Final

Organics processing technology assessment

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Abbreviations and glossary

AD	Anaerobic digestion
CO_2-e	Carbon dioxide equivalents (an internationally recognised measure of the global warming potential of greenhouse gas emissions over a 100-year period)
EPA	Environment Protection Authority NSW
GHG	Greenhouse gas
GWP	Global warming potential (a measure of the potency of GHGs)
NGER	National Greenhouse and Energy Reporting

1. Introduction

This report provides an overview of a comparative assessment of the environmental impacts associated with food organics recovery technologies and management pathways, focusing on greenhouse gas (GHG) emissions and sequestration.

Food organics make up about 10% by weight of all commercial and industrial landfilled wastes, and 20-25% of putrescible C&I waste (NSW EPA, 2015). Food can make up over 60% of the waste from many commercial kitchens and cafes (NSW EPA, 2017). It also contributes 25-40% by weight of domestic garbage in areas of NSW without food organics and garden organics (FOGO) services and the proportion of food in landfilled garbage from multi-unit dwellings is typically high (Rawtec 2020).

Decomposition under airless conditions in landfill generates methane with a global warming potential equivalent to over 2.1 tonnes of carbon dioxide (t CO_2) per tonne for food (Commonwealth of Australia 2021), and produces leachate that can contaminate groundwater (NSW EPA, 1996). Food also creates biochemical conditions in landfill that promote degradation of, and methane release from, other waste and mobilisation of heavy metals and other toxic chemicals (Bareither et al., 2013; Krause, 2016). Modern engineered landfills mitigate these risks by containing and treating leachate, and capturing methane from landfill for biogas energy recovery. However, they do not prevent all leaks, and leave a legacy of potentially polluting material buried for future generations to manage for centuries to come.

Food can also be recovered to produce soil conditioners, bioenergy and potentially protein through a range of organics processing technologies and management pathways. These include:

- **Landfill.** This can be considered as the 'baseline' of what would happen if the food was not otherwise diverted. The type of landfill receiving waste will impact on the environmental outcomes. In this review, we have considered the scenarios:
  - Minimum gas capture. This typifies smaller regional landfills where landfill gas is either not managed or is not managed until the landfill has closed. Most emissions from food will have occurred by then. In this scenario, it is assumed no landfill gas from food is recovered and oxidised.
  - Average gas capture with energy recovery. This typifies larger landfills that progressively capture landfill gas as cells close and oxidise the gas, but do not install gas energy recovery systems until the landfill has been operating for a long time. However, because food degrades rapidly in landfill, most emissions will occur within five years after deposition in landfill and landfill gas management systems are often installed after a significant portion of these emissions have already occurred.
  - Above average gas capture with energy recovery. This describes landfills designed and operated to maximise gas energy recovery. They typically start recovering gas from organics within two years of it being deposited in landfill and convert the gas to energy. These can be expected to capture 50-60% of methane emissions from food.
- **Offsite aerobic composting**, including aerated windrow and in-vessel composting of food materials.
- **Offsite anaerobic digestion (AD) with biogas energy recovery**, including AD facilities with production of soil additives from digestate sludges.
- **Offsite and onsite protein farming** using insect larvae to process food. Food can be collected and taken to a central protein farm or to onsite units that are installed and managed by a supplier.

- **Onsite management options**, where food is processed using a technology at the site on which the waste is generated. The treated outputs are either managed onsite or transported to another site for further treatment or use. Technologies considered are:
  - **Dehydration systems** that use heat to dry food organics into 'chips' of desiccated food that can be dug into soil onsite or transported to a secondary processor such as a composting facility.
  - **Bio-dehydration systems** that in addition to drying food, treat the organics with biological agents and/or enzymes to achieve some biodegradation and treatment of the dried output that can be dug into the soil onsite under certain conditions (according to the relevant resource recovery exemption) or taken to secondary treatment.
  - **Liquification for collection and transport to a secondary treatment site**. In NSW a commercial provider of 'Pulpmaster' systems promotes units that mechanically macerate and liquify food and store it in tanks that are pumped out and taken to AD biogas generators, but could also be composted or vermicomposted.
  - **Onsite protein farming** units located at sources of organics but managed by service providers.
  - **Onsite composting and vermicomposting**. These can be used where sites have sufficient room to process the food waste they generate and use the outputs onsite.

1.1 Data uncertainty and significance

The scope of this analysis was for comparative analysis of management options using best available data to identify which factors (or 'variables') have greatest impact on the net GHG emissions and other environmental performance of food organics management options. An in-depth life cycle assessment was not required.

The analysis involved reviewing available data and information on the performance and GHG intensity of management options to estimate net GHG emissions from modelled options. The modelling converted the assessment to standardised units of kg CO_2-e per wet tonne of food input.

In many instances, a range of data on performance and GHG intensity of management options is available. Blue Environment needed to aggregate and generalise to select the most representative estimates for use in modelling. Where there is significant data uncertainty for key variables, high and low performance scenarios are included.

Not all emissions are included in this analysis. Emissions per wet tonne of food input that are not directly applicable to comparing technologies are excluded, for example, emissions from transport of finished products to end use markets.

Net GHG emissions are considered a proxy for net environmental benefits of the different management options. This is because GHG impacts are the most significant environmental impact associated with the management of food waste, and management issues associated with energy use, transport and traffic, processing, and use of products can all be attributed a GHG emissions factor. Issues that fall outside this include: additional water consumption (for commercial composting systems); local amenity impacts from odour, noise, dust and pest animals; and potential biosecurity and contamination risks associated with management options. These impacts are noted where relevant.

2. Comparative analysis of options

2.1 Management pathways

For each processing technology and management pathway, food waste management from the point of food waste generation to the final use or disposal of process outputs or residues have been considered.

A summary of the management pathways assessed are summarised in Table 1 including some of the broad advantages and limitations of each.

Table 1 Summary of management pathways considered in the assessment

Management pathway	Description	Advantages	Limitations
Landfill disposal in mixed general waste.	Food waste is landfilled with general waste.	• May reduce collection costs. • Biogas energy can be recovered from larger landfills (but gas capture from food is generally too low for this to offset the impact of methane emissions from food).	• Does not meet state and national government objectives of diverting organics from landfill. • Food organics in landfill poses significant environmental risk due to generation of methane, odour and leachate.
Collection and transport to aerobic composting facilities.	Food waste is separated at source, collected and processed to produce compost products. Products are then transported and applied to land.	• Composting is proven technology that can process a variable range of organics. • Compost products improve soil and reduce the need for other inputs.	• May increase traffic - collection vehicles and transport of products to point of sale/land application.
Collection and transport to an AD facility, with digestate to fertiliser production or composting.	Food waste is separated at source, collected and delivered to a facility that used biological digestion to produce biogas energy and potentially fertiliser from digestate.	• Produces renewable bioenergy and fertiliser. • AD is proven technology.	• May increase traffic - collection vehicles, transport of digestate for offsite treatment and transport of raw or improved digestate to point of sale/land application. • There are currently limited facilities for food waste treatment via AD with biogas energy recovery in NSW.
Collection and transport to an offsite protein farm.	Food waste is separated at source, collected and delivered to a facility using insect larvae to produce protein for stockfeed and a fertiliser.	• Produces a potentially high-value protein. • Produces an organic output that can be used as fertiliser.	• The area needed to process food. • May increase traffic - collection vehicles, transport of protein to point of sale, transport of by products to point of sale/land application. • Limited facilities are currently available, but a service

