = Food waste collected with garden organics (i.e. FOGO); Green = Dedicated food waste stream collection channel (complete roll-out and trials combined). Numbers refer to each LGA as listed in Appendix 6.1.

The survey was a useful measure to efficiently gather data on the various waste treatment contracts that different LGAs have. Importantly, this informs the present study as to the development of a model of the mass flows extant in different waste management strategies. Table 2.1 highlights the trends observed in the survey and subsequent interviewing of certain Waste Management Officers regarding where LGAs in Greater Metropolitan Sydney are sending the majority of their residual, food organics and garden organics waste streams.

Regarding the processing technology for food organics (FO) waste (i.e., not when it is landfilled or combined as FOGO), it is telling that, in spite of the small sample rate of LGAs collecting food waste, only anaerobic digestion is considered. This highlights the well-developed nature of anaerobic digestion of food waste globally. It also suggests that disregarding the economics of kerbside sorting methodology and waste collection, repurposing food waste into biogas and nutrient-rich digestate is preferred as opposed to composting, or another technology. This is a key area that the present study is seeking to address.

Table 2.1: Summary of treatment options employed by Greater Metropolitan Sydney LGAs by waste sorting & collection strategy, based off survey and interviews.

<table>
<tr><th>Waste Stream</th><th>Service providers and treatment facility types</th></tr>
<tr><td>Residual</td><td>Veolia
Kerbside collection and transport to Transfer Stations at Clyde, Greenacre, Banksmeadow, and Port Botany
Transport via rail to Alternate Waste Treatment (i.e., organics recovery & landfill) facility at Woodlawn
SUEZ
Kerbside collection and transport to Transfer Stations at Artarmon, Auburn, Belrose, Rockdale, Ryde, Seven Hills, Spring Farm, Wetherill Park, Eastern Creek and Lucas Heights
Transport to Advanced Resource Recovery Technology (i.e., organics recovery & landfill) facility at Eastern Creek</td></tr>
<tr><td>FO</td><td>EarthPower (by Veolia)
Anaerobic digestion facility at Camelia</td></tr>
<tr><td>FOGO</td><td>Veolia
Kerbside collection and transport to Transfer Stations mentioned above
Transport to open windrow composting facility at Woodlawn
Australian Native Landscapes (ANL)
Kerbside collection and transport to Transfer Station
Transport to Badgerys Creek/Kemps Creek for initial inspection
Transport to composting facility at Blayney
Regroup (Shellharbour)
Kerbside collection and transfer to Shellharbour
Unknown treatment process</td></tr>
<tr><td>GO</td><td>Veolia
Kerbside collection and transport to Transfer Stations mentioned above
Transport to open windrow composting facility at Woodlawn
Australian Native Landscapes (ANL)
Kerbside collection and transport to Transfer Station (Kimbriki being one)
Transport to Badgerys Creek/Kemps Creek for initial inspection
Transport to composting facility at Blayney
SoilCo
Kerbside collection and transport to processing facility at Kembla Grange
SUEZ
Kerbside collection and transport to Organic Resource Recovery Facility or Advanced Resource Recovery Facility at Camden, Eastern Creek, Kemps Creek, Lucas Heights, and Spring Farm for open windrow composting</td></tr>
</table>

3. Literature Review of Food Waste Management Environmental Assessment Methods

The following literature review addresses the current body of knowledge relating to food waste management and the evaluation methods available to compare different kerbside waste collection strategies and treatment technologies. It commences with a review of current environmental assessment frameworks available to assess the competing options available to manage food waste, from which the Life Cycle Assessment (LCA) methodology is identified as a frontrunner. It then develops a set of principles surrounding the LCA framework based of international standards. Finally, it reviews the body of literature surrounding LCA in the food waste management industry.

3.1. Use of analytical frameworks in assessing competing alternatives

The effectiveness of a region's Municipal Solid Waste Management (MSWM) system depends not only on the treatment technologies available, but also the efficiency of kerbside collection of waste from households. A difficulty arising from this is that often the economics of the MSWM strategy dictates decision making, not necessarily the environmental aspects of the competing options. As such, a quantitative analysis of competing waste collection strategies and regimes is beneficial to inform decision makers of the various strategies they can employ. This is a key finding resulting from the Survey conducted in Section 2.

Two competing quantitative assessment tools are commonly used to inform decision and policy makers alike on alternative products, services, or strategies. They are Life Cycle Assessment (LCA) and Environmental Impact Assessment (EIA). Both are standardised practices[27], however their methodologies and application to analysing real-world projects yield quite different results.

Ecochain[27] provide that the goal of an EIA is "to assess the potential impact of policies, programs and projects, usually of public nature." EIAs only consider emissions and effects of the subject matter at the location of the process itself. They also are very limited in their scope in space and time. As such, it is critiqued as neglecting large amounts of upstream and downstream environmental impact[27]. Consequently, EIAs are often overlooked, and have very small influence on the design of projects[28].

LCA provides a more holistic snapshot of a product. It enables greater scope for the forecasting of future trends[29], and considers processes as being interdependent on one another. However, a challenge of LCA being much more technical is that a greater dataset of inputs is required. This means that it a more time-consuming process, and there is a greater reliance on unverifiable data, or data which is incomplete or inconsistent with the scope of the system being studied. Data quality frameworks have been developed to assist with validating the reliability of results in an LCA. This is a positive step towards not only acknowledging data which cannot be directly related to system being studied, but also actively encouraging the discussion of data quality, and the use of more accurate data assumptions where required.

Given LCA's strong track record at providing more quantitative and holistic analyses of differing strategies, the present study will proceed to perform an LCA on competing MSWM strategies specifically relating to the food organics waste stream.

3.2. Methodology of the Life Cycle Assessment framework

This section's aim is to review the current Literature focusing on solid waste management. The goal is to derive an LCA framework upon which the present study will be based.

LCA is an extensively developed and researched tool used to assess a product's environmental impact throughout its lifetime. It is popular due to its standardisation by the International Standards Organisation[30, 31] (ISO). Despite this, there has historically been little consistency in the Literature when applied to MSWM. Further, LCAs on this topic have been focused on comparing waste management technologies, rather than a holistic approach to the waste management system by considering collection schedules for kerbside waste collection. A number of recent studies[32-35], however, have reviewed LCA practices in MSWM with the aim of developing better frameworks for location-specific analysis of SWM.

3.2.1. ISO standards and the LCA assessment framework.

Life Cycle Analysis standards are detailed by the ISO in ISO14040[30] and ISO14044[31]. The ISO recognises LCA's usefulness as a tool to inform decision-makers in industry, government, and non-government organisations of a product's performance at various points in its lifecycle. A framework, based off the ISO standards, has been developed, and is included in Table 3.1. This will serve as the structure that the present study will utilise to assess competing MSWM strategies.

The structure detailed below and summarised in Table 3.1 has been developed from ISO14040[30] and ISO14044[31]. The primary sections critical to a successful LCA are: Goal and Scope Definition, Life Cycle Inventory analysis (LCI), Life Cycle Impact Analysis (LCIA), and interpretation of the results.

The first stage of an LCA, defines the Goal of the study. It includes discussion of the intended application of the results, motivation behind carrying out the study and intended audience for the LCA to be reported to. This is important to ensure that the analysis is contextualised and is relevant to the audience for which it is intended.

The Scoping section of the study requires consideration of the logistics of the LCA problem. This includes decisions surrounding the product system and system boundary, the functional unit of the system, LCIA methodology data requirements (i.e., developing a quality benchmark for a datapoint to be included in the study), and assumptions and limitations of the study. The functional unit is essential to ensuring comparability of the LCA to other results. It should be relatable to the audience and be consistent with its defined scope and goals. The system boundary enables the LCA to be consistently and transparently compared to past and future studies. It is also essential to discuss which unit processes are to be considered in the LCA. It can be helpful when defining the system boundary to illustrate these decisions using a process flow diagram (PFD) or block diagram, illustrating unit processes. The PFD should ideally consider elementary and energy flows which should be based off data. LCIA methodology should be clearly stated, including decisions surrounding impact categories, category indicators, and characterisation models.

The Life Cycle Inventory Analysis (LCI) is the section in the LCA where qualitative and quantitative data is collected. Ideally, this data should be collected through referenced public sources, and should be collected from the exact same system being studied. This is the section where first-hand data collection, if available/possible, should be performed. Each process unit in the LCA should be properly described. Data calculations and manipulations should be clearly stated.

The LCIA stage is where the impact categories, category indicators and characterisation models are stated. Results are considered and related back to the stated goal and scope of the study. For each impact category (i.e., acidification, toxic leeching, the greenhouse effect), indicators help quantify the category being assessed (i.e., change in albedo, ground release of toxic chemicals, H^+ release). Relevant LCI results are then selected to help provide an insight into the impact of the process in the selected impact category. A characterisation model can assist when trying to incorporate multiple

LCI results into the one impact category assessment, for instance if one were to assign NOx and SO2 emissions to a process' acidification potential.

In addition, there are several optional elements that one can add to an LCIA, including normalisation, grouping, weighting, and data quality analysis. These additions can assist in identifying an overall 'winning' strategy/process when comparing multiple processes to one another with LCA.

The final stage, interpretation, is vital to identifying significant results from the LCI and LCIA processes. It checks the results and ensures that they are complete and consistent. A sensitivity analysis or Monte Carlo simulation could also be performed if any of the data sets include ranges, as opposed to quoting discrete numerical results. Finally, this stage should highlight limitations and recommendations, and then conclude the results with the major findings.

Table 3.1: LCA Assessment Framework adapted from ISO14044[31].

Section	Subsection
Goal of the study	
	Motivation for study
	Intended use/s of study
	Target audience
Scope of the study	
	Definition of functional unit
	Definition of system boundary and product system
Life cycle inventory analysis	
	Data collection methodology included
	Qualitative and quantitative description of unit processes
	Data sources mentioned
	Any additional calculations shown
	Validation of data (i.e., quality assessment)
	Sensitivity analysis variables considered
Life cycle impact assessment	
	LCIA procedures, calculations and results shown
	Limitations of LCIA results considered
	LCIA results related to defined goal & scope
	Impact categories & category indicators considered
	Analysis of indicator results, for example sensitivity analysis
Life cycle interpretation	
	Results clearly stated
	Assumptions & limitations associated with methodology & data discussed
	Value-choices, rationales & expert judgements stated

3.3. Approaches to LCAs of the food waste management industry

Bernstad & la Cour Jansen's[23] foundational review of LCAs of food waste management systems highlighted the literature's focus on comparing treatment alternatives including landfill, thermal treatment, compost (small and large scale) and anaerobic digestion. A key trend observed was that system boundaries often vary largely from study to study. The definition of the system boundary is critical to ensuring the validity and comparability of results. This finding is confirmed by Laurent et al.[36] and more recently by Bernstad Saravia Schott et al.[37] who identify differences in methodological approach, and choices in system boundary settings as being the main factors contributing to misleading comparisons between treatment options, and uncertainty in results of LCAs. It is noteworthy that collection schedule and the impact of choosing between different collection patterns and treatment options is not identified as a major point of consideration by the literature. It is suggested that this is due to the Literature's focus on theoretical comparison between alternative treatment technologies, without consideration of the impact that such choices have on net emissions of the collection and treatment of kerbside household waste.

The scope of Lundie & Peters'[38] LCA into food waste management options is similar to the present investigation. The functional unit is defined as "management of the food waste produced by a Sydney household in one year", and its system boundary considers a range of treatment alternatives for the food waste stream: home composting, centralised composting of food & garden organics, or codisposal of food waste with residual waste. However, whilst the study does consider the impact of manufacture of bins, it does not consider the impact of changing from the present collection scenario (i.e., where households already typically have bins already issued to them), and the potential need for issuing only an additional bin in the case of separate collection of food waste. In addition, it neglects alternative technologies such as anaerobic digestion.

The need for a more holistic approach and expansion of system boundary is reiterated by Bernstad Saravia Schott et al.[37] who provide "further system boundary expansion… will have, by far, a large importance to the net GWP… and should be investigated further." The importance is also highlighted for "increased coherence in the carbon mass-balance over the food waste treatment system in order to guarantee systems equivalence between compared scenarios." Additionally, it is noted that the "use of sensitivity analyses related to assumptions made in background system modelling would increase the relevance of results gained in future life-cycle assessments of food waste management."

Thus, the literature has identified a number of key requirements that should be considered in future studies:

- Expansion of the system boundary to more accurately model the carbon mass-balance throughout the system.
- Incorporation of sensitivity analyses to relate alternatives to one another more holistically.
- Ensuring the LCA methodology follows ISO standards accurately.
- Increased transparency in assumptions made during the LCA.

A more thorough review of the literature has been performed and is presented in the following sections. The intention of this review is to guide the development of the specific scope and boundary of the present investigation.

3.3.1. Trends within system boundary and functional unit definition

A review of the literature was conducted to better understand trends relating to system boundary definition and functional unit specification. The definition of an LCA's system boundary is vital to its long-term relevance and comparability with other studies[37]. Thus, it was deemed necessary to investigate past attempts at modelling the waste collection and treatment process for kerbside municipal waste. A search was conducted to source literature which compared alternative waste treatment technologies (not necessarily just for food waste streams) and provided a diagrammatic representation of the selected system boundary. A number of these papers are discussed below.

3.3.1.1. Functional unit definition

The functional unit is a simple, yet simultaneously complex parameter to consider, and it is important to not be confused by the fact that results from the LCA can be scaled up or down to be compared to other studies and scenarios as appropriate. The reason for this is that definition of the functional unit should be made within the context of the system boundary. This is to say that whilst a study might consider a geographic region in its system boundary, if it considers one unit of waste (i.e., one tonne, or one bin's worth), inherently, assumptions are made about that one sub-component of the system representing the whole which is difficult to model, but also inherently considers the broader system as the 'functional unit' and merely scales the impact of that unit down defined functional unit for the sake of performing the analysis. Notwithstanding, it has been previously established that the literature tends to prefer one tonne (i.e., 1 Mg) of waste as the final comparative functional unit in LCAs of the waste management industry [39-43].

3.3.1.2. System boundary definition

Definition of the system boundary layer for an LCA is a complicated process[44, 45], requiring consideration of environmental, technical, geographical and temporal dimensions. Li et al.'s[44] study provides a general framework to assist with system boundary identification.

The Department of Environment, Climate Change and Water NSW[46] conducted a holistic study of Australia's recycling industry, considering a number of different sources including kerbside waste collection. Its system boundary is presented in Figure 3.1. The investigation's primary focus is on validating the environmental benefits and impacts of recycling waste materials. Its system boundary is a strong step in the right direction, however newer technologies, such as those discussed in Section 1.4 were ruled out of scope. This is a missed opportunity for the study and presents an opportunity for this gap to be filled.

The LCA conducted by Carre et al.[47] provides another strong example of system boundary definition, as presented in Figure 3.2. However, again, the focus of this study is on the dry recycling industry (i.e., paper and plastics), not MSW. Its approach to comparing the amount that recycled products offset the need for virgin production is a strong step towards realising the true environmental impact of waste management processes which produce useful by-products that can be on-sold and offset other products.

It is also noteworthy to mention Carre et al.'s[47] modelling of the collection system which, arguably, is one of the more difficult sections of the modelling as it requires either highly detailed modelling of individual waste collection lorries' routes specifically within the same regional context as the LCA, or else a number of assumptions must be made. The approach pursued in this circumstance models waste collection time as the independent variable. This can be a troublesome metric to utilise as the time of one vehicle's waste collection schedule could vary depending on the location and time of day at which the service is being run. Nonetheless, with appropriate sensitivity modelling, it would be fair to assume that the system models reality relatively accurately.