Management pathway	Description	Advantages	Limitations
			provider offers access to centralised units in the Greater Sydney area as well as onsite units that they can install and manage for larger food waste generators. • Energy consumption to heat and aerate insect habitat units.
Onsite dehydration or bio-hydration with desiccated organic outputs being collected and transported to secondary treatment (composting).	Food waste is source separated and processed using onsite dehydration or bio-hydration equipment, and the dried residual is periodically collected and processed by a facility at another site.	• Reduces the weight, volume of food organics needing to be collected by 80-90%. • In large residential flat buildings may require less space than food waste bins. • Reduces the messiness and odour potential of collected materials prior to transport offsite.	• May have high energy consumption per tonne of food processed. • May generate wastewater that needs to be discharged to sewer.
Onsite dehydration or bio-hydration with desiccated organic output managed onsite.	Organics are source separated at site, processed using dehydration or bio-dehydration equipment, and the residual organics are incorporated into gardens onsite.	• No offsite transport or processing. • Treated outputs add nutrient and organic matter to soil.	• See above. • Not all sites have sufficient gardens for ongoing application of outputs. • Dried organics can have short-term negative impacts on soils and plant growth. • If dried organics have a high salt content, they have more lasting negative effects on soils and plant growth. • Some potential pathogens can survive the process. • Stored dried organics can foster some potential gastroenteritis causing pathogens, so need to be handled with caution.
Onsite protein farming	Onsite enclosed units are installed and maintained by a service provider that harvests protein and fertiliser	• Avoided storage collection and transport of food waste • Produces a potentially high value protein. • Produces an organic output that can be used as fertiliser.	• Energy consumption to heat and aerate insect habitat units. • Organic outputs need to go to approved secondary processors or reuse.

2.2 Assessment parameters

A Microsoft Excel-based model was developed to allow comparison of the environmental impacts of different onsite organics management options. This mainly focused on net GHG emissions of the processing options and management pathways. The assessment parameters considered were as listed below.

Greenhouse gas emissions

The main potential GHG emissions from food organics management are:

- **Emissions from landfill.** The most significant potential source of GHG emissions from food is fugitive emissions of methane from the anaerobic decomposition of organic matter in landfills. Methane has a global warming potential (GWP) equivalent at least 28 times stronger than CO_2[1]. Food in landfill also provides moisture and nutrients that speed up decomposition of other organics in landfill, including high carbon materials such as paper and timber. This increases the rate of GHG emissions from landfill. National Greenhouse and Energy Reporting (NGER) factors suggest that in landfill food organics will generate methane with a GWP over a 100-year period of at least 2.1 t CO_2-e per tonne of food. Although many NSW landfills receiving putrescible waste have gas recovery systems installed, these do not capture all gas and often systems are not installed, or collected gases oxidised, until 3-5 years after waste is deposited. During that time, most of the emissions from food will have already occurred.
- **Emissions from collection and transport fuel use.** This applies to options with offsite management of either untreated or treated organics. NGER emissions factors were used to estimate these emissions for different vehicle types.
- **Emissions from energy use in processing.** Power and fuel use emissions were considered. NGERs emissions factors for NSW mains grid power and fuels were used based on available data for the different technology types.
- **Fugitive emissions from processing.** Although they are significantly less than fugitive emissions from landfill, some methane and nitrous oxide will be produced by most organics processing systems. Data for these emissions is variable and often inconsistent, but effort has been made to identify low, medium/average and high emissions profiles where such emissions are significant.

Potential GHG emissions mitigation

All the organics processing technologies help to divert food organics from landfill, and therefore mitigate emissions compared to landfilling.

Some of the organics processing technologies and management considered (AD and landfill with biogas energy recovery) can also reduce emissions of GHGs by recovering biogas energy that currently substitutes for fossil fuel generated power. This 'offset' can be expected to decline over time as the transition from fossil fuels to low emissions and renewable energy options occur. The offset was modelled on current National Greenhouse Accounts Factors (Commonwealth of Australia

[1] Global warming potential (GWP) is a measurement of the relative 'strength' of various GHGs over a 100 -year period and expressed in terms of CO_2-e. Methane is a strong GHG but does not persist in the atmosphere for more than 10-15 years. This means that over 100 years, methane has a GWP of 28-36 CO_2-e over 100 years, but around 65-85 CO_2-e over a 20–30-year period. At a time where the challenge is to rapidly reduce emissions to avoid potential 'run-away' global warming, a case for applying a higher GWP to methane could be made. Our modelling of the warming potential of CH_4 emissions use the Australian National Greenhouse and Energy Reporting emissions factors of 28 CO_2-e.

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2021 factors for electricity in NSW and also for scenarios where there are no emissions from energy (i.e. 100% net zero emissions energy). This allows comparison of technology options in the lower emissions future.

Consideration was also given to offsets from soil carbon and fertiliser substitution and, in the case of protein production, the offsets associated with substituting other forms of protein.

Water consumption

Storage for collection (liquid storage and vehicle collection systems) organics processing technologies uses water to liquify organics before treatment. Composting also typically requires additional water, but the high moisture content of food waste means additional water is rarely needed to compost food waste. It has been assumed that composting food requires no additional water.

3. Model assumptions and data

The comparative modelling of management pathways is detailed in this section. References and the basis for assumptions are provided in Appendix A.

3.1 Transport

Many of the organics management pathways involve the transport of either untreated or treated organics to offsite primary or secondary treatment as well as transport of processed outputs to the site of end use. Table *2* summarises the modelling assumptions and resulting CO_2-e emission per tonne of food waste.

Table 2 Summary of assumptions used to estimate emissions from collection and transport of organics removed from sites

Option component	Description	Assumptions used in modelling
Collection of food in general waste or via FO service (C&I or MSW)	Average waste collection vehicle servicing C&I and multi-unit dwellings collecting organics. Food comprises 25-30% of the weight of general landfilled C&I waste and >50-60% of waste from many food retail and hospitality businesses.	Fuel use per km: 1.8 L Km per hour: 20 km Fuel use per hour: 36 L Tonnes collected per hour: 7.5 t/hr Fuel use per tonne = 3.0-4.8 L/t CO_2-e emissions per L = 2.72 kg CO_2-e emissions per tonne = 8.2-13.1 kg Other issues: Increased traffic congestion if additional collection vehicles are needed
Transport of food in general waste or via FO service. These figures have also been used for the transport of pre-processed organics to secondary processing.	Collected organics or waste transported by small collection vehicle, or road or rail transport to disposal sites	**Small vehicle (for disposal to sites within 50km of source):** Av vehicle load: tonnes: 8 t Fuel use per 100 km: 28.6 L Fuel use per tonne/km: 0.04 L/t.km CO_2-e/L: 2.72 kg CO_2-e/tonne/km: 0.098 kg **Bulk haul vehicle:** Av vehicle load: 25 t Fuel use per 100 km: 53 L Fuel use per tonne/km: 0.02 L CO_2-e /L: 2.72 kg CO_2-e /tonne/km: 0.058 kg **Rail transport** CO_2-e /tonne/km: 0.026 g
Transport of organic outputs to end use	Treated organics from onsite systems and organic outputs from secondary processes to end uses	An emissions factor of 0.058 kg CO_2-e/t.km was assumed for transporting outputs to market. Total emissions will depend on processing weight-losses. Assuming 80-90% losses, emissions would be 6-11 g CO_2-e/t of input food per kilometre. Assuming most products are used within 50 km of where they are produced, the impact will be less than 0.3-0.6 kg CO_2-e/t.km per tonne of input food. Due to these low numbers and the unknown distances to each end use, transport to end use was not included.

These assumptions were used in assessing management options requiring offsite collection and transport of raw or pre-treated organics.

3.2 Landfill options

Table 3 shows assumptions used in modelling net GHG impacts of landfilling food. These have been used as a baseline to show how diversion of organics reduces GHGs.