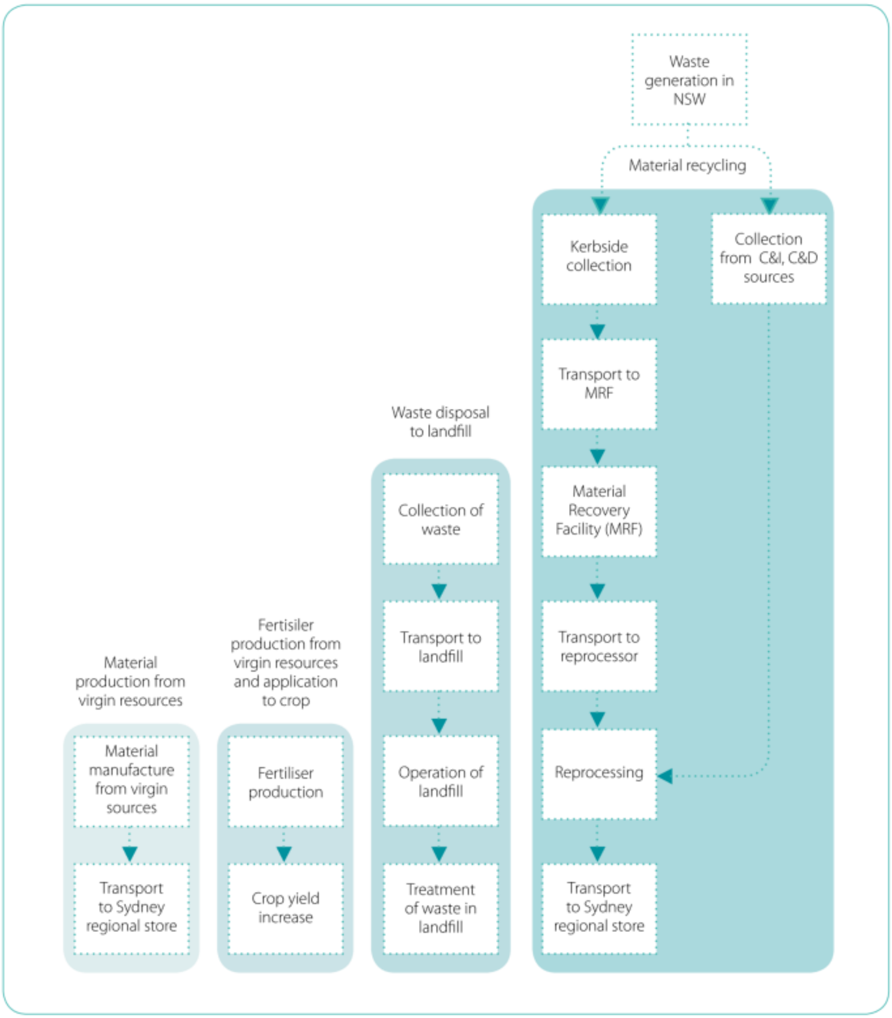

Figure 3.1: System boundary as defined by the Department of Environment, Climate Change and Water NSW[46].

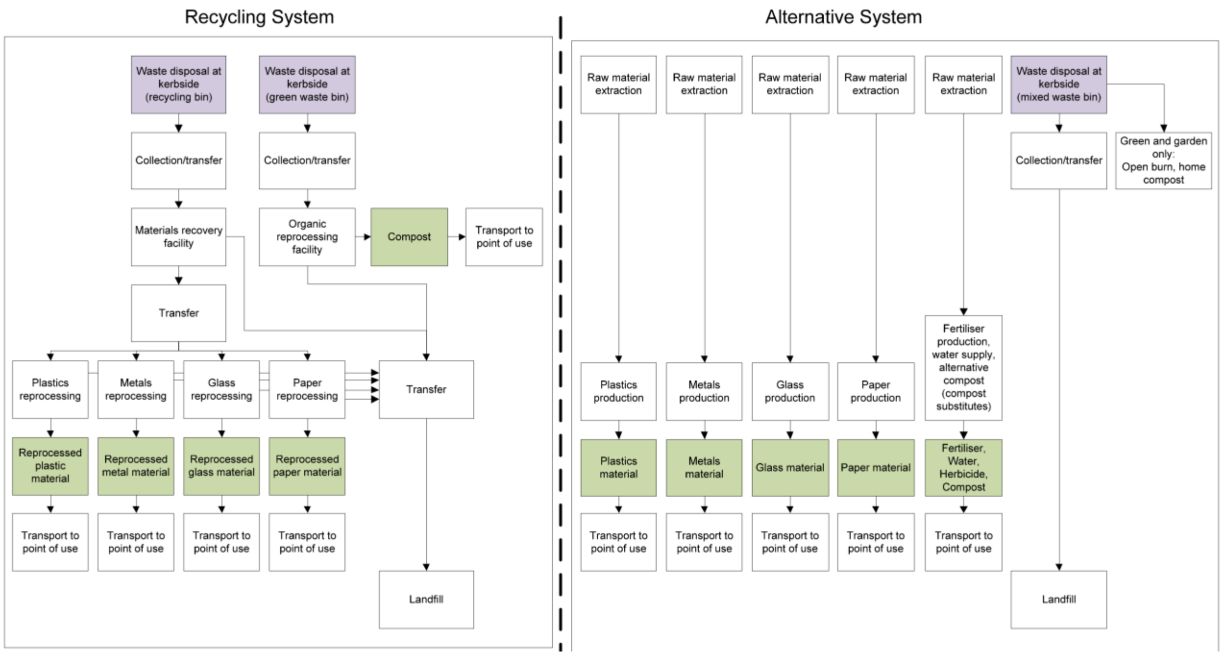

Figure 3.2: System boundary as defined by Carre et al.[47].

Ahamed et al.'s[48] LCA specifically considers varying food waste management technologies, and is an example of studies which more specifically look at competing technologies rather than the holistic waste collection picture. This a good study to consider as it sets a foundational understanding of the major emissions considerations for anaerobic digestion facilities. A difficulty associated with this study, however, is the lack of transparency surrounding the collection modelling process.

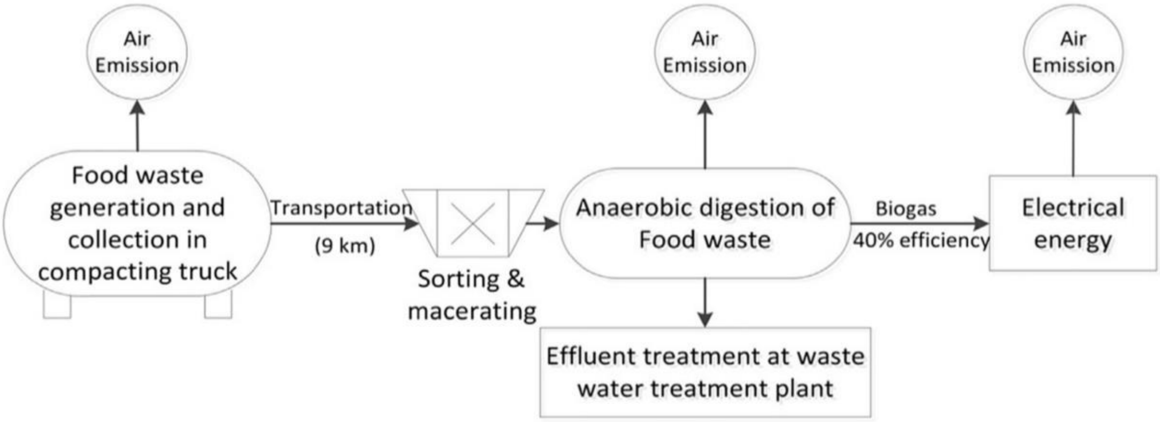

Figure 3.3: System boundary of Ahamed et al.'s[48] anaerobic digestion waste treatment stream.

Maalouf & El-Fadel's[49] LCA is the final system boundary considered in-depth. The study considers collection within its system boundary, and models anaerobic digestion of organic fractions of municipal solid waste. However, there is again little transparency with regard to the methodology followed in modelling this stage of the waste treatment process.

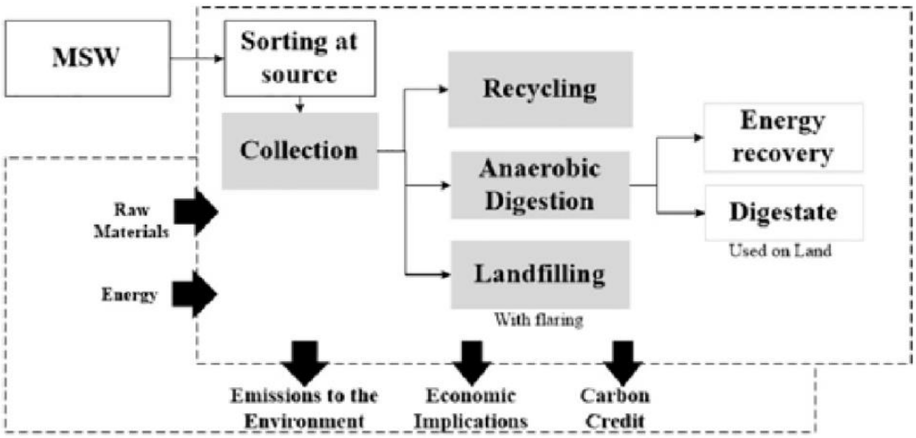

Figure 3.4: System boundary presented in Maalouf & El-Fadel's[49] LCA of solid waste management in Lebanon for

A major insight from the analysis of system boundary alone is that there tends to be little consideration in the literature for the impact that varying waste collection schedules have on the viability of different bin service combinations. This demonstrates that whilst the literature acknowledges that a significant part of the waste treatment process is its initial at-source collection, little attention has been directed towards appropriately considering the ramifications of different collection regimes (i.e., the need for weekly or fortnightly collection depending on bin capacity and chemical/biological stability of that particular waste stream.

3.4. Conclusions from the Literature Review

This review has presented the alternative assessment frameworks available for quantitatively comparing different attitudes towards assessing competing strategies. The result of this was the decision to progress with a life cycle assessment of differing MSWM strategies. The methodology of life cycle assessment was then presented, based off ISO standards.

Next, competing methodologies and approaches in the literature towards LCA of MSWM were identified and learnings to help shape the present study were drawn from this process. It has been useful to gain a greater insight into both previous work in the field, as well as to help define the present study. In the LCI stage of the LCA, it is expected that additional sources will be used to obtain estimates of key parameters such as inputs and outputs for a process, or to help define the functional unit proportional to the steady state production of different waste streams.

4. Life Cycle Assessment of Three Food Waste Management Scenarios in NSW

This section forms the body of the Thesis. It has been designed to rigorously adhere to the ISO standards for Life Cycle Assessment[30, 31], as summarised in Table 3.1, and as such does not necessarily follow traditional report formatting. Sections 4.1, 4.2 and 4.3 constitute a traditional Methodology, whilst Sections 4.4 and 4.5 are more appropriate to stand as Results and Discussion. Given that the LCA process is iterative, it is important to understand that whilst this report is presented in a linear fashion, each section is interdependent on one another.

4.1. Goal

4.1.1. Intended application

The present study sets out to address optimal sorting and collection strategies for kerbside waste, with a particular focus on achieving net zero emissions from landfill by addressing the food organics waste stream. The study will focus on the jurisdiction of Greater Metropolitan Sydney (GMS), Australia, and the functional unit will be the yearly production of combined residual, food organics, and garden organics waste streams, proportional to their steady-state production in GMS. It also intends to validate current policy directions, namely that reductions in emissions from landfill can be achieved through diversion of food waste.

4.1.2. Rationale behind the study

This study is time sensitive due to the New South Wales Government's NSW Waste and Sustainable Materials Strategy 2041 (the Strategy) which was released in June 2021. The Strategy mandates net zero emissions of carbon from organics in landfill by 2030 and encourages Local Government Areas (LGAs) (i.e., local Councils) to separate the food organics waste stream from residual waste by this time.

A review of the literature[50] (Section 3) and interviews with key decision makers within some Sydney LGAs' Waste Management Departments (Section 2) has revealed that there is confusion and little evidence supporting the competing kerbside waste sorting strategies. Mostly driven by the economics of competing processes, LGAs are impervious to the environmental choices that they are making through deciding on a collection strategy. The present study intends to model current and future collection strategies through LCA.

4.1.3. Intended audience

The audience intended for the present study, therefore, is key decision makers in both LGA Waste Management Departments, as well as for those in relevant State agencies, and other bodies interested in the subject matter.

4.1.4. Intended use of results

The results of this LCA are intended to be used by decision-making authorities in LGAs within Greater Metropolitan Sydney, other bodies interested in the subject matter, as well as for similar organisations in other jurisdictions as appropriate. It is intended that these results will help to catalyse a number of future studies into food waste management in Sydney and NSW.

4.2. Scope

4.2.1. Product system

The major processes and systems to be considered in the present study (i.e., the differing collection strategies) have been modelled off present and emerging technologies available within the jurisdiction of New South Wales, as well as considering the waste hierarchy. Therefore, the different waste collection and treatment methods outlined in Table 4.1 have been selected for the present investigation.

Table 4.1: Bin lid colour combinations & treatment methods under each scenario considered.

Scenario	**Scenario 0 (i.e., base case, or business-as-usual)**		**Scenario 1**		**Scenario 2**		
Bin Lid Colour	Red	Green	Red	Green	Red	Green	Burgundy
Contents	Residual + FO	GO	Residual	FO + GO	Residual	GO	FO
Destination	Landfill	Open windrow composting	Landfill	Open windrow composting	Landfill	Open windrow composting	Anaerobic digestion

The main processes considered within each collection & treatment system above are:

- Landfill & open windrow composting models
    - Collection of bin's contents from kerbside and transport to transfer facility
    - Processing at transfer facility
    - Transport from transfer facility to treatment facility
    - Processing at treatment facility
- Anaerobic digestion model
    - Collection of bin's contents from kerbside and transport to AD facility
    - Processing at AD facility

4.2.2. Functional unit

The functional unit has been defined as the yearly steady-state production of residual, food organics, and garden organics waste streams discarded at kerbside within Greater Metropolitan Sydney. The Environment Protection Authority[51] regularly reports on waste and resource recovery data within NSW. The Appendix to the NSW Local Government Waste and Resource Recovery Data Report 2018–19[52] provides a high level of detail about LGA-by-LGA kerbside waste collection statistics, by waste stream. It enables the functional unit to be accurately defined in such a manner. The Report details the yearly kerbside collection of residual waste in Greater Metropolitan Sydney to be 1,055,090 tonnes in 2018-19, and of garden organics to be 267,585 tonnes. Rawtec's[17] report for the Environment Protection Authority analyses audit data of kerbside red lid bins in NSW. It details the average composition of food waste in residual waste streams is 45%. Accordingly, the breakdown of residual waste collected in Greater Metropolitan Sydney has been assumed to be 44% residual, 36% food organics, and 20% garden organics.

In order to correspond to the typical functional unit used in the Literature of 1 Mg waste, the yearly steady-state production value will be normalised to one tonne, equivalent to 439 kg residual, 359 kg food organics, and 202 kg garden organics. This is consistent with past approaches as identified in Section 3.3.1.1.

4.2.3. System boundary

Definition of the system boundary was conducted to incorporate the main findings the Literature Review. Figure 4.1 shows the system boundary which considers the inputs of residual, food organics and garden organics waste streams, and the outputs of compost, digestate and biogas from each process. Note that other inputs such as energy, infrastructure, water supply and diesel have not been shown for simplicity of the model.

4.2.4. Allocation procedures

Allocation in LCA relates to attributing elemental flows to & from the process to impacts on the environment. This means that elemental flows are aggregated into broader categories such as global warming potential, acidification potential, and land and water use, and converts these impacts into a grouped, quantifiable metric. For instance, it is well known that not only does carbon dioxide contribute to global warming, but so too do methane and water vapour emissions. The measured units, therefore, of global warming potential, one of the common indicators to consider in-depth in LCAs, is kg CO2 eq. This unit factors in the varying greenhouse potential of the different elemental flows and relates them to a single parameter.

There is a broad range of impact categories and LCIA methods available. Dastjerdi et al.[40] investigated a number of LCIAs and found that the popular ones used in the literature are CML, IPCC, and ReCiPe. CML and IPCC tend to narrow their focus on a small number of impact categories, whereas ReCiPe considers a broad range of impact categories. In order to more holistically compare the different scenarios, it was decided to proceed with the ReCiPe Midpoint (H) method of impact category selection.

A further level of detail provided by the ReCiPe LCIA method is the ability to adjust cultural perspective, which is equivalent to the timeframe within which impacts are considered. The three perspectives are Individualise (I), Hierarchist (H), and Egalitarian (E). Sphera[53] provides the following definitions of the three perspectives:

- "Individualist (I) is based on the short-term interest, impact types that are undisputed, technological optimism as regards to human adaptation. Uses the shortest time frame e.g., a 20-year timeframe for global warming, GWP20
- "Hierarchist (H) is based on the most common policy principles with regards to time-frame and other issues. Uses the medium time frame e.g., a 100-year timeframe for global warming, GWP100
- "Egalitarian (E) is the most precautionary perspective, taking into account the longest time-frame, impact types that are not yet fully established but for which some indication is available, etc. Uses the longest time frame e.g., a 1000-year timeframe for global warming, (GWP1000) and infinite time for ozone depletion (ODPInf)"

As the above points provide, the ReCiPe midpoint (H) method is based off common policy principles. This is a factor that contributes to its popular use in the literature[40]. As such, this LCIA method will be used in the present study since it provides a greater level of insight into the relative performance between scenarios.