Table 3 Assumptions for estimating emissions from landfill

Option component	Description	Assumptions used in modelling
Collection	Stop-start collection of general waste containing food.	CO_2-e emissions per tonne = 8.2 - 13.1 kg.
Transport	Assumed transport mode and distances.	Modelled round trip transport distances of: - 100km = 10.9 kg CO_2-e/t (small vehicle) - 200km = 10.9 kg CO_2-e/t (large vehicle) - 400km = 21.8 kg CO_2-e/t (large vehicle) - rail from Sydney to Woodlawn (450km return) = 22.5kg CO_2-e /t.km.
Deposition in landfill	Compaction and covering of materials.	Fuel use: 1.1 L /t waste Emissions per L of fuel: 1.82g CO_2-e Emissions per tonne of food: 2g CO_2-e.
GHG emissions from landfill	Methane emissions.	Generated from food: 2.1 t CO_2-e/year.
Level of landfill gas recovery and oxidisation from food	Capture of life cycle emissions of methane from food. Gas recovery and oxidisation systems are typically not installed	Basic: 0% = 2.1 CO_2-e /t food Average: 30% = 1.47 t CO_2-e /t food Best practice: 60% = 0.84 t CO_2-e /t food.
Energy recovery from landfill gas from food	Captured biogas converted to electricity at a rate of 33% efficiency.	Carbon offset from landfill gas energy (current emissions profile for electricity in NSW) Basic, per t food: 0 kWh = no offset Average, per t food: 115 kWh = 0.11 t CO_2-e offset Best practice, per t food: 229 kWh = 0.22 t CO_2-e offset.
Sequestration of carbon	Assume that non-degraded organic carbon in landfill from food remains in landfill for over 100 years.	Degradable organic carbon in food: 15%, fraction degraded = 84%. Carbon remaining in landfill per tonne of food: 24 kg. Equivalent amount sequestered: 88 kg CO_2-e /t food.

Other impacts

Landfilling of food also generates leachate and creates biochemical conditions that result in more rapid degradation of other organics and mobilisation of heavy metals and other toxins. Nitrates, organic toxins and organic compounds containing heavy metals can leak from landfills and contaminate groundwater and migrate to surface water (Krause, 2016). Most modern landfills are engineered to contain leachate, but some leakage occurs from most sites and landfill liners will eventually fail (US EPA, 2017). The quantities of leachate generated will depend on rainfall and evaporation at the landfill site but, because food has a high-water content and breaks down into

CO_2, methane and water, it is a source of liquid and leachate. One tonne of food can contribute over 800 litres of water. Some of this will be lost as water vapour, but most will contribute to leachate.

3.3 Offsite composting systems

A common method of managing food organics is onsite source-separation and collection and transport to a commercial composting facility. These facilities use controlled aerobic (i.e. with oxygen) processes to convert raw organics into soil-conditioner and mulch products. All composting systems mix food with other shredded woody organics and maintain moisture, oxygen and temperature conditions to favour the composting bacteria that convert raw organics into useful humus and other beneficial soil-conditioning outputs. The common systems used are discussed below.

Open-turned windrow systems place mixed organics into piles or ‘windrows’ that are kept aerobic through mechanical turning. Piles are turned at least three to five times during the initial ‘hot’ composting phase and then turned additional times during the product curing and maturation stage. This, as well as pre-composting mixing and post-composting screening of outputs, uses considerable amounts of fuel. Composts typically need water to be added to piles to keep conditions moist enough for bacteria to thrive. However, because food consists mainly of water and highly degradable organic compounds, Blue Environment has assumed no additional water is needed to compost food waste.

The benefits of this process are that it has lower capital costs than other composting systems and can be undertaken on a smaller scale in regional areas.

Limitations of this system include: higher odour risks than other composting methods; more fuel use per tonne; slower processing so more space required; and more exposed compost piles adding to odour and dust risks. For this reason, open window facilities are not suited to management of food organics onsite within 1,000-2,000 m of sensitive land uses such as houses, recreational areas and workplaces. There are also higher emissions of the potent GHGs methane and nitrous oxide where piles become oxygen starved and are then cut open for turning.

Aerated pile systems form compost piles over mechanised aeration piles or floors that pump air through the base of materials. Some systems use covers to contain exhaust air. These systems have the advantage of always keeping organics aerobic and being able to prevent piles from overheating by using air flow. They are suited to receiving solid food, liquified food, dehydrated food, and grease trap interceptor organics. Compared with open-turned windrow systems:

- piles need less frequent turning, reducing fuel needs
- piles can typically be taller so the site footprint and exposed surface area is lower
- the composting process can be completed more rapidly
- capital costs per tonne of capacity is typically higher and operating costs are lower
- fuel use from pre-processing, movement of materials and post-compost screening is lower.

In-vessel aerated composting systems shred and mix organics before loading it into enclosed vessels that are kept aerobic through pumped aeration through the floor. Exhaust gases are collected and treated to remove odour. In-vessel systems contain odour risks and can rapidly pasteurise and partially stabilise organics. However, unless materials are processed in vessels for 4- 6 weeks, outputs need maturation using turned or aerated windrow treatment. These facilities can receive solid food, liquified food, dehydrated food, and grease trap interceptor organics. Energy use and emissions from in-vessel facilities are like aerated pile compost systems. They typically have higher capital costs per tonne of capacity than aerated pile or open-turned windrow systems.

The GHG impacts from power use in aerated pile and in-vessel composting systems can be reduced by purchasing renewable power or using onsite solar power, to either directly power aeration units or to generate and export to the grid power equivalent to, or potentially greater than, that used to power the aeration units.

Modelling assumptions for composting systems are shown in Table *4*.

Table 4 Assumptions for estimating emissions from offsite composting

Component	Description	Assumptions used in modelling
Collection	Stop-start collection of general waste containing food.	CO_2-e emissions per tonne = 8.2 - 13.1 kg.
Transport	Assumed transport mode and distances.	Have modelled round trip transport distances of: - 100km = 10.9 kg CO_2-e/t (small vehicle) - 200km = 10.9 kg CO_2-e/t (large vehicle) - 400km = 21.8 kg CO_2-e/t (large vehicle).
Energy use in processing	Energy from compost management process.	**Open turned windrow:** Fuel use per tonne: 5-6 L (average 5.5 L) Power use per tonne: 0.13 kWh CO_2-e/tonne food: average 15.1 kg With green power: 15 kg CO_2-e/tonne food **Aerated piles and in-vessel:** Fuel use per tonne: 0.5-1 L Power use per tonne: 4-16 kWh (average 10 kWh) CO_2-e/t food: average 10.3 kg With green power: 1.4 kg CO_2-e/tonne.
Other processing emissions	Methane and nitrous oxide emissions.	Turned windrow: 0.05-1.0 kg CO_2-e/t (average 0.075 kg CO_2-e/t), which assumes good management of piles. Aerated pile: 0.05 kg CO_2-e/tonne.
Sequestered carbon	% of carbon in food sequestered to soil.	Sequestered carbon: 8 kg CO_2-e /tonne of input food Compost will also improve soil function and add nutrients that will result in increased plant and root growth and soil carbon, but it is difficult to reliably quantify this. Previous US EPA modelling of soil carbon benefits assumed this benefit of compost application would be similar to the benefit achieved from the carbon contained in the compost. However, in the absence of evidence that this would occur in all situations, this benefit has not been included in the modelling.
Fertiliser effect and benefits	Nutrients in composts have potential to substitute for synthetic fertilisers (mainly nitrogen and phosphorous,	It is difficult to quantify fertiliser benefits because composts are not widely used primarily as fertiliser. They will provide some nutrient benefit and have potential to reduce synthetic fertiliser use, but this is not a given in most applications of compost. The nitrogen, phosphorous and other nutrients in compost are generally released slowly and although strategic repeated use of products could result in reduced need for synthetic fertilisers, the composts are generally not used as

Component	Description	Assumptions used in modelling
	but also some micro nutrients).	fertilisers. Typically, less than 10% of nitrogen in composts are available to plants when first applied (Lee 2016). There is also uncertainty about the proportion of nitrogen in food organics that is retained in the final compost because significant losses of nitrogen can occur during the composting process (Hwang *et al*, 2020). The potential GHG benefits of nitrogen substitution from compost are estimated as follows: • Assuming average N content of food is 0.75% wet weight and 3% dry weight. • If there are 50% losses during composting = 3.75 kg N retained in compost per wet tonne of food input. • Assuming that 90% of this nitrogen becomes available to plants over three years = 3.4kg N fertility per tonne of input food organics. • The GHG benefits of N fertilisers are in the order of 6kg CO_2-e/kg of N as urea or ammonia nitrate fertiliser (Cowie, 2004; Walling and Vaneeckhaute, 2020). • Therefore, the reduced GHG emissions from compost used to substitute for synthetic fertiliser is estimated at around 20kg CO_2-e/tonne of input food. • Nitrous oxide emissions and soil carbon benefits from N in compost use will depend on the maturity of product and how and where it is applied. It is assumed this will be negligible per tonne of input food and similar or less to emissions from the application of other sources of nitrogen such as fertiliser or manure. For these reasons emissions and soil carbon benefits from N in compost have not been included in the estimates of net impacts. The fertiliser/fertility benefits of compost from other nutrients per unit of food are minor. For example, the phosphorous contribution per tonne of mixed food is expected to be less than 0.5-1.0 kg per wet tonne (based on the P content of common food types) and plant-available P in composts made from municipal food and garden organics is typically low. The GHG intensity of P fertilisers depends on the type of fertiliser used varying from 3.3- 40 kg CO_2-e/kg of P (Cowie, 2004; Walling and Vaneeckhaute, 2020), which would mean potential emissions reductions of less than between 1.7 and 40kg CO_2-e/tonne of input food. Because plant available P in most composts is low, any fertiliser substitution would occur over time and may not appreciably reduce farmers actual or perceived need for P fertiliser. Composts can stimulate soil biology to make native and mineral P more plant available, but this is not a function of P in the compost or food inputs. Similarly, other nutrients from food inputs are expected to have low fertiliser value for tonne of input food and no GHG emissions savings from reduced fertiliser input for these have been assumed in the modelling. Based on this analysis, the combined fertiliser substitution benefits of composting food are assumed to be 20-30 kg CO_2-e per tonne of input food composted.

3.4 Offsite anaerobic digestion systems

The Greater Sydney area has access to AD bioenergy gas facilities that can convert food and other wet organics to methane which is combusted to generate power. The Earthpower facility also converts digestate sludge from the AD plant into fertiliser. Other AD facilities for food and other waste organics are being developed and expanded.

Sydney Water recovers biogas energy from wastewater treatment sludges and is actively pursuing supply of macerated food organics to increase biogas energy production. Sydney Water is also developing options for injecting cleaned biogas into the reticulated gas network to substitute for fossil-carbon natural gas. The AD options considered below describe facilities where food and other organics are transported to the facility by vehicle and not by sewer.

These existing AD facilities can receive solid, liquified and dehydrated food, and grease trap interceptor organics. AD converts food waste to a renewable, carbon-neutral substitute for natural gas and contributes a nutrient-rich 'digestate' sludge that can substitute for GHG-intensive synthetic fertilisers. The AD process is contained, limiting the potential for offsite odour if receival areas are also fully contained. The Earthpower facility serving Greater Sydney exports 80% of the power it generates (i.e. 20% of the power is used to operate the facility). Physical contamination of input streams needs to be well managed to avoid blockages and contamination of digestate, but generally AD is well suited to source-separated food and other wet organic streams. At the time of writing, however, there are few options to send food to AD in most of NSW.

Assumptions about the performance of AD facilities are shown in Table *5* (overleaf).

Table 5 Assumptions for estimating emissions for offsite anaerobic digestion

Option component	Description	Assumptions used in modelling
Collection	Stop-start collection of general waste containing food.	CO_2-e emissions per tonne = 8.2 - 13.1 kg .
Transport	Assumed transport mode and distances.	Have modelled round trip transport distances of: - 100km = 10.9 kg CO_2-e/t (small vehicle) - 200km = 10.9 kg CO_2-e/t (large vehicle) - 400km = 21.8 kg CO_2-e/t (large vehicle).
Processing emissions	Fugitive emissions from process.	< 25 kg CO_2-e /tonne of food (NGERS Solid Waste Calculator, 2019-20). The NGERs figure for fugitive emissions may be higher than the performance of Earthpower and Sydney Water facilities.
Energy offsets	Offsets for fossil fuel power generation.	Assumed 300 kWh/tonne of food, with 80% exported to the grid. Offset emissions: 213.6 kg CO_2-e/t of input food.
Sequestered carbon	% of carbon in food sequestered to soil.	Assumed the equivalent of 30% of organic carbon in food remains in digestate and 10% of this persists in soil for 100 years. Sequestered carbon: 16.5 kg CO_2-e /tonne of food. Digestate will improve soil function and add nutrients that will result in increased plant and root growth and soil carbon, but this has not been quantified.
Fertiliser benefits and substitution of synthetic fertilisers	Nutrients in digestate have potential to substitute for synthetic fertilisers (mainly nitrogen and phosphorous, but also some micro nutrients).	The AD process will concentrate nutrients in food in digestate sludge that, at Earthpower, is converted to a solid fertiliser pellet or granule, or otherwise sent for secondary treatment via composting. The main fertiliser benefit will be nitrogen substituting for synthetic fertiliser. Assuming: a N content of input food of 7.5 kg N/wet tonne of food; retention of 80% of N in the digestate; and the N is mostly in a plant available form and will be released within the first 3 years, then the fertiliser substitution is in the order of 6 kg N per wet tonne of input food. If N fertiliser substitution reduced GHG emissions by 6 kg CO_2-e/kg of N fertiliser, then the digestate used as a fertiliser could reduce emissions by around 36kg CO_2-e per wet tonne of food input. It is assumed GHG emissions and soil carbon benefits from the use of the digestate would vary depending on where and how it is applied, but would be similar to those from use of synthetic fertilisers or manures so these have not been counted in the analysis.
Transport of solid outputs to secondary treatment or markets.	Digestate from AD facilities need to be transported to either secondary processors or markets for products.	Transport emissions from bulk haul transport of digestate to markets are estimated to be around 0.5-0.8 kg CO_2-e/tonne of input food per 100 km of bulk haul transport. For this reason, transport emissions from the transport of digestate-derived products to end-markets has not been included in the assessment because this will be small and vary depending on where the facility is located and the nature of the digestate product. Because of losses during processing the quantities of digestate per tonne of food input will be low.

3.5 Onsite hydration and bio-dehydration systems

These units use electrical or gas power to heat and dry organics, reducing it to friable 'flakes' of desiccated food. With the loss of water and some decomposition, the weight and volume of food waste requiring management is typically reduced by 80-90%. Some systems also treat the organics with biological agents and enzyme additives to partially biodegrade organics and to convert it into a form that is said to biodegrade more rapidly when added to soil. The outputs from such units need to be managed through an EPA-approved management pathway. This typically means transport to a secondary processor such as an approved composter or, where the dehydration unit is located at a site with suitable garden areas, reuse as a soil additive. The outputs from these unit are typically very biologically active once they are rewetted, and wetted organics will often rehydrate into recognisable pieces of food matter. When added to compost or AD (or if landfilled) it is assumed the organic inputs will have similar characteristics to 'wet' food waste.