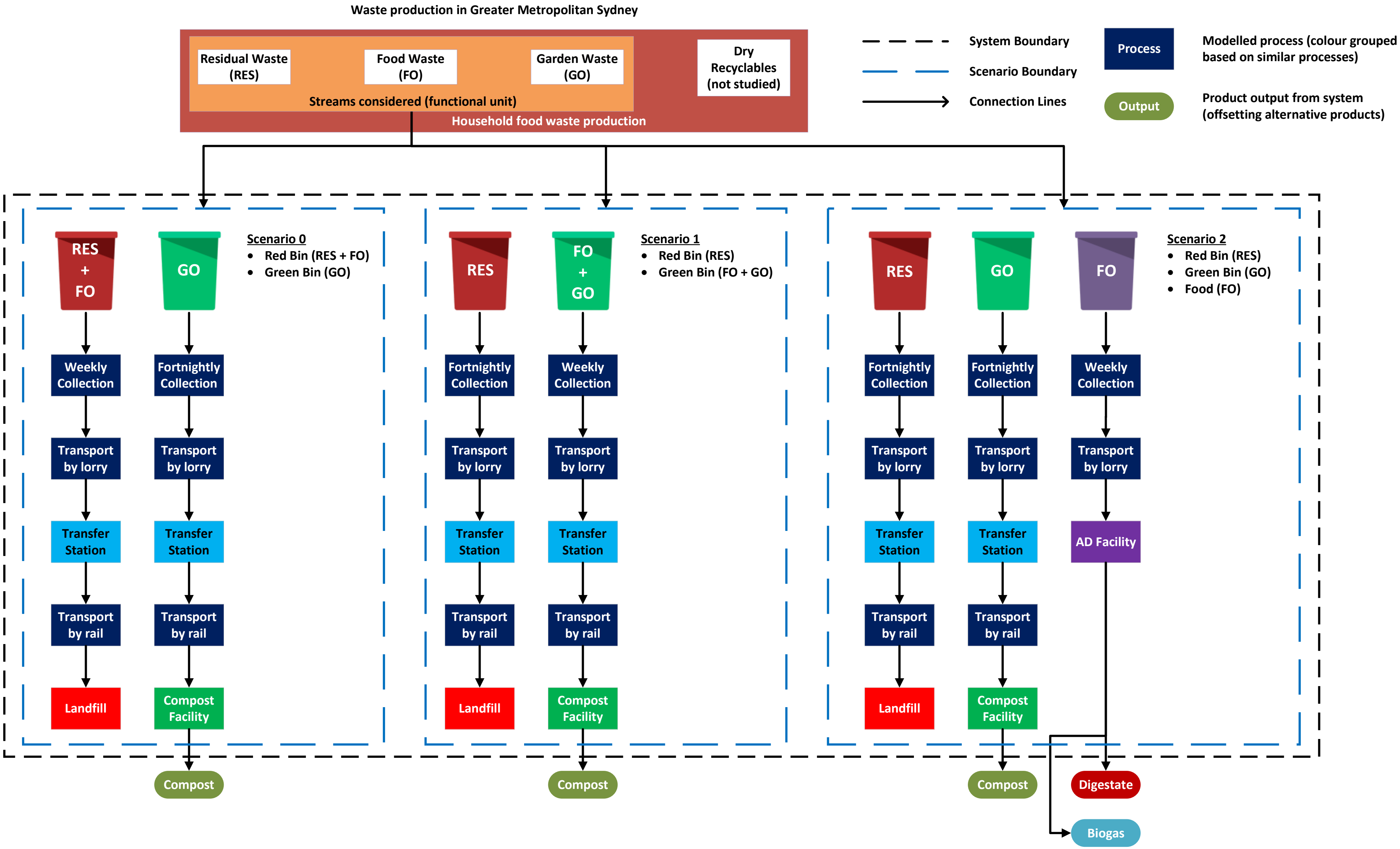

Figure 4.1: System boundary of the study.

4.2.5. Impact category selection

Within ReCiPe, there are both midpoint and endpoint categories which correlate to environmental impacts (i.e. increased chemical concentration in a lake) and environmental damages (i.e. extinction of species), respectively[54]. PRé Sustainability[54] suggests that endpoint analysis provides a higher-level understanding of the comparison between scenarios, whilst midpoint enables greater insight into the trade-offs that different scenarios might display between impact categories. Figure 4.2 visually represents the distinction between the two methods.

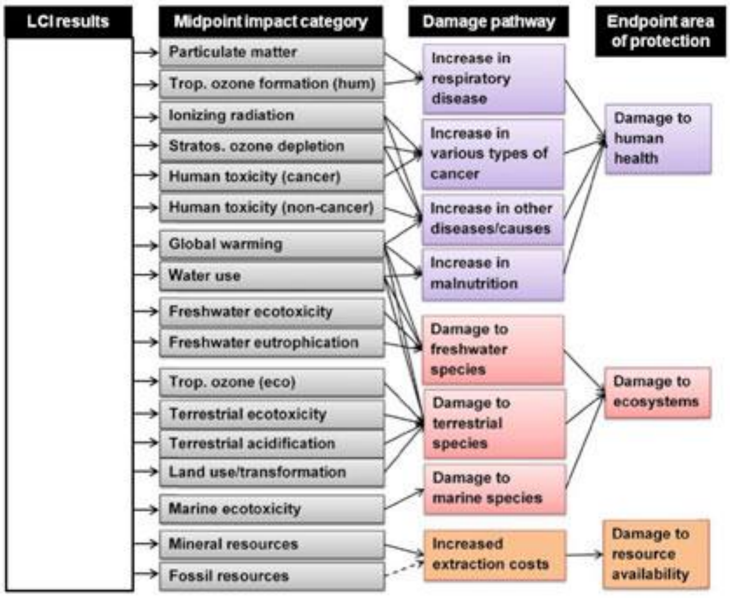

Figure 4.2: Overview of ReCiPe midpoint/endpoint LCIA structure (from SimaPro[55]).

Refer to Table 6.1 in Appendix 6.1 for a list of all impact categories considered in the study, as well as providing a description about each indicator's benchmark values.

4.2.6. Data requirements

This study intends to quantify the performance of the two proposed scenarios against the business-as-usual scenario for Greater Metropolitan Sydney. Whilst the system boundary has been designed to holistically consider the waste collection and treatment system within this region, it is worth noting that subsystems of these scenarios, for instance the anaerobic digestion facility, would be worth considering through detailed LCA studies in their own right[47]. Consequentially, this study relies significantly on secondary data sources such as other LCA studies of subprocesses, and other reporting material.

The Data Quality Systems (DQS) are frequently used in LCA software packages to assess the quality of data output from the life cycle inventory (LCI) stage[56]. One such provider of a DQS is Ecoinvent[57], whose pedigree matrix approach[58] assesses data sources based on reliability, completeness, temporal correlation, geographical correlation and further technological correlation. Ecoinvent's DQS has been found to perform well compared to other commercial data quality management tools[59], and given that there is access to the Ecoinvent 3.6 package, it was decided to utilise this DQS in the study.

4.2.7. Limitations

Given that the ability to collect primary data (i.e., from laboratory analysis, field trips, etc.) is difficult to undertake as a result of the University's current COVID-19 policies, the study will rely heavily on secondary data. As such, the study is limited to the assumptions taken when deciding whether to incorporate one study's findings or not in the LCI stage of the study.

4.3. Life Cycle Inventory Analysis (LCI)

Each individual process within the system boundary outlined in Figure 4.1 was studied in detail and a number of secondary data sources were used to create an inventory of flows. For ease of this process, the freeware openLCA was used to collate and analyse results. The Ecoinvent 3.6 database was the primary source of secondary data used in the study. This was based off a previous review of the literature which indicated that it is one of the most used databases by LCA studies[33]. The core processes for each bin lid type considered by the inventory are described below. They have been developed based off findings of the typical model for each type of waste stream collection method available in Greater Metropolitan Sydney. Refer to the Literature Review (Section 1.2) for additional information.

Red Lid bin

The primary objective of the Red Lid bin is to model landfilling of its contents. The following processes involved in this are:

> **Collection and transport** – operation of 21 tonne[60] garbage collection vehicles to collect bins and transport waste materials to intermediate processing facility.
>
> **Processing at local transfer facility** – operating of local transfer facility including bulk movement of materials into rail transport. Energy requirements for this facility are of particular interest, in the form of electricity and diesel consumption.
>
> **Transport to regional treatment facility (landfill)** – transport by heavy rail to treatment facility.
>
> **Processing at treatment facility (landfilling)** – landfilling of all material and associated elemental flows into environment. Electricity and diesel account for the main components consumed through this process.

Green Lid bin

The primary objective of the Green Lid bin is to model open windrow composting of its contents. The following processes involved in this are:

> **Collection and transport** – see Red Lid bin's corresponding stage.
>
> **Processing at local transfer facility** – see Red Lid bin's corresponding stage.
>
> **Transport to regional treatment facility** – see Red Lid bin's corresponding stage.
>
> **Processing at treatment facility (open windrow composting)** – mechanical processing and composting of material. Considers both elemental emissions resulting from the process and the offset of new products resulting from the production of useful products such as topsoils and composts. Energy requirements in the form of diesel and electricity are the main types considered.

Burgundy Lid bin

The final bin lid colour modelled is the Burgundy Lid bin, which is designed to model the anaerobic digestion of its contents. The processes involved in this are:

> **Collection & transport** – operation of 21 tonne[60] garbage collection vehicles to collect bins and transport waste materials to final processing facility.

Processing at treatment facility (anaerobic digestion) – mechanical and biological processing of material. Includes electricity costs for a broad number of components of the plant, and other machinery and process requirements. Additionally, the production of useful gasses, sludges and other products are considered to offset the production of virgin materials otherwise required for the process.

Each sub-system described above is discussed in further details in Section 4.3.1.

4.3.1. Inventory sub-systems

4.3.1.1. Collection

The majority of waste in Greater Metropolitan Sydney is collected by 21-tonne front-, back- or side-loading trucks. This type of collection vehicle is modelled in the Ecoinvent database requiring the input units of distance-mass ($t \times km$). The benefit of using a pre-existing Ecoinvent model is that a broad range of environmental impacts are already factored into the parameter. Therefore, a model was developed to simulate the different waste collection patterns for each waste type, based off the mass and volume each truck could collect, and therefore the number of households it could service, before it reaches capacity and is required to return to the intermediary facility to empty its contents.

The distance-mass requirements for each waste combination type studied is detailed in Table 4.2

Table 4.2: Distance-mass inputs used in the Collection sub-system. Refer Appendix 6.4 for methodology and calculations.

Waste type combination	Distance-mass, normalised to 1 tonne, t km
Residual	21.7
Residual + Food Organics	14.7
Food Organics	6.7
Food Organics + Garden Organics	7.0
Garden Organics	8.3

The distance-mass calculations are sensitive to a number of input parameters; however, the most important factor is density of the material being collected. This is because this directly correlates to how full a truck can get before it reaches its capacity. It is for this reason that denser waste streams such as residual and residual + food organics incur a higher distance-mass requirement, compared to more the denser food organics, garden organics and food organics + garden organics.

The model assumes both a fixed component to distance-mass calculations, as well as a variable component which depends on the number of households being serviced by a collection vehicle. These variables correlate to the net distance between the transfer station and the collection area, and an assumed average distance between each household. Refer to Appendix 6.4 for further information on the development of this model, and associated calculations.

Whilst the development of this model is based on a number of key assumptions, it is anticipated that the collection processes will only account for a small amount of each Scenario's overall contribution to key indicators. This assumption will be validated in Section 4.4.2.

4.3.1.2. Processing at local transfer facility

The main purpose of the local transfer facility is to collect and sort waste, and then to load it on to a freight train for bulk transport to the regional treatment facility. As such the main inputs to this process are electricity and heavy material-moving machinery. Andersen et al. [61] modelled an open windrow composting facility, and accounted for fuel and electricity use based off a range of machinery requirements. Of particular interest to the present study is the analysis of diesel consumption attributable to turning and machinery operation, and electricity use due to general plant illumination, and use in administration buildings. It has been assumed that the consumption of both energy sources per unit mass of waste processed by the facility is relatively equivalent, irrespective of the type of waste stream that the facility processes. As such, Table 4.3 presents the parameters per tonne of waste processed, for facilities in the circumstances of both residual, residual + food, food organics + garden organics and garden organics transfer stations.

Table 4.3: Inputs to the transfer facility.

Input	Consumption	Units
Diesel	1.54	L $tonne^{-1}$
Electricity	0.2	kWh $tonne^{-1}$

4.3.1.3. Transport via rail to regional processing facility

The Survey of LGAs (Section 2) revealed that in Greater Metropolitan Sydney, once waste was processed at the transfer facility, it was transported via heavy rail to the final processing facility. In Sydney, there is one facility each servicing landfill and open windrow composting, with the former located in Woodlawn, and the latter located in Blayney. Table 4.4 presents the assumed distances between Sydney and each of the facilities that have been used to model the distance-mass of heavy rail transport of waste.

Table 4.4: Assumed distances from Sydney transfer facilities to the Red and Green bin processing facilities.

Facility	Assumed distance from Sydney to facility (km)
Landfill at Woodlawn	230
Composting facility at Blayney	230

An identical process to that outlined in Section 4.3.1.1 and Appendix 6.4 was followed to determine the input parameters for this process, which are described in Table 4.5.

Table 4.5: Distance-mass inputs used in the rail transport sub-system. Refer Appendix 6.5 for methodology and calculations.

Waste type combination	Distance-mass, normalised to 1 tonne, t km
Residual	1.7
Residual + Food Organics	1.1
Food Organics + Garden Organics	0.5
Garden Organics	0.6

4.3.1.4. Final processing at treatment facilities

It is said that many sub-systems within more holistic LCAs of broader industries require LCAs in their own right. This is certainly the case when considering the final stage of each bin lid combination for the present study. This fact is due to each process' complicated and immense number of inputs and outputs. As such, for the present LCA, past mass balances and LCI stages of other studies, and pre-existing datasets on the Ecoinvent database were used.

4.3.1.4.1. Landfill

A literature search was conducted to obtain a mass balance/inventory analysis of landfilling with waste streams of different compositions (i.e., residual and residual + food organics), however few studies relevant to the Australian context were retrieved. A geographic correlation, and comparability between waste types treated is important, therefore searches for LCAs from similarly-developed regions was also conducted, including Europe and North America. A comparative study of an open-cut landfill (those that proliferate in Australia) accepting residual versus residual + food organics waste streams could not be sourced. Accordingly, the same mass flow conditions have been assumed for both potential compositions of the Red Lid Bin. For ease of developing the openLCA model, it was decided to proceed with modelling this stage of the process off a pre-existing flow in Ecoinvent called "municipal solid waste", in the circumstance where food organics is present (i.e., Scenario 0), and "inert waste, for final disposal" in the circumstance where only residual waste is sent to landfill (i.e., Scenarios 1 & 2).

This is not ideal; however, it still provides valuable insight into land use characteristics, and other factors consumed in operating a landfill including mechanical machinery, etc.

4.3.1.4.2. Open windrow composting

Andersen et al.[61] modelled a garden waste windrow composting plant in Aarhus, Denmark. The study comprehensively details a range of inputs and outputs for the process. Whilst Denmark has a cooler climate that Sydney, its garden waste characteristics are similar, and it is appropriate to approximate an Australian open windrow garden waste composting facility with that considered in this study. As such, the mass flows detailed in Table 4.6 will be input to the simulation.

Table 4.6: Inventory of main inputs and outputs for garden organics open windrow composting. From Andersen et al.[61].

Main Inputs		Main Outputs	
Garden waste	1 tonne	Compost	649 kg
Diesel for machinery	3.04	N_2O	0.05 kg
Electricity	0.2 kWh	CH_4	1.9 kg
		CO_2	86 kg
		CO	0.12 kg

It proved more difficult to source credible LCIs/mass balances of a FOGO open windrow composting facility. It is presumed that especially methane emissions would be greater, however it is difficult to quantify this effect without appropriate measurements. As such, the inventory described in Table 4.6 was also used to describe open windrow composting of FOGO.

4.3.1.4.3. Anaerobic digestion

Opatokun et al.[62] conducted an LCA on a number of competing food waste treatment processes, including anaerobic digestion. Data was collected from "a functional industrial one-stage anaerobic digestion food waste treatment plant in Sydney, laboratory tests, methods, and analysis of samples." Given that this data was taken from a facility situated within the area being studied, it was decided that results from this LCI would accurately reflect a current mass balance of the system. Therefore, the main inputs and outputs of this process were used in the present LCA. Table 4.7 details these parameters.