Dehydration and bio-dehydration units can convert large volumes of potentially odorous wet food organics into a neutral/'baked'-smelling form that, if kept dry, can be stored for longer. Along with the very significant reduction in volume and weight, this reduces collection costs. For example, a commercial kitchen that would otherwise require daily collection of a 120L wet food bin might have a single weekly, or even fortnightly, collection. This reduces not only private costs but traffic congestion and pollution impacts too. Our modelling assumed reductions in collection and transport emissions of 80%. Another advantage is that dehydrated organics can often be managed by open-windrow composting systems because of lower odour potential. As discussed above, these have lower gate fees than alternatives and are often more accessible.

Limitations of the systems include:

- If sufficient liquid condensate is generated by units, approvals may be needed to discharge this to sewer. However, most commercial systems vent water moisture to the atmosphere and have small volumes of condensate with low organic load that can typically be managed without the need for additional approvals.
- High energy consumption per kilogram of food. This has a financial and environmental impact. The GHG emission intensity of the process can be reduced if the unit is powered by renewable energy. Our modelling considered scenarios using conventional electricity or renewable energy. Those considering using such systems should ask about energy consumption and consider purchasing renewable energy to power them.
- Air emissions are potentially odorous, which needs management. Some units can pass exhaust through odour filters, but this adds to costs.
- Dehydrated organics are immature and may result in nutrient draw down and short term phytotoxicity when first added to soil. This will dissipate rapidly if the dehydrated organics are applied at rates recommended by the system provider. Use outputs from these systems requires EPA approval and, in most instances, need to go to a secondary processor (usually composting or AD) for further treatment.
- Dehydrated organics can rehydrate under humid conditions if they are not stored in sealed containers.
- Dehydrated organics may not be fully pasteurised by the process and can contain bacteria that may cause gastroenteritis if ingested.

Blue Environment has reviewed technology suppliers' information for different types and scales of dehydration and bio-dehydration systems. A summary of assumptions used in modelling is shown in Table *6* (overleaf). This considered best case, expected case and worst-case scenarios.

Table 6 Assumptions for estimating emissions for onsite dehydration and bio-dehydration

Option component	Description	Assumptions used in modelling
Energy use in processing	Energy is needed to heat food in chambers.	The energy consumption per unit of food varies depending on the size of units and whether that are filled to capacity each time. Based on specifications of units., the following scenarios have been modelled: Low energy use = 570 kWh/t ≈ 0.5 t CO2-e /t food Average energy use = 1,000 kWh/t ≈ 0.9 t CO2-e /t food High energy use = 1,350 kWh/t ≈ 1.2 t CO2-e /t food. The energy consumption per tonne varies significantly. It is recommended any business or organisation considering installing a unit asks about energy consumption per day and per tonne of food processed. Note GHG emissions from energy use could be reduced through the purchased of renewable power.
Processing emissions	Fugitive emissions of methane and nitrous oxide could occur from processing.	It has been assumed negligible GHG emissions occur during process because materials are maintained under aerobic conditions and heated to temperatures that would inhibit most biological activity.
Collection	Food mass and volume reduced by 80-95%.	85% reduction in emissions per tonne of food input results in emission of 1.2-2.0 kg CO2-e /tonne of input food.
Transport	Food mass and volume reduced by 80-95%.	85% reduction in emissions per tonne of food input results in emission of 0.8 kg CO2-e /tonne of input food if delivered to a processing site 25km away.
Secondary processing emissions	Assumed composting used.	It is assumed the desiccated food will have a similar emissions profile as raw food sent to processing.
Sequestered carbons	Proportion of carbon in food that is sequestered to soil carbon. Soil carbon sequestration achieved from soil improvement.	Sequestered carbon: 8kg CO2-e /tonne of input food. This is based on the proportion of organic carbon in food that will remain after composting and persist in soil. Compost will also improve soil function and add nutrients that will result in increased plant and root growth and soil carbon, but it has been difficult reliably quantify this. Previous US EPA modelling of soil carbon benefits assumed this benefit of compost application would be like the benefit achieved from the carbon contained in the compost. However, in the absence of evidence that this would occur in all situations, this benefit has not been included in the modelling.

3.6 Onsite and offsite protein production

A novel option for the management of food waste is to use it to raise insect larvae that can be harvested for protein. The commercial outputs from this process are protein suited to stockfeed (insect meal) and nutrient-rich soil conditioner (frass). The insect larvae and breeding adults are raised in secured units, with control of air emissions. The process is aerobic, and the insect species used do not generate significant methane or nitrous oxide. Food waste can either be collected and taken to offsite processing facilities, or onsite units can be installed and maintained by businesses providing this service.

The benefits of protein farming include:

- reduced collection and transport costs (if units are onsite)
- fully contained management of food with odour control
- production of protein, which can substitute for more GHG intensive sources of protein and produce a non-restricted animal material stockfeed that can be fed to mammalian livestock
- production of an organic fertiliser.

Potential limitations include power use to heat and aerate units, the need for management of liquid leachate and condensate and the current need in NSW for outputs to go to secondary processing if they are managed offsite. Processing emissions and sequestered carbon are expected to be similar per tonne to aerated in-vessel composting systems. Energy demands can be relatively high and are expected to be comparable to the more efficient dehydration units on a per tonne basis. Those considering using such a service should ask about energy consumption and consider purchasing renewable energy as part of the supply contract. Some nitrous oxide and other GHG emissions can occur during processing, with estimates of in the order of 8-15 g CO_2-e/kg of dry protein output (Parodi et al, 2020)

The GHG benefits of protein substitution depend on the alternative source of protein. The literature provides various estimates of the greenhouse intensity of protein. For the purposes of this analysis, the carbon offset of protein is estimated to be about 100 kg CO_2-e/kg of mammalian protein substitute produced, 10 kg CO_2-e/kg of non-mammalian protein, and an average of 55 kg CO_2-e/kg of protein (based on Bryngelsson et al., 2016; Poore and Nemecek 2018). Larvae can produce around 100 kg protein substitute per tonne of wet food and 200 kg of frass, which has soil carbon and fertiliser benefits. This translates to an average protein offset of 5.5 tonnes CO_2-e per tonne of input food, but a much higher rate, at up to 10 tonnes CO_2-e per tonne, if it substitutes for mammalian protein.

If the frass has an organic carbon content of 30% by weight and 10% of this persists in the soil for 100 years, the sequestered carbon benefit would be in the order of 22 kg CO_2-e per tonne of input food.

3.7 Commercial (offsite) vermiculture and vermicomposting

Emissions from offsite vermiculture and vermicomposting have not been quantified in this study due to a lack of reliable data about systems management and performance under Australian conditions. Well managed vermiculture and vermicomposting systems should have low emissions, but poorly managed systems with anaerobic or semi-anaerobic conditions could generate significant nitrous oxide and methane. One comparative study found nitrous oxide and methane emissions from vermicomposting were about double emissions from well managed aerobic composting (Hwang et al., 2020).

3.8 Onsite composting and vermicompost systems

Onsite composting or vermicompost (worm farm) systems can be used where a site has suitable land to use organic outputs. These may be an option where sites produce small amounts of food waste and have gardens where products can be used, but are they usually not an option for sites producing large amounts of food waste. Food storage and pre-treatment systems such as Bokashi systems are included in this category.