Table 4.7: Inventory of main inputs and outputs for anaerobic digestion. From Opatokun et al.[62].

Main Inputs		Main Outputs	
Food waste	1 kg	Electricity from biogas	0.240 kWh
Water	0.569 kg	Heat	0.369 kWh
Electricity	0.008 kWh	Organic fertiliser	0.030 kg
Caustic soda	0.005 kg		

4.3.2. Other assumed inputs to the LCA

A number of additional assumed inputs to the LCA were made either due to ease of development of modelling, or else due to the fact that there was little evidence in the Literature of such systems. As such, Table 4.8 details the additional assumptions and the justification behind each assumed input's inclusion in the LCI.

Table 4.8: List of additional assumed inputs to the LCI and rationales behind their selection.

Assumption	Rationale
At-source sorting • **Households are assumed to have the necessary infrastructure (i.e., caddy bins, bin liner bags, etc.). Such inputs have not been included in this study.**	A literature search for a life cycle inventory of the issue of a new bin to households returned few relevant results, none of which were reliable.
Issue of new Food Waste bin for Scenario 2 ignored • **The issuance of a new food waste bin to every household has been ignored**	Past LCAs of waste management processes did not focus on the need to supply & replace garbage bins as needed. It was felt, though, that this would be useful especially in Scenario 2 to reflect the need for an additional bin. However, it was difficult to source a reliable LCA or similar study that clearly specified inputs to the manufacture & delivery of such a bin, and as such it was decided to exclude this from the System Boundary.
Truck transportation from train station at treatment facility to facility gate ignored	There is a relatively short transfer distance between the rail offloading facility at Woodlawn to the landfill. This is facilitated by large trucks, however, has been ignored in the present modelling as this relatively short transfer distance is deemed to have little impact on the overall impact of the scenario.
100% participation in food waste diversion	Due to lack of data to indicate otherwise, the LCA assumes that 100% of food waste disposed of by households is diverted to the correct bin for treatment.

4.4. Life Cycle Impact Assessment (LCIA)

4.4.1. Summary Results

This section describes the results of the life cycle impact assessment for the assumed functional unit of 1 Mg combined residual, food organics, and garden organics in proportion to their steady state production. As discussed in Section 4.2.4, the ReCiPe 2016 Midpoint (H) assessment method has been used to aid the LCIA for this study. Table 4.9 presents the impact category results for each of the three scenarios. It is advised to refer to Section 4.5.3 for further discussion of the quality of these results.

Table 4.9: Impact category results for each scenario.

Impact Category	Scenarios			Reference unit
	0	1	2	
Fine particulate matter formation	0.10	0.04	-0.08	kg PM2.5 eq
Fossil resource scarcity	14.49	8.82	5.80	kg oil eq
Freshwater ecotoxicity	328.1	0.18	-0.60	kg 1,4-DCB
Freshwater eutrophication	3.29E-02	8.25E-04	-3.20E-03	kg P eq
Global warming	797.4	129.6	22.49	kg CO2 eq
Human carcinogenic toxicity	16.16	0.28	-0.35	kg 1,4-DCB
Human non-carcinogenic toxicity	7070	3.83	-44.12	kg 1,4-DCB
Ionizing radiation	1.06	0.30	-0.50	kBq Co-60 eq
Land use	1.59	0.46	-8.21	m2a crop eq
Marine ecotoxicity	431.2	0.27	-0.79	kg 1,4-DCB
Marine eutrophication	0.27	0.00	-0.02	kg N eq
Mineral resource scarcity	0.12	0.03	-0.03	kg Cu eq
Ozone formation, Human health	0.24	0.13	0.10	kg NOx eq
Ozone formation, Terrestrial ecosystems	0.25	0.14	0.11	kg NOx eq
Stratospheric ozone depletion	2.67E-04	3.88E-04	-1.62E-04	kg CFC11 eq
Terrestrial acidification	0.17	0.07	-0.41	kg SO2 eq
Terrestrial ecotoxicity	283.9	39.00	-74.83	kg 1,4-DCB
Water consumption	0.33	0.08	0.11	m3

The most notable result arising from Table 4.9 is that which relates to the motivation for this study, i.e., Global warming potential. Scenario 0 has been estimated to emit 797.4 kg CO2 eq, whilst proposed Scenarios 1 and 2 emit 129.6 kg CO2 eq and 22.49 kg CO2 eq, respectively. This is a dramatic saving of between 83.7% and 97.2% CO2 emissions for Scenarios 1 and 2, respectively.

Additional results of note include many of the indicators for Scenario 2 which reflect negative values. This is significant as it reflects the fact that not only are environmental burdens reduced by the alternative scenarios, but they can actually have a net positive impact on the environment by substituting by-products (i.e., electricity from biogas & digestate) produced by other means. This suggests that Scenario 2 may be a frontrunner in net environmental impact.

Water consumption is another noteworthy result to consider as the result for Scenario 0 (0.11 m3) reflects a higher consumption of water in the anaerobic digestion of food waste, than the open windrow composting of organic matter (0.08 m3). Nonetheless, both Scenarios perform better than Scenario 0 (0.33 m3), which is due to the amount of rainfall on open-cut landfills that their contents render unpotable. This active consumption of water by the anaerobic digestion process may be burdensome to the process in the event of drought and water restrictions.

A more comparative visualisation of these results which normalises each scenario's performance by displaying each result relative to the maximum obtained in that impact category is presented in Figure

4.3. This analysis yields an interesting insight into the relative performances of different scenarios across the impact categories, and highlights that within the context of particular categories, each scenario performs varyingly.

A noteworthy observation, however, is that the base case (i.e., Scenario 0) does not achieve relatively better performance in any of the impact categories. That is, it either ranks poorest, or neither best nor poorest, in all aspects of this comparative environmental analysis. This is important because it confirms the strategy behind seeking alternative MSWM strategies.

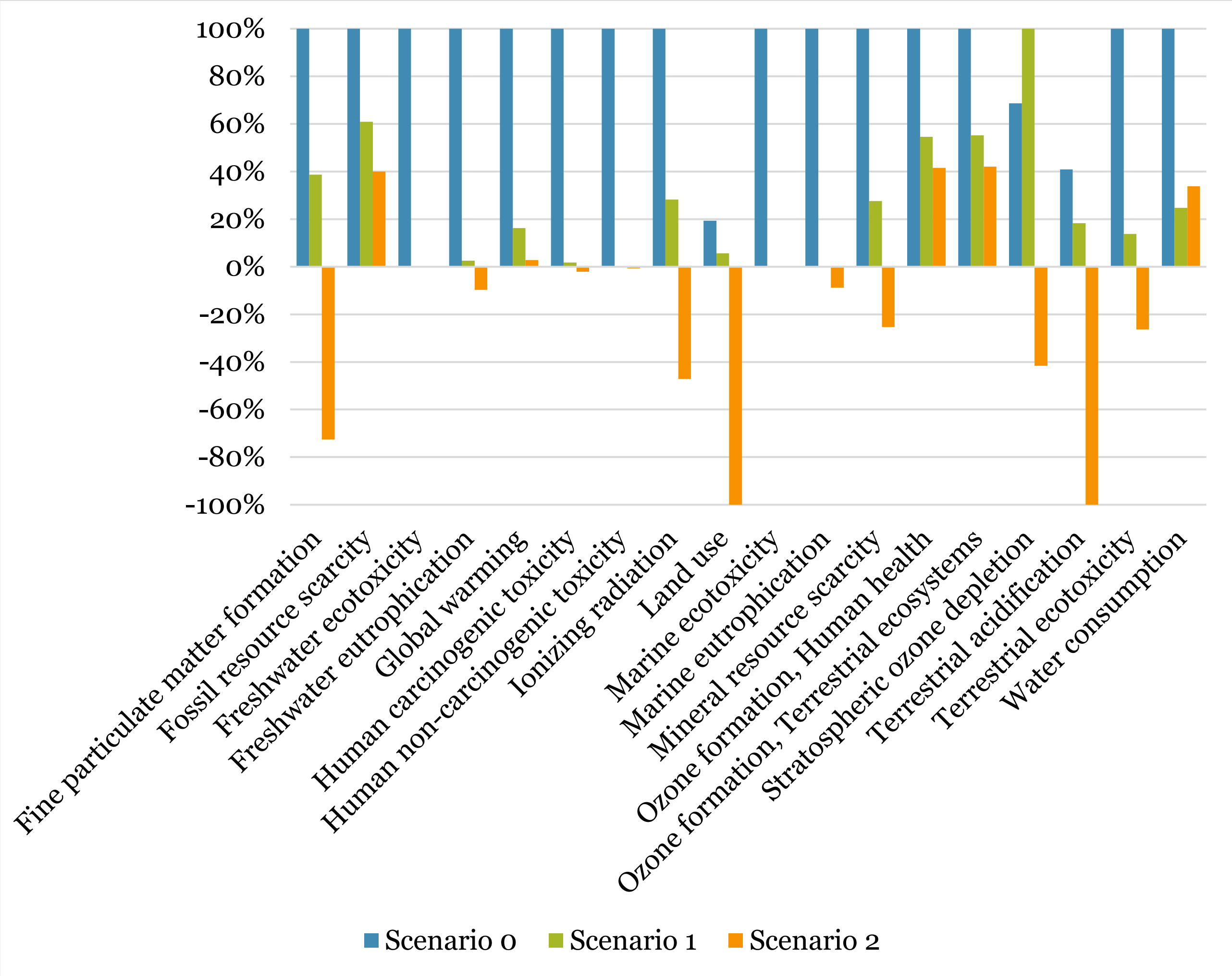

Figure 4.3: Presentation of relative results, normalised to be relative to the maximum result for that indicator category.

As shown in Figure 4.3, both Scenario 1 and Scenario 2 show lower impacts in every indicator category, with the exception of Stratospheric ozone depletion in which Scenario 1 is highest.

An additional manipulation of the results to aid with comparison is presented in Table 4.10 which decomposes the results from Scenarios 1 and 2 into the percentage reduction in environmental indicator from Scenario 0's value.

Table 4.10: Percentage reduction in environmental impact from the base case (i.e., Scenario 0).

Impact Category	% Reduction from Scenario 0	
	1	2
Fine particulate matter formation	-60%	-180%
Fossil resource scarcity	-39%	-60%
Freshwater ecotoxicity	-99.9%	-100.2%
Freshwater eutrophication	-97%	-110%
Global warming	-84%	-97%
Human carcinogenic toxicity	-98%	-102%
Human non-carcinogenic toxicity	-100%	-101%
Ionizing radiation	-72%	-147%
Land use	-71%	-616%
Marine ecotoxicity	-99.9%	-100.2%
Marine eutrophication	-100.0%	-107%
Mineral resource scarcity	-75%	-125%
Ozone formation, Human health	-46%	-58%
Ozone formation, Terrestrial ecosystems	-44%	-56%
Stratospheric ozone depletion	45%	-161%
Terrestrial acidification	-59%	-341%
Terrestrial ecotoxicity	-86%	-126%
Water consumption	-76%	-67%

The following Table 4.11, Table 4.12, and Table 4.13 present a breakdown of each Scenario's overall environmental indicators into their subprocesses. This enables a more detailed analysis behind each indicator's performance. Section 4.4.2 then presents a number of selected categories as graphical representations of the contribution of each sub-process to that Scenario's overall performance.

Table 4.11: Process breakdown of environmental impacts for Scenario 0. Values are relative to 1 FU (i.e., 1 Mg MSW).

Indicator	Scenario total	Red - collection	Red - transport	Red - treatment	Green - collection	Green - transport	Green - treatment	Burgundy - collection	Burgundy - treatment	Unit
Fine particulate matter formation	1.05E-01	2.39E-02	1.06E-04	7.41E-02	3.43E-03	1.33E-05	3.19E-03	0	0	kg PM2.5 eq
Fossil resource scarcity	1.45E+01	4.74E+00	1.40E-02	8.38E+00	6.79E-01	1.75E-03	6.78E-01	0	0	kg oil eq
Freshwater ecotoxicity	3.28E+02	9.10E-02	1.00E-03	3.28E+02	1.30E-02	1.93E-04	1.37E-02	0	0	kg 1,4-DCB
Freshwater eutrophication	3.29E-02	3.16E-04	7.50E-06	3.25E-02	4.53E-05	9.28E-07	7.79E-05	0	0	kg P eq
Global warming	7.97E+02	1.50E+01	4.80E-02	7.41E+02	2.15E+00	6.00E-03	3.96E+01	0	0	kg CO2 eq
Human carcinogenic toxicity	1.62E+01	9.45E-02	3.20E-03	1.60E+01	1.35E-02	4.08E-04	3.83E-02	0	0	kg 1,4-DCB
Human non-carcinogenic toxicity	7.07E+03	2.20E+00	2.00E-02	7.07E+03	3.16E-01	2.44E-03	2.04E-01	0	0	kg 1,4-DCB
Ionizing radiation	1.06E+00	1.47E-01	1.20E-03	8.65E-01	2.10E-02	1.50E-04	2.45E-02	0	0	kBq Co-60 eq
Land use	1.59E+00	7.31E-02	1.99E-03	1.50E+00	1.05E-02	2.50E-04	4.98E-03	0	0	m2a crop eq
Marine ecotoxicity	4.31E+02	1.37E-01	2.00E-03	4.31E+02	1.96E-02	2.53E-04	1.96E-02	0	0	kg 1,4-DCB
Marine eutrophication	2.74E-01	2.90E-05	1.00E-06	2.74E-01	4.17E-06	6.75E-08	6.65E-06	0	0	kg N eq
Mineral resource scarcity	1.21E-01	1.50E-02	2.65E-04	9.99E-02	2.15E-03	3.32E-05	3.58E-03	0	0	kg Cu eq
Ozone formation, Human health	2.44E-01	1.06E-01	5.40E-04	1.21E-01	1.51E-02	6.77E-05	1.91E-03	0	0	kg NOx eq
Ozone formation, Terrestrial ecosystems	2.54E-01	1.11E-01	5.48E-04	1.25E-01	1.59E-02	6.86E-05	2.33E-03	0	0	kg NOx eq
Stratospheric ozone depletion	2.67E-04	1.06E-05	2.30E-08	1.20E-04	1.52E-06	3.00E-09	1.35E-04	0	0	kg CFC11 eq
Terrestrial acidification	1.67E-01	5.20E-02	2.62E-04	1.05E-01	7.45E-03	3.28E-05	2.69E-03	0	0	kg SO2 eq
Terrestrial ecotoxicity	2.84E+02	2.20E+01	1.22E-01	2.56E+02	3.16E+00	1.53E-02	2.47E+00	0	0	kg 1,4-DCB
Water consumption	3.30E-01	7.11E-03	1.66E-04	3.20E-01	1.02E-03	2.08E-05	1.52E-03	0	0	m3

Table 4.12: Process breakdown of environmental impacts for Scenario 1. Values are relative to 1 FU (i.e., 1 Mg MSW).

Indicator	Scenario total	Red - collection	Red - transport	Red - treatment	Green - collection	Green - transport	Green - treatment	Burgundy - collection	Burgundy - treatment	Unit
Fine particulate matter formation	4.06E-02	1.95E-02	8.73E-05	4.10E-03	8.01E-03	3.15E-05	8.85E-03	0	0	kg PM2.5 eq
Fossil resource scarcity	8.82E+00	3.85E+00	1.15E-02	1.48E+00	1.59E+00	4.14E-03	1.88E+00	0	0	kg oil eq
Freshwater ecotoxicity	1.84E-01	7.38E-02	1.26E-03	4.04E-02	3.04E-02	4.56E-04	3.81E-02	0	0	kg 1,4-DCB
Freshwater eutrophication	8.25E-04	2.57E-04	6.09E-06	2.37E-04	1.06E-04	2.20E-06	2.16E-04	0	0	kg P eq
Global warming	1.30E+02	1.22E+01	3.92E-02	2.29E+00	5.02E+00	1.40E-02	1.10E+02	0	0	kg CO2 eq
Human carcinogenic toxicity	2.78E-01	7.68E-02	2.68E-03	5.99E-02	3.16E-02	9.65E-04	1.06E-01	0	0	kg 1,4-DCB
Human non-carcinogenic toxicity	3.83E+00	1.79E+00	1.60E-02	7.12E-01	7.38E-01	5.76E-03	5.67E-01	0	0	kg 1,4-DCB
Ionizing radiation	3.00E-01	1.19E-01	9.85E-04	6.16E-02	4.91E-02	3.55E-04	6.81E-02	0	0	kBq Co-60 eq
Land use	4.64E-01	5.95E-02	1.64E-03	3.64E-01	2.45E-02	5.90E-04	1.38E-02	0	0	m2a crop eq
Marine ecotoxicity	2.71E-01	1.11E-01	1.66E-03	5.70E-02	4.58E-02	5.98E-04	5.45E-02	0	0	kg 1,4-DCB
Marine eutrophication	7.12E-05	2.37E-05	4.43E-07	1.87E-05	9.74E-06	1.60E-07	1.85E-05	0	0	kg N eq
Mineral resource scarcity	3.33E-02	1.22E-02	2.18E-04	5.91E-03	5.01E-03	7.86E-05	9.94E-03	0	0	kg Cu eq
Ozone formation, Human health	1.33E-01	8.59E-02	4.44E-04	5.99E-03	3.53E-02	1.60E-04	5.29E-03	0	0	kg NOx eq
Ozone formation, Terrestrial ecosystems	1.41E-01	9.00E-02	4.50E-04	6.41E-03	3.70E-02	1.62E-04	6.47E-03	0	0	kg NOx eq
Stratospheric ozone depletion	3.88E-04	8.61E-06	1.90E-08	1.70E-06	3.54E-06	7.00E-09	3.74E-04	0	0	kg CFC11 eq
Terrestrial acidification	7.47E-02	4.23E-02	2.15E-04	7.22E-03	1.74E-02	7.76E-05	7.48E-03	0	0	kg SO2 eq
Terrestrial ecotoxicity	3.90E+01	1.79E+01	1.00E-01	6.71E+00	7.37E+00	3.62E-02	6.87E+00	0	0	kg 1,4-DCB
Water consumption	8.16E-02	5.79E-03	1.36E-04	6.90E-02	2.38E-03	4.91E-05	4.24E-03	0	0	m3

Table 4.13: Process breakdown of environmental impacts for Scenario 2. Values are relative to 1 FU (i.e., 1 Mg MSW).

Indicator	Scenario total	Red - collection	Red - transport	Red - treatment	Green - collection	Green - transport	Green - treatment	Burgundy - collection	Burgundy - treatment	Unit
Fine particulate matter formation	-7.61E-02	1.95E-02	8.73E-05	4.10E-03	3.43E-03	1.33E-05	3.19E-03	0.00E+00	-1.11E-01	kg PM2.5 eq
Fossil resource scarcity	5.80E+00	3.85E+00	1.15E-02	1.48E+00	6.79E-01	1.75E-03	6.78E-01	9.76E-01	-1.88E+00	kg oil eq
Freshwater ecotoxicity	-6.02E-01	7.38E-02	1.26E-03	4.04E-02	1.30E-02	1.93E-04	1.37E-02	1.87E-02	-7.63E-01	kg 1,4-DCB
Freshwater eutrophication	-3.20E-03	2.57E-04	6.09E-06	2.37E-04	4.53E-05	9.28E-07	7.79E-05	6.51E-05	-3.89E-03	kg P eq
Global warming	2.25E+01	1.22E+01	3.92E-02	2.29E+00	2.15E+00	6.00E-03	3.96E+01	3.09E+00	-3.69E+01	kg CO2 eq
Human carcinogenic toxicity	-3.49E-01	7.68E-02	2.68E-03	5.99E-02	1.35E-02	4.08E-04	3.83E-02	1.95E-02	-5.60E-01	kg 1,4-DCB
Human non-carcinogenic toxicity	-4.4E+01	1.79E+00	1.60E-02	7.12E-01	3.16E-01	2.44E-03	2.04E-01	4.54E-01	-4.76E+01	kg 1,4-DCB
Ionizing radiation	-5.00E-01	1.19E-01	9.85E-04	6.16E-02	2.10E-02	1.50E-04	2.45E-02	3.02E-02	-7.58E-01	kBq Co-60 eq
Land use	-8.2E+00	5.95E-02	1.64E-03	3.64E-01	1.05E-02	2.49E-04	4.98E-03	1.51E-02	-8.66E+00	m2a crop eq
Marine ecotoxicity	-7.86E-01	1.11E-01	1.66E-03	5.70E-02	1.96E-02	2.53E-04	1.96E-02	2.82E-02	-1.02E+00	kg 1,4-DCB
Marine eutrophication	-2.43E-02	2.37E-05	4.43E-07	1.87E-05	4.17E-06	6.75E-08	6.65E-06	6.00E-06	-2.44E-02	kg N eq
Mineral resource scarcity	-3.07E-02	1.22E-02	2.18E-04	5.91E-03	2.15E-03	3.32E-05	3.58E-03	3.08E-03	-5.78E-02	kg Cu eq
Ozone formation, Human health	1.01E-01	8.59E-02	4.44E-04	5.99E-03	1.51E-02	6.77E-05	1.91E-03	2.17E-02	-2.99E-02	kg NOx eq
Ozone formation, Terrestrial ecosystems	1.07E-01	9.00E-02	4.50E-04	6.41E-03	1.59E-02	6.86E-05	2.33E-03	2.28E-02	-3.08E-02	kg NOx eq
Stratospheric ozone depletion	-1.62E-04	8.61E-06	1.90E-08	1.70E-06	1.52E-06	3.00E-09	1.35E-04	2.18E-06	-3.10E-04	kg CFC11 eq
Terrestrial acidification	-4.09E-01	4.23E-02	2.15E-04	7.22E-03	7.45E-03	3.28E-05	2.69E-03	1.07E-02	-4.80E-01	kg SO2 eq
Terrestrial ecotoxicity	-7.4E+01	1.79E+01	1.00E-01	6.71E+00	3.16E+00	1.53E-02	2.47E+00	4.54E+00	-1.10E+02	kg 1,4-DCB
Water consumption	1.11E-01	5.79E-03	1.36E-04	6.90E-02	1.02E-03	2.08E-05	1.52E-03	1.47E-03	3.24E-02	m3

4.4.2. Key findings: Scenario break-down of results

This section analyses the three Scenarios' performance in the following selected indicator categories:

- Global warming potential
- Water consumption
- Land use
- Fossil resource scarcity

Further to the net impact of each bin on performance in this indicator, further analysis was conducted to confirm the assumption in Section 4.3.1.1 and Appendices 6.4 & 6.5 that the collection regime contributes a minimal amount to the overall impact on key indicators such as Global warming potential.

4.4.2.1. Global warming potential

The Global warming potential category is of particular interest to the present study as this is part of the foundations that inspired this work. As such, a more detailed investigation of this indicator, and of which stages in each of the three Scenarios contribute to the Scenario's overall performance, was performed. This analysis, attributing net positive or negative impacts on the overall Scenario's performance is presented in Figure 4.4.

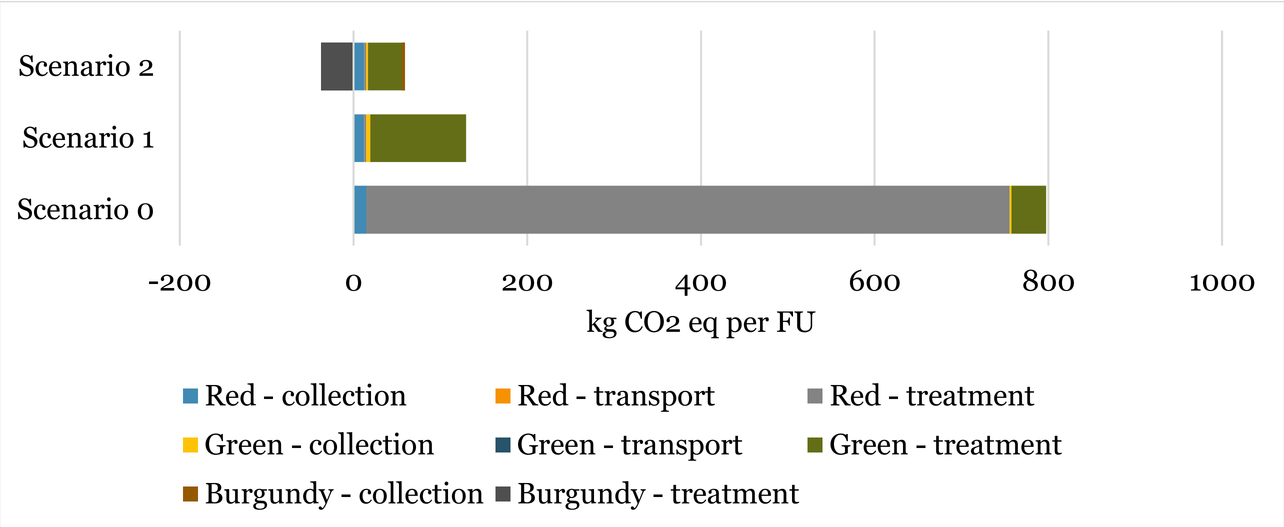

Figure 4.4: Global warming potential for each Scenario broken down into the net impacts of each treatment method.

A notable observation from Figure 4.4 is the impact that removing organics from landfill has. In Scenario 1, landfilling accounts for 740.1 kg CO_2 eq per FU (i.e., 1 Mg residual + food organic + garden organics disposed), whereas in Scenarios 2 & 3, emissions from landfill equals only 2.29 kg CO_2 eq, an over 99% reduction in CO_2 emissions from the red bin treatment step. This is a dramatic reduction and illustrates the significant impact that diversion of organics from landfill can have.

This analysis also confirms the validity of the assumptions made in Sections 4.3.1.1 & 4.3.1.3, and Appendices 0 & 6.5, namely with respect to the fact that the collection regime only contributes a minor aspect each Scenario's overall environmental impact.

4.4.2.2. Water consumption

Another indicator of note, and particularly relevant to the Australian context given its tendency to suffer from drought, is Water consumption. A break-down of the net impacts of the three bin lid colours reveals a dramatic saving in water consumption by diverting food waste to an alternative treatment method, with Scenario 1 leading to a 75.2% saving in water, and Scenario 2 resulting in a 66.2% reduction compared to Scenario 0. This analysis is presented in Figure 4.5.

Notably, anaerobic digestion (0.0324 m3) accounts for a significantly higher amount of water proportional to that demanded by the food fraction when treated via open windrow composting (0.0027 m3). This is because AD requires water as an input to the process to ensure that an ideal consistency is maintained to sustain biological activity. It is also used extensively in cleaning equipment & machinery, more so than composting requires.

This analysis emphasises LCA's long-term approach to accounting for environmental flows because it incorporates both short-term water consumption (i.e., that required in anaerobic digestion processes), and long-term consequences of landfilling waste in terms of water that the landfill 'consumes' in terms of rainfall that is rendered unusable due to it passing through the landfill's substrate.

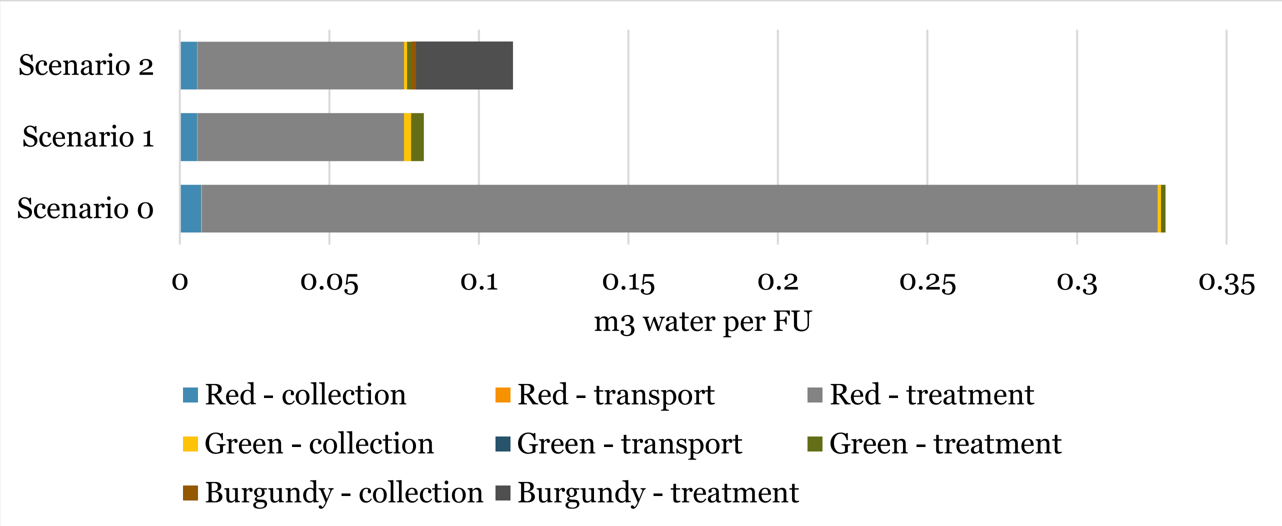

Figure 4.5: Water consumption indicator for each Scenario broken down into the net impacts of each treatment method.

Figure 4.5 also provides an interesting analysis of the difference between water consumption for Scenario 1 and Scenario 2, namely it enables the comparison of water requirements for treating food waste via combined composting with garden organics (i.e., FOGO composting) and anaerobic digestion. Treatment of food waste via FOGO increases consumption of water by 0.0027 m3 water, compared to composting garden organics alone, whilst treating food waste via anaerobic digestion, accounts for 0.032 m3 water, which is roughly 12 times the amount of water required compared to FOGO composting. This is significant in the context of Greater Metropolitan Sydney which frequently experiences periods of drought.

4.4.2.3. Land use

It was noted in Section 1.2 that part of the reason why landfilling is so popular in Australia is because land is inexpensive. An interesting analysis is the net impact that each bin type has on this indicator. Figure 4.6 highlights that Scenarios 1 and 2 greatly reduce the amount that landfilling contributes to land use. It also demonstrates the large offset provided by anaerobic digestion which reduces land use from other processes that produce the by-products from anaerobic digestion.

This representation highlights the significant amount of land that both Scenarios 1 and 2 achieve due to the fact that both processes involve a reduction waste volume sent to landfill, and that both composting and anaerobic digestion facilities repurpose waste, rather than landfill which is considered an end-of-life process.

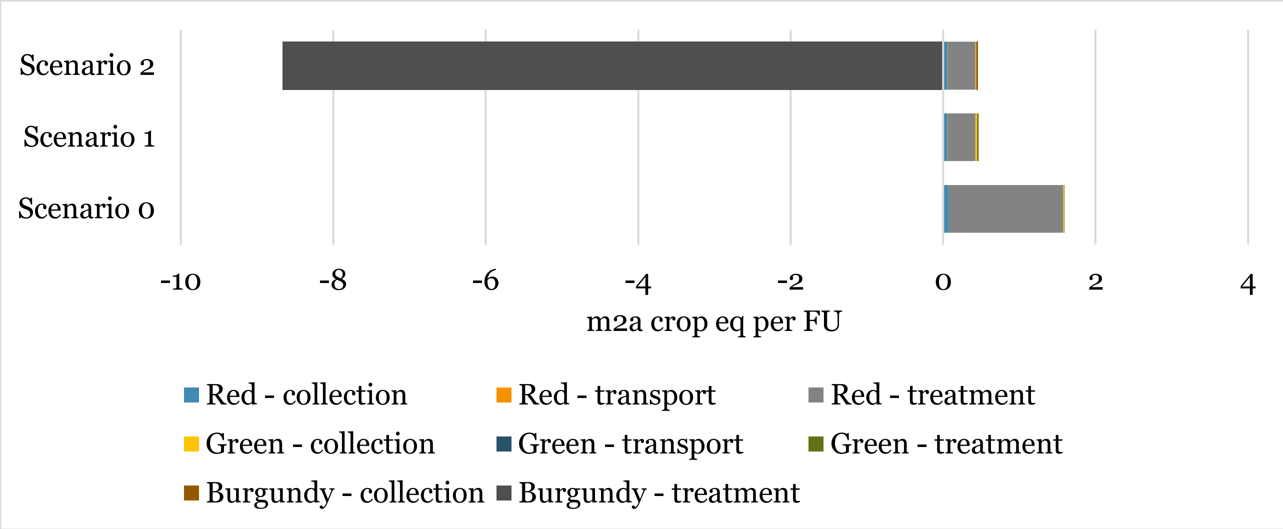

Figure 4.6: Land use indicator for each Scenario broken down into the net impacts of each treatment method.

4.4.2.4. Fossil resource scarcity

The final noteworthy impact category results analysed in this section focuses on the Scenarios' performance in the Fossil resource scarcity indicator, as presented in Figure 4.7. This indicator more closely considers relative performance based off the consumption of non-renewable resources, from which the diesel and coal that is required for transportation and treatment stages can be compared.