The main advantage of onsite composting and vermicompost systems is that they avoid collection and transport costs and environmental impacts. They can also produce treated organic soil conditioners. However, the systems have limitations. To function well, they require knowledge, skills and effort to operate and maintain. Poorly maintained composts and worm farms can generate greenhouse and odour gases, foster pest insects and vermin, and produce organic outputs that damage soil and plants. Where sites have dedicated personnel that can correctly maintain systems, onsite composting and vermicompost systems can be beneficial, but they are not suitable in most situations.

The modelling of these systems considered best and worst-case scenarios, with best case being a GHG profile similar to a commercial composting facility, and the worst case assuming higher levels of nitrous oxide and methane generation based on previous studies of emissions from home compost (Chan et al., 2011; Ermolaev et al., 2013). These studies found a wide range in emissions from home composting and vermicompost systems. No impacts were assumed from collection, transport, or energy used to process. The sequestered carbon was assumed to be the same as for commercial compost.

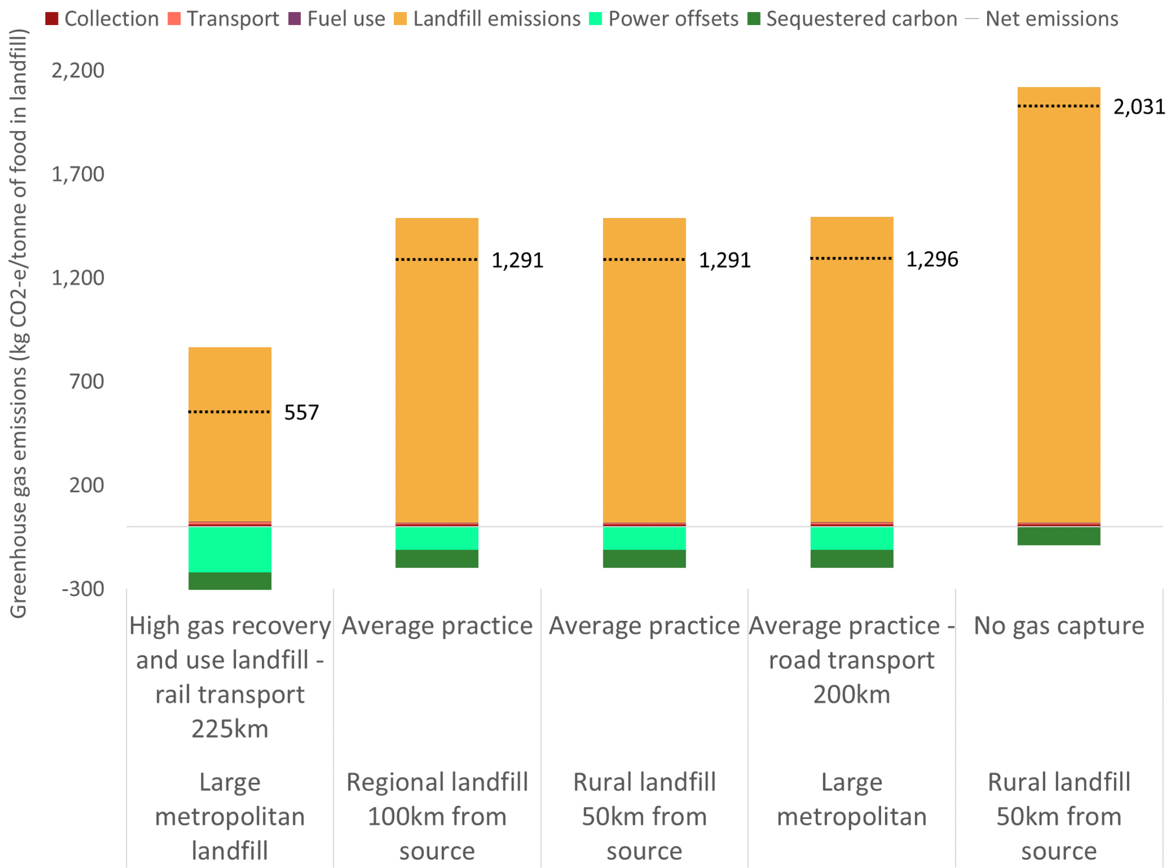
4. Modelled comparative analysis

Data and assumptions about the performance of options were used to undertake a comparative analysis of various scenarios. The following section assesses the performance of different food organics management options. It provides graphs showing the performance of options. The numeric data used in the production of these tables are provided in Appendix B.

4.1 Landfill scenarios

Figure *1* shows different landfill scenarios for metropolitan, regional and rural areas based on the assumed levels of landfill gas energy recovery and distance from sources. The modelling is for food in general waste and is the baseline for other management options. It shows that landfill gas energy recovery significantly reduces the emissions profile of landfills, but still results in emissions of over 0.6 tonnes CO_2-e/tonne of food landfilled unless more than 60% of methane from food is captured and converted to energy. Some sequestration of carbon in food can be expected in landfill, but this is negligible compared to methane emissions. Over the coming 10-20 years it is expected fossil fuel electricity will be replaced by renewables, reducing the offset benefits of landfill gas energy recovery and increasing its GHG impacts. It should be noted that the long transport distances from metropolitan Sydney to best practice landfills reduces the GHG benefits of this option, but emissions from transport remain a relatively small component of total emissions from landfilling food waste.

Figure 1 Estimated GHG emissions from landfill scenarios (kg CO_2-e/wet tonne of food input)



4.2 Offsite composting scenarios

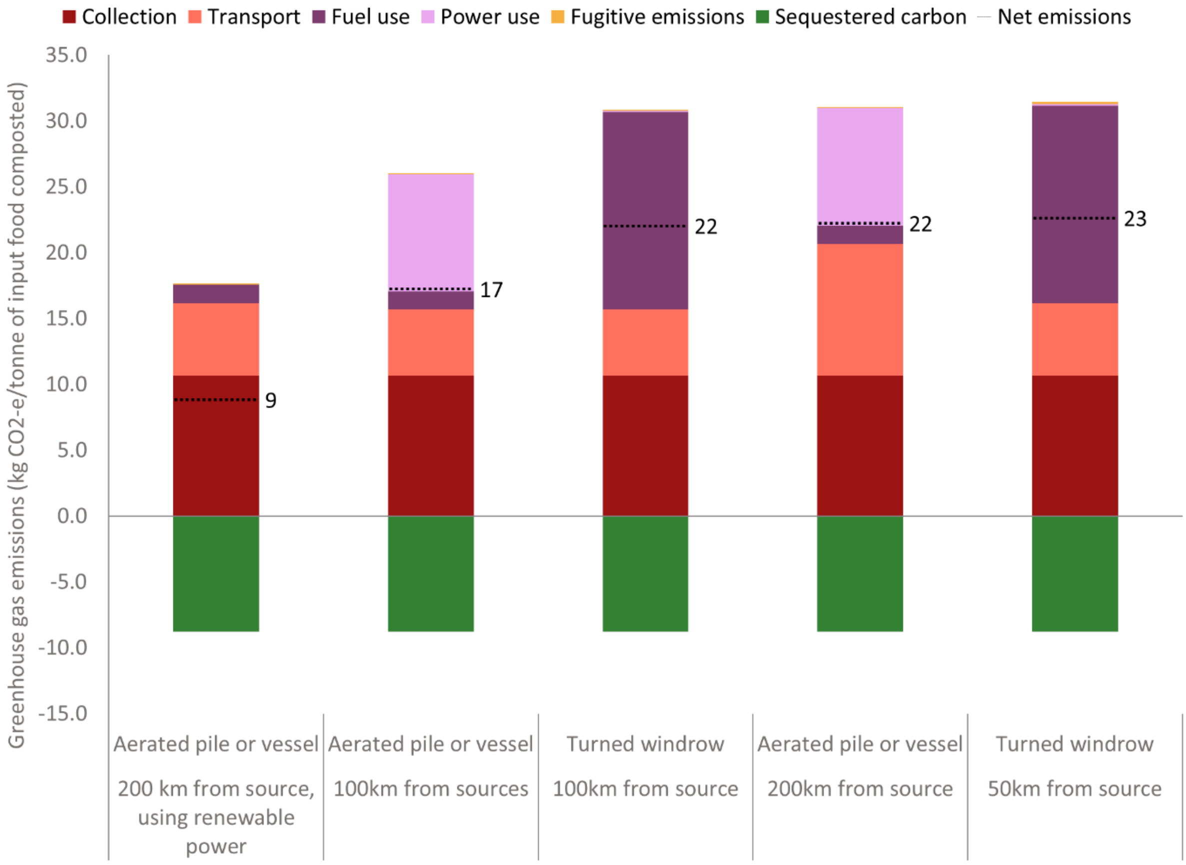
Figure *2* shows estimated GHG emissions from offsite food waste composting scenarios. It is important to note the vertical axis of this chart is different to the one used in Figure 2 for landfills. The net emissions from composting are 2–4% those of the landfill scenarios. The chart shows net GHG emissions from all composting scenarios based on the input assumptions. Turned windrow operations have higher emissions due to fuel use, and potentially can be higher if they are not well-managed to avoid methane and nitrous oxide emissions.