Collection and transportation stages for Scenario 0 accounts for 37.4% of this category's environmental impact, whilst it accounts for 61.7% of Scenario 1's, and 94.9% of Scenario 2's overall performance in this category. These results are of interest because it demonstrates that Scenario 2 is most sensitive to the collection regime in this category, whilst for Scenarios 0 and 1, other processes such as the diesel machinery requirements for landfilling, and open windrow composting, weight more heavily on the process.

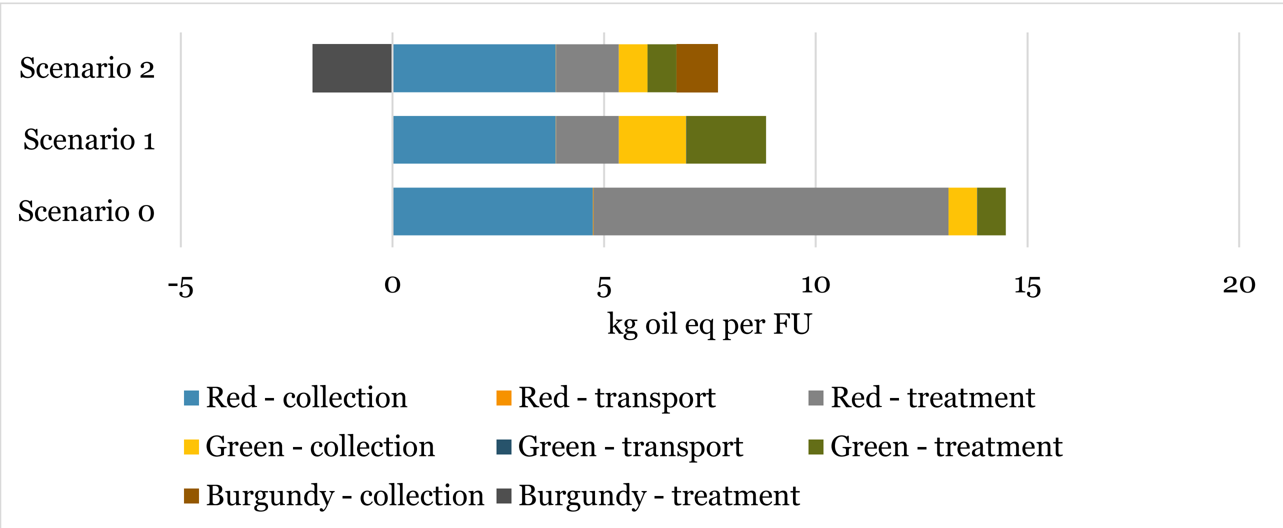

Figure 4.7: Fossil resource scarcity indicator for each Scenario broken down into the net impacts of each treatment method.

4.5. Life Cycle Interpretation

This final section of the LCA typically validates that the results from the LCA align with the originally intended goal & scope. It is also a means for results to be summarised, a conclusion to be drawn, and limitations and further work discussed. Given that this LCA is a part of this thesis as a whole, however, conclusions and discussion of limitations and recommendations will not be included in the present section and will instead be contained in the thesis' overall set of conclusions in Section 5.

4.5.1. Realising the Goal & Scope of the LCA

This section aims to affirm that the present study addresses the Goal & Scope which are outlined in Sections 4.1 and 4.2. The study's intended application set out to "address optimal sorting and collection strategies for kerbside waste, with a particular focus on achieving net zero emissions from landfill" (with a particular focus on the food waste stream). Sections 4.4.1 & 4.4.2 both generally, and specifically address this concern. Notably, the results highlight that by diverting food waste from landfill, CO_2 emissions from landfill are reduced by over 99%. The findings from analysing this indicator alone affirm the possibility of the NSW Government's policies towards achieving net zero emissions from landfill.

The study presents a range of additional environmental indicators which serve to further aid decision-makers in understanding the payoffs associated with the competing alternative Scenarios 1 and 2. That is to say, the study sets the groundwork for next steps to be performed to validate the results obtained in this thesis.

4.5.2. Key issues

A number of key issues arise from the present study. These are discussed further in the following points.

- **Validation of NSW Government imposition of restrictions on food organics waste streams**

As discussed above, this LCA validates the rationale behind mandating the diversion of food waste from landfill. In every inventory category except for Stratospheric ozone depletion, the two alternative Scenarios proposed (i.e., combine food organics with garden organics and compost, or anaerobically digest the food organics) lead to lower total emissions from the MSWM system.

- **Identification of the better performing strategy in terms of global warming potential (i.e., carbon emissions)**

The LCA also provides a quantitative basis to support the consideration of a range of alternative treatment processes for food waste. In this LCA, only open windrow composting as FOGO, and anaerobic digestion of food waste were considered. This is based off the current infrastructure available for use in Sydney. The study therefore provides two competing strategies that could be employed under the status quo of waste management infrastructure in Sydney, highlighting that the anaerobic digestion of food waste could yield improved carbon emissions due to the process' by-products offsetting the need for such goods to be produced via other, less environmentally-friendly means.

- **Relative performance of the two competing proposed Strategies 1 and 2 in other environmental indicators**

This study not only considers the three Strategies' Global warming potential (i.e., CO_2 emissions), but also indicates their performance in a range of other environmental aspects. This is useful for decision-makers to consider as it provides a more in-depth picture of the alternatives. For instance, the study indicates that whilst Scenario 2 performs better in most indicator categories, such as Fine particulate matter formation, Global warming potential, Land use, and Terrestrial acidification potential, Scenario 1 consumes a smaller amount of water in the long-term, which could be significant in the Australian context given that droughts are commonplace, as has been discussed previously in this report.

4.5.3. Evaluation of results: Data quality

This section presents an evaluation of the LCA's results based on the quality of data used as inputs in each stage of constructing the model in openLCA. It is determined using the Ecoinvent DQS. Results from the Ecoinvent database contain "quantitative and qualitative information about the uncertainty of each individual elementary exchange"[63]. Uncertainty analysis and Monte Carlo simulation can be performed; however, the 5-category Pedigree matrix approach tends to provide a better interpretation of why certain aspects of results are of greater or lesser quality, rather than just providing an uncertainty range.

The Pedigree matrix consists of 5 categories: Reliability (R), Completeness (C), Temporal correlation (T), Geographical correlation (G), and Further technological correlation (F). The quality of every data point input to the database is then assessed by assigning a rank between 1 and 5, with 1 being the best, and 5 being the worst at reflecting that particular category's quality. Refer to Appendix 6.6 for a description of the ranking of each matrix category.

Once the LCI is finalised, a detailed data quality assessment report can then be generated to assess the aggregated quality of each impact category result within the 5 categories. Table 4.14, Table 4.15 and Table 4.16 present the data quality assessment matrices for the results of Scenarios 0, 1 and 2, respectively.

Scenario 0's results are comparatively the best performing in the majority in terms of quality of results, with the average of all its data quality indicators equal to 2.2, whilst Scenario 1's is 2.4, and Scenario 2's is 2.7. This reflects the fact that a greater number of assumptions, particularly around combine food waste with garden organics, and the anaerobic digestion process had to be made in the two latter Scenarios. This reflects the fact that secondary data sources were used to estimate inputs and outputs for these processes, whilst in the case of landfilling (which dominates Scenario 1) the Ecoinvent database was used for modelling.

Table 4.14: Data quality assessment for Scenario 0 results (same values as those presented in Table 4.9).

Impact category	Result	Unit	R	C	T	G	F
Fine particulate matter formation	0.10	kg PM2.5 eq	2	2	4	3	1
Fossil resource scarcity	14.49	kg oil eq	1	2	4	2	1
Freshwater ecotoxicity	328.1	kg 1,4-DCB	1	1	4	3	1
Freshwater eutrophication	3.29E-02	kg P eq	1	1	3	2	1
Global warming	797.4	kg CO2 eq	1	1	4	3	1
Human carcinogenic toxicity	16.16	kg 1,4-DCB	1	1	4	3	1
Human non-carcinogenic toxicity	7070	kg 1,4-DCB	1	1	4	3	1
Ionizing radiation	1.06	kBq Co-60 eq	1	1	5	1	1
Land use	1.59	m2a crop eq	2	2	5	4	2
Marine ecotoxicity	431.2	kg 1,4-DCB	1	1	4	3	1
Marine eutrophication	0.27	kg N eq	1	1	4	4	1
Mineral resource scarcity	0.12	kg Cu eq	1	2	4	1	1
Ozone formation, Human health	0.24	kg NOx eq	2	1	4	3	1
Ozone formation, Terrestrial ecosystems	0.25	kg NOx eq	2	1	4	3	1
Stratospheric ozone depletion	2.67E-04	kg CFC11 eq	1	3	4	4	2
Terrestrial acidification	0.17	kg SO2 eq	2	2	4	3	1
Terrestrial ecotoxicity	283.9	kg 1,4-DCB	2	2	4	3	1
Water consumption	0.33	m3	3	3	4	3	3

Another trend observed is that the temporal correlation of results in all three Scenarios tends to be considerably higher in most impact categories, than the other quality categories. This is likely due to the fact that the Ecoinvent database used in this LCA was version 3.6, which was released in 2019, which means that already the default data is at least 2 years old. An additional reason for the worse performance in temporal scope is that the other studies used as inputs (i.e., Opatokun et al.[62] and Andersen et al.[61]) are themselves from 2017 and 2010, respectively.

Table 4.15: Data quality assessment for Scenario 1 results (same values as those presented in Table 4.9).

Impact category	Result	Unit	R	C	T	G	F
Fine particulate matter formation	0.04	kg PM2.5 eq	2	2	5	4	1
Fossil resource scarcity	8.82	kg oil eq	1	2	4	2	1
Freshwater ecotoxicity	0.18	kg 1,4-DCB	1	1	2	1	1
Freshwater eutrophication	8.25E-04	kg P eq	1	1	4	1	1
Global warming	129.6	kg CO2 eq	1	4	4	5	2
Human carcinogenic toxicity	0.28	kg 1,4-DCB	1	1	5	4	1
Human non-carcinogenic toxicity	3.83	kg 1,4-DCB	2	2	3	2	1
Ionizing radiation	0.30	kBq Co-60 eq	1	1	5	1	1
Land use	0.46	m2a crop eq	2	3	5	5	2
Marine ecotoxicity	0.27	kg 1,4-DCB	1	1	2	2	1
Marine eutrophication	0.00	kg N eq	1	2	4	2	1
Mineral resource scarcity	0.03	kg Cu eq	1	2	4	1	1
Ozone formation, Human health	0.13	kg NOx eq	2	1	5	5	1
Ozone formation, Terrestrial ecosystems	0.14	kg NOx eq	2	1	5	5	1
Stratospheric ozone depletion	3.88E-04	kg CFC11 eq	1	4	4	5	2
Terrestrial acidification	0.07	kg SO2 eq	3	2	5	4	1
Terrestrial ecotoxicity	39.00	kg 1,4-DCB	3	4	5	4	1
Water consumption	0.08	m3	3	3	4	3	3

Notwithstanding the underperformance in temporal correlation of these results, the rest of the values obtained in the LCA perform relatively well in data quality assessment, and it would be useful to consider the results presented in Section 4.4.1 within the context of this data quality assessment framework.

Table 4.16: Data quality assessment for Scenario 2 results (same values as those presented in Table 4.9).

Impact category	Result	Unit	R	C	T	G	F
Fine particulate matter formation	-0.08	kg PM2.5 eq	3	4	5	4	2
Fossil resource scarcity	5.80	kg oil eq	1	2	4	2	1
Freshwater ecotoxicity	-0.60	kg 1,4-DCB	1	1	2	1	1
Freshwater eutrophication	-3.20E-03	kg P eq	1	1	4	2	1
Global warming	22.49	kg CO2 eq	2	3	5	5	2
Human carcinogenic toxicity	-0.35	kg 1,4-DCB	1	2	5	3	2
Human non-carcinogenic toxicity	-44.12	kg 1,4-DCB	2	2	5	4	1
Ionizing radiation	-0.50	kBq Co-60 eq	1	1	5	1	1
Land use	-8.21	m2a crop eq	2	1	5	4	1
Marine ecotoxicity	-0.79	kg 1,4-DCB	1	1	2	2	1
Marine eutrophication	-0.02	kg N eq	2	2	5	5	1
Mineral resource scarcity	-0.03	kg Cu eq	2	2	4	1	1
Ozone formation, Human health	0.10	kg NOx eq	2	2	5	5	1
Ozone formation, Terrestrial ecosystems	0.11	kg NOx eq	2	2	5	5	1
Stratospheric ozone depletion	-1.62E-04	kg CFC11 eq	3	4	5	5	3
Terrestrial acidification	-0.41	kg SO2 eq	4	4	5	4	3
Terrestrial ecotoxicity	-74.83	kg 1,4-DCB	2	4	5	4	3
Water consumption	0.11	m3	3	3	4	3	3

5. CONCLUSIONS AND RECOMMENDATIONS ARISING FROM THIS THESIS

The primary focus of this thesis has been to validate the potential of achieving net zero emissions from landfill due to the food organics waste stream, and then to propose two alternative scenarios to achieve this.

Initially, this work establishes current and future directions with respect to food waste management, by reviewing relevant policies and technologies. The New South Wales Government's Sustainable Materials Strategy 2041[1] was specifically highlighted as a policy which is driving the waste management sector towards achieving net zero emissions from organics in landfill. The Strategy mandates that by 2030, all Local Government Areas (LGAs) in New South Wales will be required to no longer accept food waste as part of the residual waste stream that is sent to landfill. Consequently, a number of competing alternative technologies are then discussed to help achieve this, including combined collection with garden organics (i.e., FOGO), and anaerobic digestion of food waste.

In order to contextualise the changes required to achieve the 2030 mandate, a survey was performed to collect first-hand data from key decision-makers in Local Government Areas throughout Greater Metropolitan Sydney. The survey found that over 85% of LGAs in Sydney currently have no alternative strategy to incorporating food waste in landfilled waste streams (or at least do not currently offer this to residents). Furthermore, it highlighted that around the years 2025-26, most LGAs' current kerbside waste collection & management contracts will expire, meaning that by this time it is expected that a tipping point will be reached that will see more food waste diverted from landfill. An additional finding arising from this process was that there is a gap in understand towards which alternative food waste treatment strategy performs best and is therefore the superior option for LGAs to consider transitioning their waste collection services towards. Thus, the main outcome of this survey was the finding that it would be beneficial to perform a quantitative analysis of both the current business-as-usual waste collection scenario, as well as of a number of alternative treatment scenarios.

Subsequently, this work considers a number of quantitative environmental assessment frameworks in order to decide how best to proceed with obtaining reliable data to assist decision-makers. It was decided to proceed with a detailed Life Cycle Assessment (LCA) of the competing methods available for large-scale addressal of food waste within the municipal solid waste stream.

To understand current approaches towards LCAs of municipal solid waste collection & management processes, a Literature Review was conducted. The main finding arising from this process was that there exists a lack of LCAs that focus on the holistic kerbside waste system, from collection at point-of-disposal, to final treatment and/or on selling of by-products such as composts, digestates and electricity from biogas.

Therefore, a detailed Life Cycle Assessment was performed with the intention of quantifying the environmental performance of three scenarios: the base case where food waste is landfilled in the residual waste stream, a scenario where food waste is combined with garden organics (i.e., as FOGO) to be sent to open windrow composting, and the separate collection of food waste and treatment via anaerobic digestion.

The LCA uncovered a number of significant findings relating to the three scenarios' environmental performance. It was revealed that the diversion of food waste from landfill can yield up to a 99% reduction in CO2-equivalent emissions from landfill (excluding the impacts of the collection & transportation system). Overall, per 1 Mg of kerbside combined residual, food organics and garden organics waste streams, the base case contributes 797.4 kg CO2 eq to Global warming potential, whilst the scenario where it is combined as FOGO and composted produces 129.6 kg CO2 eq of emissions, and the scenario where food waste is collected separately and anaerobically digested contributes only 22.49 kg CO2 eq.

The benefits of the alternative treatment scenarios exist across other environmental indicators as well. With respect to Land use, the base case is the highest consumer, at 1.59 m2a crop eq per 1 Mg kerbside combined waste. In contrast, the FOGO composting scenario only contributes 0.46 m2a crop eq (mostly attributable still to the land taken up by inert landfilling), whilst the anaerobic digestion system offsets land use by -8.21 m2a crop eq, reflective of the fact that the nutrient-rich digestate and electricity produced from biogas offsets the need for these goods to be produced via other means.

In spite the performance of the two alternative scenarios proposed, a mixed outcome is observed in other categories such as stratospheric ozone depletion, where landfilling contributes to 2.67E-04 kg CFC11 eq, whilst FOGO composting contributes 3.88E-04 kg CFC11 eq, and anaerobic digestion accounts for -1.62E-04 kg CFC11 eq.

Notwithstanding, the results from the LCA indicate that in most environmental indicators, landfill performs the least of the three scenarios considered, and that anaerobic digestion of food waste tends to perform better environmentally than in combined composting as FOGO.

5.1. Limitations

The results from the LCA are challenged by the fact that the study relies exclusively on secondary data sources. This is problematic as it means that the results of the study are sensitive to the constraints of secondary data sources, which may have different data collection methods, inconsistencies in approaching uncertainty in results, different temporal scopes, and different boundary systems. Nonetheless, it does provide preliminary evidence to guide further study into each of the processes investigated. It also provides scope for the consideration of additional MSWM processes, as mentioned in Section 1.4. Another limitation of the study is the development of the collection system which, whilst it contributes only a small amount to overall environmental performance in many of the indicators studied, has been made based off a linear model involving a small number of variables and constants based off best guess approximations.

Through the survey process, via interviews with a number of present and former managers of LGAs' waste departments, and employees of private FOGO processing firms, a number of key obstacles to implementation of dedicated food waste management initiatives exist. These are presented below.

Firstly, it was revealed that certain LGAs find great difficulty in communicating new waste management policies to constituents (particularly in linguistically diverse communities). This can be for a range of reasons, however particularly for communities where a proportion of residents have grown up in developing countries and then moved to Australia, little attention can sometimes be placed on the sorting of waste. This LCA is limited in its capacity to account for the potential deviation of participation rates from 100% participation because there is little to no published data on this phenomenon. It is noted that a number of Council-run trials within Greater Metropolitan Sydney, and more broadly in New South Wales, are currently underway to assess the practicalities of at-source sorting of food waste from residual, however data from these studies are yet to be finalised, and as such have not been incorporated into the present analysis.

Secondly, the interviews revealed that, in the case of the scenario where food waste is collected as FOGO and composted via open windrows, the quality of product can be negatively impacted by variations in the feed. This is problematic due to the reduced value that such a product might attract in the market, which affects the economics of this process.

The final issue of note is the fact that the present LCA has only considered two alternatives to addressing food waste. The rationale behind these selections was that the alternatives proposed are pre-existing technologies within the Greater Metropolitan Sydney market. The prospect of now alternative processing treatments facilities, such as incineration, gasification, and pyrolysis plants, was considered low within the context that these types of facilities have either failed to gain any real planning support by authorities for a number of years, or that they are still emerging technologies and are therefore still a considerable amount of time away from full-scale commercial plants. It would be an improvement to the present study to expand the range of scenarios considered, and investigate such alternatives to managing food waste, and potentially other waste streams more generally.

5.2. Recommendations arising from this thesis

To improve the quality of data arising from the LCA, a number of recommendations for further work are detailed as follows:

1. Perform first-hand collection of data on, particularly, open windrow composting (contrasting GO with FOGO inputs). Alternatively, an LCA specifically comparing the performance of GO versus FOGO in open windrow composting facilities should be performed. Ideally, to remain relevant to the present scope and system boundary, this study should focus on waste arriving at the gate of the facility and should consider the offsetting effects of on-selling the produced fertilisers/composts/soil mixtures. Additionally, further first-hand data collection should be performed to accurately model the energy and other inputs and outputs from the transfer stations which, in the present model, has not been modelled due to lack of data available.

2. Further study on the composting facility and anaerobic digestor facility's environmental flows during the plants' construction & procurement stages would also be beneficial, as the Ecoinvent database modelling the landfills in all three scenarios considers the development of a landfill, as much as the ongoing environmental impact of operating that landfill. This reiterates problems associated with the use of secondary data sources rather than first-hand data collection which can be better adapted to the LCA investigation.

3. Affirm and refine the use of the waste collection strategy employed in this thesis' LCA, or otherwise develop a new model which better replicates the collection regime of different waste streams in the Scenarios considered.

4. Investigate alternative food waste treatment strategies, including centralised facilities such as incinerators and gasification plants & decentralised initiatives such as home-based composting.

5. Undertake first-hand data collection of the chemical/biological activity of each waste stream to determine the emissions as a function of time from each stream starting from the point at which that material is disposed. This should also be incorporated into a broader study into optimal collection cycles for each waste stream depending on its contents.

Several additional interesting research points are presented below. These are not intended to be relevant to the present study, however, they still generally address food waste management, with the aim of aiding decision-makers as to the best strategies available. They are as follows:

6. A comparative LCA between centralised composting facilities (which attempt to limit the amount of methane and other emissions released into the environment) and decentralised (i.e., home-based) composting, such as compost bins and worm farms, would also be an interesting analysis for further discussion on the relative performance of managing food waste at a hyper-local level, versus on a city- or state-wide scale.

7. A technoeconomic analysis of the systems presented in this LCA, and other food waste management facilities would be highly relevant to providing further decision-making evidence to authorities. This would also enable the quantification of reductions in quality of product from FOGO composting facilities, as opposed to the output from a GO composting facility. Furthermore, such an analysis could factor in changes to other economic instruments and forces at play in the waste management industry, such as changes in gate fees, and the financial incentive to return electricity produced at an anaerobic digestor, as well as changes in market prices to soil substrates and nutrient-rich sludges produced at facilities.

6. APPENDICES

6.1. Impact categories and descriptions

Table 6.1: Impact categories selected for the study.

Indicator	Unit	Description
Fine particulate matter formation	kg PM2.5 eq	Measures the damage to human respiratory health due to PM2.5 (particles of diameter <2.5 μm).
Fossil resource scarcity	kg oil eq	Equates the consumption of non-renewable/fossil fuels consumed in running petrol vehicles, burning coal to produce electricity, etc. Normalised to the amount of equivalent crude oil consumed.
Freshwater ecotoxicity	kg 1,4-DCB	Determines the impact to freshwater aquatic life of toxic substances such as heavy metals and organic toxins. Normalised to the amount of 1,4-dichlorobenze equivalent emitted.
Freshwater eutrophication	kg P eq	Measures emissions primarily to land and water than lead to an increase in aquatic plant growth attributable to excess nutrients. Normalised to the amount of equivalent phosphorous released into the environment.
Global warming	kg CO2 eq	Impact of emissions-to-air normalised to the equivalent amount of carbon dioxide released.
Human carcinogenic toxicity	kg 1,4-DCB	As with Freshwater ecotoxicity but with respect to the impact on human life, with a particular focus on materials which are carcinogenic.
Human non-carcinogenic toxicity	kg 1,4-DCB	As with Freshwater ecotoxicity but with respect to the impact on human life, with a particular focus on materials which are non-carcinogenic, but still toxic to life.
Ionizing radiation	kBq Co-60 eq	Relates to the long-term genetic damage caused by ionising radiation emission of radionuclides. Normalised to the amount of atomic nuclear decay per second.
Land use	m2a crop eq	Measures the degree to which the process renders arable land unusable.
Marine ecotoxicity	kg 1,4-DCB	As with Freshwater ecotoxicity but with respect to marine settings and marine life.
Marine eutrophication	kg N eq	As with Freshwater eutrophication but with respect to marine settings and marine life.
Mineral resource scarcity	kg Cu eq	Relates to the consumption of non-renewable minerals that are consumed in the process of fulfilling a product or service. Normalised to the amount of equivalent mined copper consumed.

Ozone formation, Human health	kg NOx eq	Characterises the level of emissions of oxides of nitrogen that can lead to the formation of ozone posing damage to human health. Normalised to the amount of nitrous oxide emitted to the atmosphere.
Ozone formation, Terrestrial ecosystems	kg NOx eq	As with Ozone formation, Human Health but with respect to the amount of ozone formation that impacts the environment, such as to tree stomata.
Stratospheric ozone depletion	kg CFC11 eq	Characterises the amount of ozone-destructive emissions from a process that lead to depletion of ozone in the Earth’s ozone layer. Normalised to the amount of CFC-11 released to the atmosphere.
Terrestrial acidification	kg SO2 eq	Relates to the equivalent emissions of sulphur dioxide and associated issues such as acid raid, the damage to plants and the stripping of nutrients from topsoils.
Terrestrial ecotoxicity	kg 1,4-DCB	As with Freshwater ecotoxicity but with respect to land-based species and environments.
Water consumption	m3	Relates to the volume of freshwater that a process consumes and/or renders unusable to the environment.

6.3. LGA Waste Survey

This Appendix provides further data on the findings from the survey of Local Government Areas within Greater Metropolitan Sydney. Table 6.2 presents a key to match the choropleth in Figure 2.1 with each LGA's current approach to food organics collection.

Table 6.2: Map key and data for LGAs displayed in Figure 2.1.

Corresponding number on map	LGA Name	FO Stream collection method
1	Bayside	Red bin
2	Blacktown	Red bin
3	Blue Mountains	Red bin
4	Burwood	Red bin
5	Camden	Red bin
6	Campbelltown	Red bin
7	Canada Bay	Red bin
8	Canterbury-Bankstown	Red bin
9	Central Coast	Red bin
10	Cumberland	Collected as FOGO
11	Fairfield	Red bin
12	Georges River	Red bin
13	Hawkesbury	Red bin
14	Hornsby	Red bin
15	Hunters Hill	Red bin
16	Inner West	Dedicated FO collection/trial
17	Ku-ring-gai	Red bin
18	Lane Cove	Red bin
19	Liverpool	Red bin
20	Mosman	Red bin
21	North Sydney	Red bin
22	Northern Beaches	Red bin
23	Parramatta	Dedicated FO collection/trial
24	Penrith	Collected as FOGO
25	Randwick	Collected as FOGO
26	Ryde	Red bin
27	Strathfield	Red bin
28	Sutherland Shire	Red bin
29	Sydney	Dedicated FO collection/trial
30	The Hills Shire	Red bin
31	Waverley	Red bin
32	Willoughby	Red bin
33	Wollondilly	Red bin
34	Woollahra	Collected as FOGO

In addition, the written responses to the questions asked in the survey are presented in Table 6.3.

Table 6.3: Individual feedback to survey questions from each LGA in Greater Metropolitan Sydney. Note that some responses have minor alterations, however all written advice is consistent with feedback received. If N/A is displayed in either the 'Date response received' or 'Written advice/feedback' columns, that specific council did not respond to the Survey questions.

LGA	Date response received	Written advice/feedback
Bayside	21/07/2021	In 2016/17, some of Council's material in the red-lidded bin was processed through an Alternate Waste Treatment (AWT) facility, recovering materials including organics. This is no longer the case as AWT was restricted in NSW in 2018/19.
Blacktown	4/08/2021	Council is considering introducing a green waste collection within next 3 to 5 years. Garbage goes to Suez, UR3R at Eastern Creek and Clean Up goes to Blacktown waste Services at Marsden Park.
Blue Mountains	16/09/2021	Green bin, ANL Blayney; Red bin, Blaxland landfill; Yellow bin, VISY Smithfield.
Burwood	N/A	N/A
Camden	5/08/2021	The following waste streams are treated/disposed as per the following: Garbage/General waste – 1487 tonnes sent to an Alternative Waste Treatment (ASWT) facility then 886.25 tonnes disposed to landfill; Green waste/Garden Organics – 95% was recycled (i.e., composted); FO specific is unlikely to be addressed - it is likely to be part of an all-encompassing waste management strategy.
Campbelltown	29/07/2021	Council will be entering into new (separate) contracts for collection services and disposal/processing services in 2024, when current contracts expire. Both Red & Green bid lid streams are delivered to the Spring Farm Resource Recovery Centre operated by SUEZ. The mixed waste is mostly landfilled with minor amounts of resource recovery, and garden organics are processed in an open-windrow composting facility. Council is about to invite tenders for the next waste and resource recovery processing/disposal contract which will include food waste/FOGO as a separate stream. Council recognises the importance of removing organics from landfill disposal, particularly as food organics comprise approx. 50% of the volume of mixed waste in the Campbelltown LGA and thus is a major contributor to greenhouse gas emissions from landfill. The challenges for Council include structuring appropriate source separation systems for single households and medium and high-density dwellings to maximise the long-term recovery of organics, supported by a tailored community education strategy.
Canada Bay	3/08/2021	Residual general waste – Veolia Woodlawn Bioreactor (transported via Veolia Clyde Transfer Station); Garden Organics – ANL Badgerys Creek (transported via Veolia Greenacre processing and transfer station). Management of household food waste is incorporated into the Resource Recovery and Waste Strategy recently adopted by Council. This strategy includes a commitment to tender for collection and processing of household food waste, most likely

LGA	Date response received	Written advice/feedback
		as FOGO, at the end of our current collection and disposal contracts in 2025. We have committed to tendering for collection of food waste, most likely as FOGO, at the end of our current collection and disposal contracts in 2025.
Canterbury-Bankstown	4/08/2021	General Waste – Veolia, Woodlawn; Recycling – Visy, Smithfield; Garden Organics – SoilCo, Kembla Grange. Council conducted a FOGO trial in 2017-2018 with mixed results. Generally speaking, the trial was conducted across both SUDs and MUDs but saw low participation and high contamination of the FOGO bin with non-organic material. Following the trial, we have explored other strategies such as: • Household Chicken Trial 2020: Council subsidised backyard chickens to select residents to collect and measure the amount of food scraps consumed by backyard chickens as a way to divert household food scraps away from landfill and reused as chicken feed. Throughout the duration of the short-term trial (3 months), it was found that chickens diverted 382 kgs of food scraps. • Promoting ShareWaste since 2019: ShareWaste is a free online platform that connects users to help accept or donate food scraps to local neighbours who can compost/have chickens/worm farms etc. Council have been promoting to our residents to join the ShareWaste community since 2019, with 712 kgs of food waste diverted from landfill by the ShareWaste community (to date) and 258 users registered in our LGA. You can visit cb.city/sharewaste for more information. • 'Scraps to Soil' food organics (FO) collection trial for MUDs 2021: Council offered a FO collection service to MUDs given the challenges they face such as limited greenspace for composting, restrictions due to shared common areas. During the 6-month trial, the selected apartments collected over 5000kgs of food waste that was diverted from landfill and turned into compost or processed to produce green electricity. Council is still collecting and assessing the results given the trial has just wrapped up.
Central Coast	19/08/2021	Fogo is being considered
Cumberland	29/07/2021	At this stage we are under contract for different streams, we will review all types including FOGO. The following web link provides further information: https://www.cumberland.nsw.gov.au/sites/default/files/inline-files/waste-services-charter.pdf All recycling waste goes to Visy and the rest to our processing plant to be treated and others to landfills
Fairfield	N/A	N/A
Georges River	23/07/2021	A separate Strategy for Food Organics will not be developed as this risks the waste stream being addressed in isolation. Council's

LGA	Date response received	Written advice/feedback
		Waste Strategy 2041 is a holistic document that addresses all waste streams.
Hawkesbury	18/08/2021	General waste is taken to Council's waste facility in South Windsor. Garden Organics is taken to Suez Environment Australia at Eastern Creek Sydney NSW. This is a processing plant where what is in the bin gets ground up into open wind rows to compost over time, reground up and turned into a reusable product in our gardens. Recycling goes to Visy Industries at Smithfield Sydney NSW. This is a MRF (Material Recovery Facility) where all that is in each bin is sorted into all various recyclable products to be reused. Kerbside clean-up waste is taken to Blacktown waste services at Marsden Park who have a resource recovery licence and typically recover between 40-50% of the material effectively diverting it from landfill. Council is currently putting together information together a strategy to deal with household food waste, which is to be built into all of the waste contracts. These contracts are due to expire in 2023.
Hornsby	20/07/2021	The following web links provide advice on Council's current and future waste management strategy: https://www.hornsby.nsw.gov.au/property/waste/waste-questions-and-tips https://www.hornsby.nsw.gov.au/__data/assets/pdf_file/0016/147112/Final-Waste-Matters-Strategy-Report-Digital.pdf
Hunters Hill	23/07/2021	Veolia processes red bin. It goes to a tip at Clyde, then to Goulburn. Green is treated by SUEZ at Eastern Creek - recovered as a fertiliser. For Food Organics, a 15-week trial under way later this year - 200 businesses will be involved in the trial.
Inner West	3/08/2021	Garbage, Veolia Woodlawn; Recycling, Visy Smithfield; Garden Organics Veolia, composted; Food organics (apartments), Earthpower anaerobic digestion Council's strategy will implement implemented Food recycling for apartments and working on FOGO over next few years (lack of transfer stations and processing facilities for Sydney Metro). NSW DPIE Organics section have more info on this online. Council is also focusing on food waste avoidance education and home composting. Council's food waste collection program currently collects approximately 12 tonnes food from apartments weekly.
Ku-ring-gai	20/07/2021	Waste is landfilled at Veolia's bioreactor landfill at Woodlawn. Some of the general waste is processed through Veolia's MBT facility also at Woodlawn in a joint contract with neighbouring Councils, where collectively 33,000 tonnes of the region's waste is processed each year. Garden organics are contracted to Suez for processing. The Food organics stream will be addressed by 2030