Aerated systems have lower emissions from fuel consumption, but higher emissions from mains grid power unless renewable energy is purchased or generated onsite. Aerated systems have some emissions due to use of mains grid fossil fuel electricity and this could be reduced If renewable energy sources are used. Some aeration systems are mainly or fully powered by solar panels, but renewable power could also be purchased.

Sequestration benefits for compost from food are low due to a low organic carbon content per tonne, most of which is driven off during the composting process.

Systems that reduce the need for frequent collection, (e.g. daily or more than three to four times per week), such as maceration and storage systems, will reduce the GHG intensity of offsite composting.

Figure 2 Estimated GHG emissions from offsite composting of food (kg CO_2-e/wet tonne of food input)

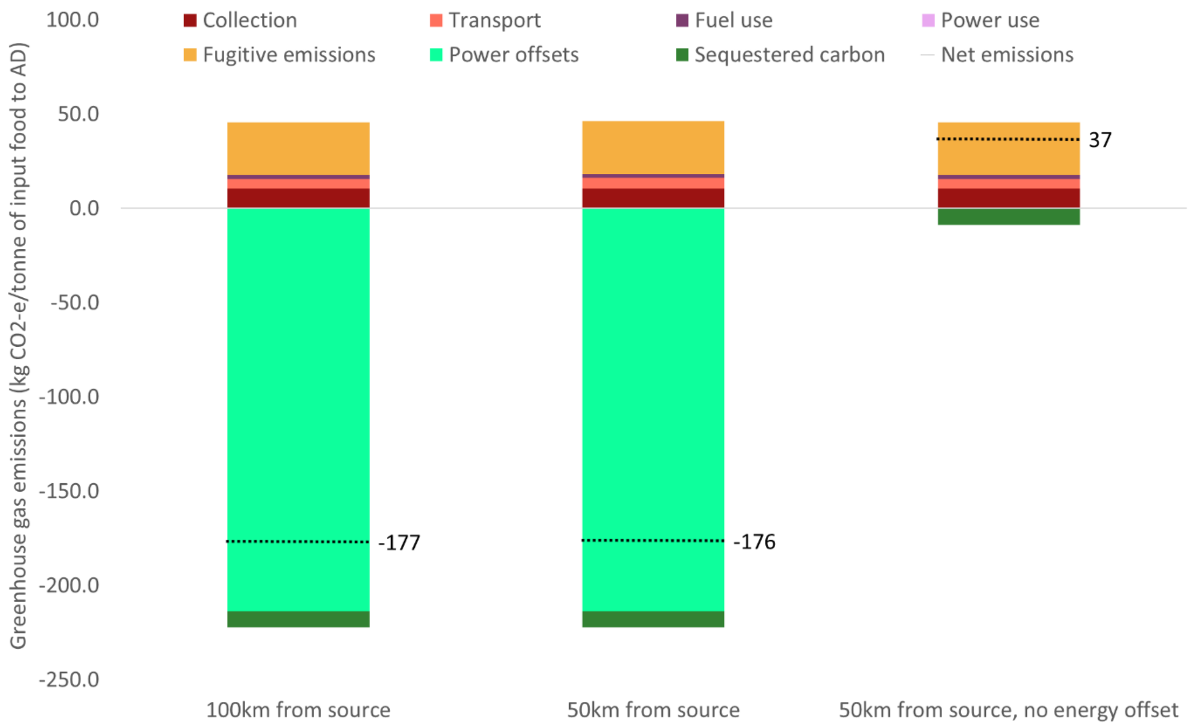


It should be noted that composts can also provide GHG abatement benefits associated with the substitution of GHG intensive synthetic fertilisers, but the contribution to the main nutrients, nitrogen and phosphorous, from food are small per wet tonne of food and most municipal composts are not used as fertiliser. It is estimated the GHG benefits of synthetic fertiliser are a reduction in the order of 20kg CO_2-e per wet tonne of food input where products are used as fertilisers, or as part of a nutrient management plan that reduced use of synthetic fertilisers over time due to the use of compost. This would make the above scenarios close to, or better than, carbon neutral. Most compost is not used as a fertiliser, and where composts are primarily used as soil conditioners rather a fertiliser, increased harvested yields will remove more nutrients and may require increased fertiliser application using composts or synthetic fertilisers. For these reasons the offset from nutrients in compost have not been shown in the chart.

4.3 Anaerobic digestion scenarios

Estimated GHG emissions from various AD scenarios are shown in Figure *3*. This shows AD scenarios can result in a net reduction in GHG emissions by offsetting fossil fuel power energy sources. Some carbon is sequestered, but is low for food on a per tonne basis. Fugitive methane emissions from AD facilities is also significant and efforts to minimise these will reduce the impacts of these facilities. Collection and transport remain relatively minor contributors to emissions.

Figure 3 Estimated emissions from anaerobic digestion scenarios (kg CO_2-e/wet tonne of food input)