LGA	Date response received	Written advice/feedback
		Council is currently contracted with the above arrangement until 2025 with the option of contract extensions. Where after this point we will have to move to a FOGO collection as mandated by the EPA.
Lane Cove	23/07/2021	Veolia processes red bin. It goes to a tip at Clyde, then to Goulburn The green bin is treated by SUEZ at Eastern Creek - recovered as a fertiliser Council will run a 15-week trial for food organics collection later this year - 800 households will be included in the pilot.
Liverpool	20/07/2021	Red lidded garbage bin - Prior to October 2018, Council sent this material to the Kemps Creek AWT facility where a proportion of organic matter was diverted from landfill. Green lidded garden bin - This is taken to ANL at Kemps Creek Council is currently looking at implementing a FOGO collection. Implementation will more than likely be July 2024 which would align with the ending of our current disposal contracts. Council does not have a dedicated food waste strategy. Councils waste strategy looks at food waste. This will be released publicly in Q4 2021.
Mosman	4/08/2021	Waste is taken to the Veolia transfer station in Banksmeadow, paper and comingled recycling are taken to Kimbriki resource recovery facility. Green waste is also taken to Kimbriki for processing onsite.
North Sydney	N/A	N/A
Northern Beaches	30/07/2021	The contents of the red-lid bin first go to Belrose transfer station and then transported to Eastern Creek. The contents are sorted to remove any recyclables and the rest of the putrescible waste undergoes Advanced Waste Treatment. Mixed Waste Organic Output is currently sent to landfill after processing. The volume is reduced by approximately 1/3 after going through this process and it reduces approximately 43,200 tonnes of CO2 per year. In 2019 Council also distributed close to 4,000 compost bins and worm farms to residents to provide them with the opportunity to home compost their food organics. Council continues this offer to any resident who attends a workshop at the Kimbriki Eco House and Garden. We also promote some great waste reduction tips on our website: https://www.northernbeaches.nsw.gov.au/services/rubbish-and-recycling/waste-reduction The website includes leftovers, growing veggies from food scraps, preserving, chickens and more. The red-lid bin contents are processed at Global Renewables, Eastern Creek: https://www.globalrenewables.com.au/; The green-lid bin contents are processed at Kimbriki, with the compost process managed by Australian Native Landscapes: https://kimbriki.com.au/ & https://www.anlscape.com.au/ Council is currently comprehensively reviewing the feasibility of a range of options which Council could adopt to divert more

LGA	Date response received	Written advice/feedback
		waste from the red-lid bin and separately collect food scraps, which also meet the needs of the Northern Beaches community.
Parramatta	27/07/2021	Residual Waste: SUEZ UR3R Eastern Creek; Recycling: VISY Smithfield MRF; Garden Organics: SUEZ Eastern Creek; FOGO is currently being investigated as an option for council's next waste contract. FO trial currently underway with 1000 units. As outlined in Councils Waste Strategy – we are investigating alternative service arrangements for our next round of Waste contracts. This will include strong consideration of the reforms currently proposed by the NSW Government in their Waste and Sustainable Materials Strategy which include the potential mandating of the separation of food and garden organics for households. See - https://www.dpie.nsw.gov.au/our-work/environment-energy-and-science/waste-and-sustainable-materials-strategy. Noting that prior to the NSW Government revoking the orders on Mixed Waste Organic Output (MWOO) from Alternative Waste Treatment (AWT) facilities, the organic content from our residual bin was being separated out at the receiving facility and reprocessed into a commercial product for use on mine rehabilitation, forestry and agriculture. https://www.epa.nsw.gov.au/your-environment/recycling-and-reuse/resource-recovery-framework/mixed-waste-organic-material
Penrith	5/08/2021	Residual: Suez/SAWT Elizabeth Drive Kemps Creek; Organics: ANL / Kemps Creek All single-unit dwellings in Penrith LGA currently have a FOGO service. 80% of these properties have selected a service with a fortnightly residual waste bin and weekly FOGO bin. This service was rolled out in the urban areas in 2009, and the rural areas in July 2019. More information about our future developments can be found in our waste strategy https://www.penrithcity.nsw.gov.au/waste-environment/waste/waste-strategy Annual total estimates were reported in the tender evaluation. This can be found online at https://bizsearch.penrithcity.nsw.gov.au/pccbps/Open/2018/06/CNL_25062018_AGN_AT.PDF on Page 37
Randwick	19/08/2021	Council's garbage is sent to SUEZ's AWT facility in Badgery's Creek. FOGO is sent to Re.Group's facility at Shelharbour.
Ryde	21/07/2021	General waste – is sent to an Alternate Waste Treatment (AWT) plant at Woodlawn, Goulburn. All material in the general waste bins is sorted, any metals, and plastics are separated and recycled. Organic materials are separated and processed, and the output is used for mine remediation. Recycling is sent to the VISY MRF in Smithfield where all recycling gets sorted and processed; Green waste is processed by SUEZ at Eastern Creek and turned into compost.

LGA	Date response received	Written advice/feedback
		Currently, we encourage residents to compost, or worm farm their food waste through free workshops and heavily subsidised compost bins and worm farms as incentives to lowering their food waste from households. We also run behaviour change projects which specifically targets reducing food waste in households.
Strathfield	8/11/2021	Previously, organics were sent to an AWT facility (UR3 @ Eastern Creek) – the organic product from which is on-sold. The Gov't stopped this because of the build-up of heavy metals in the environment. Council's waste collection is contracted to Veolia. Red (landfill to Woodlawn) & Green (soil conditioners & composts to ANL). Council does offer an alternative food waste collection stream but is not in favour of this because it relies on high degree of compliance from the community.
Sutherland Shire	22/09/2021	Sutherland Shire Council does not offer a food waste collection service at this time; however, we are currently working with a consultant to develop our 20-year Waste Strategy which will provide strategic direction and an action plan for a food waste service in line with the requirements of the recently released NSW Waste and Sustainable Materials Strategy 2041. It is envisioned that councils waste strategy will be endorsed by mid next year.
Sydney	28/07/2010	Garbage/General Waste - Suez; Recycling – VISY recycling; Garden Organics - Veolia; Food Scraps Recycling Trial – EarthPower. There are no current expectations for the above to differ in the immediate future.
The Hills Shire	20/07/2021	Free composting & worm farming workshops hosted throughout the year & free compost bins/worm farms provided to households who attend. Council is looking to integrate a FOGO system by 2030 in line with the state government's new 20 year waste strategy: https://www.dpie.nsw.gov.au/our-work/environment-energy-and-science/waste-and-sustainable-materials-strategy The Council has received funding approval to develop a new waste strategy this financial year to align with the state government's new 20-year waste strategy, which would include strategies for household food waste.
Waverley	3/08/2021	Council may be required to change collection streams as a result of the NSW DPIE's Net Zero Organics by 2030 strategy, which focuses on the diversion of organic waste from landfill More information about processing for each stream can be found on this webpage: https://www.waverley.nsw.gov.au/residents/waste_and_recycling/where_your_waste_goes Compost Revolution, a program started by Waverley, Woollahra and Randwick Councils to help locals learn how to compost and reduce food waste, turned 10 in 2020. From a pilot program

LGA	Date response received	Written advice/feedback
		offering workshops to residents in the eastern suburbs, Compost Revolution has grown to become Australia's largest community of composters and worm farmers with more than 61,000 households joining in the revolution. Over 14,000 eastern suburbs residents have joined the program. Worm farming and composting reduces the amount of waste sent to landfill. It also reduces greenhouse gas emissions from transport. Since 2010, Waverley residents have diverted 3,708 tonnes from landfill saving 7,044 tonnes of GHGs; Council will soon undertake the development of the Environmental Action Plan, which will set out targets and actions related to waste, water, energy and biodiversity. Public consultation will follow council elections and be consolidated into the Community Strategic Plan.
Willoughby	N/A	N/A
Wollondilly	N/A	N/A
Woollahra	23/07/2021	Veolia does both General & FOGO streams. Council has been doing FOGO since 2008, however it has been through a few different processing facilities with varying levels of success. We are now with VEOLIA and a dedicated FOGO program which has been given a lot more publicity this year and allowed compostable bags as part of the program. We will do an audit at the end of the year to check participation rates and diversion. - FOGO bins are about 90% or more garden organics. After collection from your green bin, food and garden organics are taken to a transfer station, where it is collected by Australian Native Landscapes (ANL) and transported to their Badgery's Creek facility. There is an initial inspection at Badgery's Creek to remove contaminants. Material is then transferred to ANL's composting facility at Blayney. This material is processed by windrow composting. This involves forming long piles (called windrows) and mechanically aerating them periodically to make a uniform mixture.; The entire process takes approximately 20 weeks. High quality compost is produced and supplied to agricultural and horticultural systems. As you can see, unlike landfill, this is a sustainable waste management alternative which results in more positive, long term environmental outcomes for our community.

6.4. Distance-mass calculations used in the Collection sub-system

The first step in determining distance-mass calculations was data collection on: waste stream properties, waste collection vehicles, and the collection area.

The 21-tonne waste collection truck is a standard component of many waste collection fleets [64, 65]. Therefore, it was decided to proceed modelling waste collection capacity based off such a vehicle's dimensions. Truck capacity was assumed to equal 28 m^3, which is equivalent to a 7m x 2m x 2m void.

Next, the density of each possible combination of waste stream was determined as outlined in Column 1 of Table 6.4. Collection frequency (Column 2) was also determined based off a review of current practices in Greater Metropolitan Sydney, as well as from other case studies in Australia and globally.

Full garbage truck capacity (Column 3) in tonnes was then calculated as follows:

$$Truck\ capacity_{mass\ of\ particular\ waste\ stream} = \frac{28\ m^3}{density_{particular\ waste\ stream}}$$

Weekly household production rate (Column 4) was determined by multiplying the average weekly household production rate of residual, food organics and garden organics waste streams of 17.9 kg wk^{-1} [51] by the proportional breakdown of the functional unit as described in Section 4.2.2. From this, the bin weight of each type of waste stream combination (Column 5) could be determined by multiplying the weekly household production by the collection frequency:

$$M_{bin\ \ at\ end\ of\ collection\ cycle} = \dot{M}_{household,weekly} \times f_{collection}$$

Next, the number of households a truck can service (Column 6) was determined by dividing the full garbage truck capacity (Column 3) by a full bin's weight (Column 5), ensuring consistency in units:

$$No._{households\ serviced\ per\ truck} = \frac{Truck\ capacity_{mass\ of\ particular\ waste\ stream}}{M_{bin\ \ at\ end\ of\ collection\ cycle}}$$

Next, assuming that there are 1.856 million households in Greater Metropolitan Sydney, as based off the 2016 Census[66], the number of collection services required in the collection area per fortnight was determined (Column 7):

$$No._{collection\ services\ completed\ by\ collection\ fleet} = CEILING\left(\frac{No._{households\ in\ GMS}}{No._{households\ serviced\ per\ truck} \times \frac{Collection\ frequency}{2}}, 1\right)$$

Next, a model of the waste collection route length (Column 8) was considered. It is noted that the literature has attempted to model vehicle routing in the past[67], however such models are not designed for use in the present application, and did not yield collection distance as a well-defined distinct variable. As such, the model was developed as follows. It was assumed to construct the model based off one variable: the number of households visited on a single collection route; and two constants: an assumed average distance between the transfer station and the collection area, and the distance between each house along the collection route. After analysing the placement of the number of transfer facilities servicing Greater Metropolitan Sydney, the first constant, the transfer station-to-collection area distance, was assumed to equal 20 km, and the second constant, the average distance between houses, was assumed to equal 15 m. These assumptions are of course only based off a best guess of reality, which has been noted and suggested as one of the improvements in this report. Nonetheless, the LCA results demonstrate that the waste collection stage is only a small component that impact the overall performance between different strategies (see Section 4.4.2). Accordingly, distance travelled by the truck collection fleet is calculated by (ensuring consistent application of units):

$$d_{fleet,per\ fortnight} = No._{collection\ services\ completed\ by\ collection\ fleet} \times (2 \times d_{transfer\ station-to-collection\ area} + d_{between\ households} \times No._{households\ serviced\ per\ truck})$$

Column 9 describes the total fortnightly waste production in the area modelled. It is calculated by multiplying the population of the area under study by a full bin's weight, and the frequency (per fortnight) of waste collection:

$$M_{waste\ produced\ in\ GMS\ per\ fortnight} = No._{households\ in\ GMS} \times \frac{2\ weeks}{f_{collection}} \times M_{bin\ at\ end\ of\ collection\ cycle}$$

Finally, for ease of input into the openLCA software, the results were normalised to the mass-distance for one tonne of waste (Column 10):

$$Mass - distance = \frac{M_{waste\ produced\ in\ GMS\ per\ fortnight}}{d_{fleet,per\ fortnight}}$$

Refer to Table 6.4 for documentation of all assumed and calculated values used for this section.

Table 6.4: Waste profile and values calculated to determine distance-mass.

Waste combination	Density (kg m^{-3})	Collection frequency (weeks)	Full garbage truck capacity (tonnes)	Weekly household production rate (kg hh^{-1} wk^{-1})	Bin weight at end of collection cycle (kg)	Number of households a full truck can service	Number of truck services required in area modelled (fn^{-1})	Distance travelled by truck collection fleet (km fn^{-1})	Total waste production in area modelled (kg fn^{-1})	Normalised distance-mass for purpose of LCI input (t kg)
Column No.	1	2	3	4	5	6	7	8	9	10
RES	70[68]	2	2.0	6.1	12.1	160	11599	491798	22529	21.7
RES + FO	105[68]	1	2.9	13.9	13.9	210	17674	762633	51684	14.7
FO	296[68, 69]	1	8.3	7.9	7.9	1050	3535	197076	29155	6.7
FO + GO	250[68-71]	1	7.0	11.8	11.8	590	6291	307315	43732	7.0
GO	223[70, 71]	2	6.2	3.9	7.9	790	2350	121848	14577	8.3

6.5. Distance-mass calculations used in the rail transport sub-system

An identical procedure to that outlined in Appendix 6.4 was followed. For rail car volumetric capacity, it was assumed that each rail car could carry 33 m^2 (based off the standard volume of a 6 m long shipping container), and that each train could carry 116 shipping containers (based off the average length of rail car as given by Transport for NSW[72] being 700 m, and dividing this by the average shipping container length).

Waste combination	Density (kg m^{-3})	Collection frequency (weeks)	Loaded train capacity (tonnes)	Number of households a full train can service	Number of trains services required in area modelled (fn^{-1})	Distance travelled by trains fleet (km fn^{-1})	Total waste production in area modelled (kg fn^{-1})	Normalised distance-mass for purpose of LCI input (t kg)
Column No.	1	2	3	5	6	7	8	9
RES	70	2	268	22112	84	38640	22529	1.7
RES + FO	105	1	403	28916	129	59340	51684	1.1
FO + GO	250	1	959	81366	46	21160	43732	0.5
GO	223	2	855	108868	18	8280	14577	0.6

6.6. Ecoinvent Data Quality System

Ranking	Reliability	Completeness	Temporal correlation	Geographical correlation	Further technological correlation
1	Verified data based on measurements	Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations	Less than 3 years of difference to the time period of the data set	Data from area under study	Data from enterprises, processes and materials under study
2	Verified data partly based on assumptions or non-verified data based on measurements	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Less than 6 years of difference to the time period of the data set	Average data from larger area in which the area under study is included	Data from processes and materials under study (i.e., identical technology) but from different enterprises
3	Non-verified data partly based on qualified estimates	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Less than 10 years of difference to the time period of the data set	Data from area with similar production conditions	Data from processes and materials under study but from different technology
4	Qualified estimate (e.g., by industrial expert)	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Less than 15 years of difference to the time period of the data set	Data from area with slightly similar production conditions	Data on related processes or materials
5	Non-qualified estimates	Representativeness unknown or data from a small number of sites and from shorter periods	Age of data unknown or more than 15 years of difference to the time period of the data set	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)	Data on related processes on laboratory scale or from different technology

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