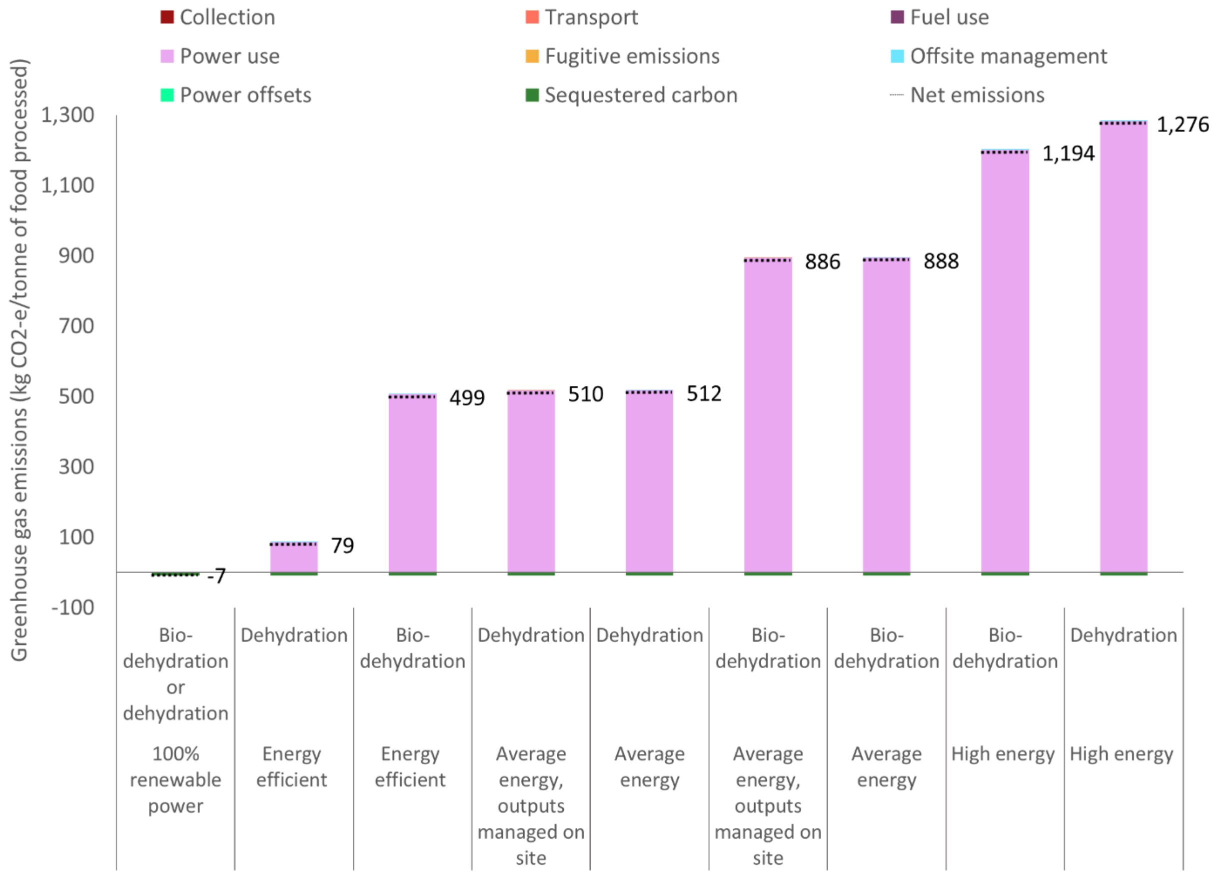


It should be noted that use of digestate products as a substitute for synthetic fertilisers will provide an additional GHG abatement benefit. This will depend on how the digestate is applied and the type of fertiliser it replaces, but the benefit is estimated to be in the order of 36 kg CO_2-e/wet tonne of inputs.

4.4 Onsite dehydration and bio-dehydration

Figure *4* compares the modelled performance of different types and scales of dehydration and bio-dehydration units. This shows considerable variability due to the levels of power use per tonne of organics. Overall, the units have a higher GHG impact than offsite composting and AD biogas energy recovery due to higher energy demand. However, if units are powered using renewable energy their GHG profile falls and, due to reduced emissions from collection and transport, could outperform turned windrow and aerated composting systems powered by fossil fuel electricity.

Figure 4 Estimated emissions from dehydration and bio-dehydration systems (kg CO_2-e/wet tonne of food input)



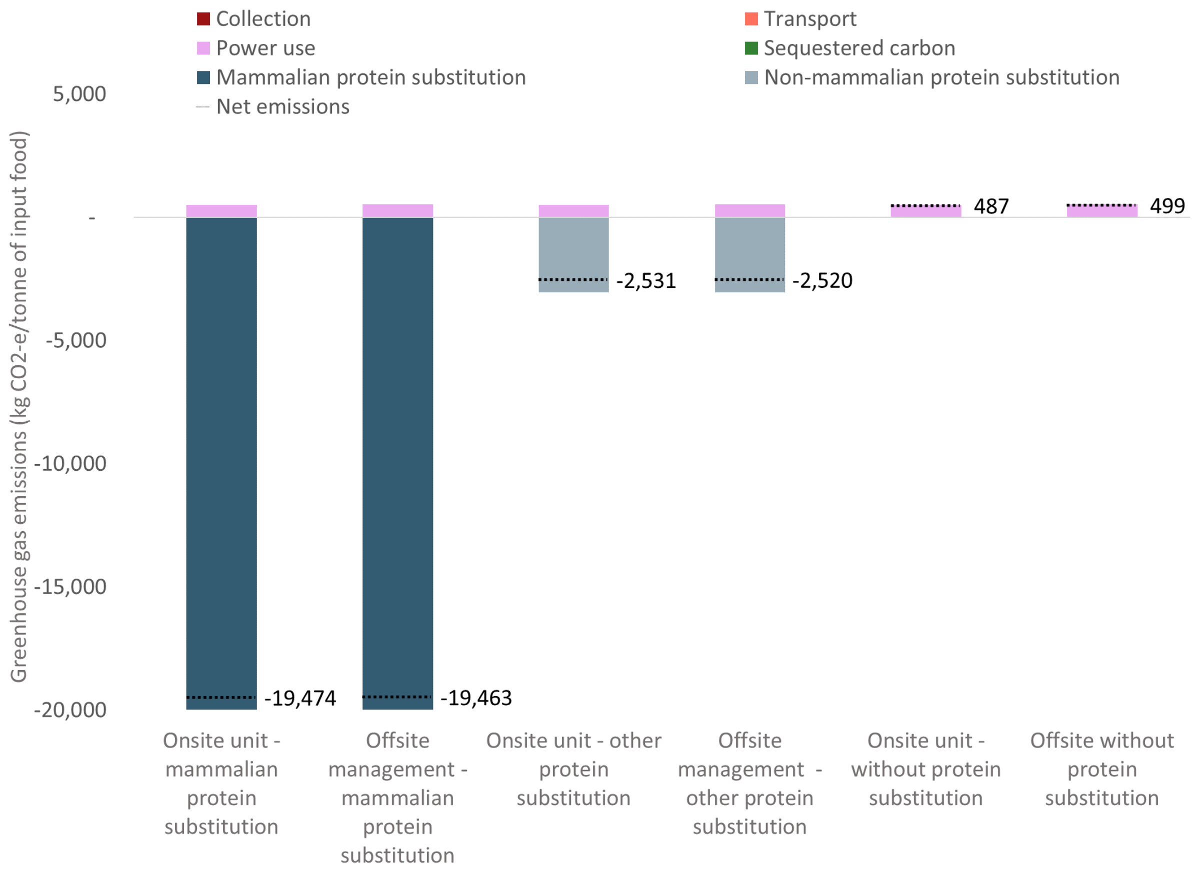
Note this assessment (except columns 4 and 8) assumes offsite processing at a composting facility after dehydration and does not include the use of dehydrated organics at AD facilities. If outputs are sent off site after dehydration for processing in AD offsets of current grid power equivalent to around 200kg CO_2-e /wet tonne of food input would be generated.

4.5 Onsite and offsite protein farming

Figure *5* compares scenarios where either protein farm units are installed onsite and maintained by the service provider or organics are collected and transported to centralised units. Onsite units reduce collection and transport emissions and costs. The units have significant energy costs, the emissions from which can be reduced by the purchase of renewable energy.

A key finding is the potential offset of protein achieved by insect larvae’s conversion of food into protein. This offset is only valid if the protein causes a reduction in the production of mammalian protein, and this is questionable because stockfeed protein is typically non-mammalian or derived from by-products from meat processing. However, the assessment shows there is a significant potential benefit in insect larvae protein substituting other forms of protein.

Figure 5 Modelled performance of protein farm options (kg CO_2-e/wet tonne of food input)



5. Key findings and conclusions

The assessment found the most significant impacts of various food organics management options on net GHG emissions are:

1. Landfill gas emissions. This is the most significant benefit of food waste diversion and common to all scenarios that divert food from landfill.
2. Processing energy requirements. Fuel and power used to process organics can be GHG intensive. This is most significant for dehydration units and some composting technologies using fossil carbon derived fuel and power.
3. Collection emissions. The stop-start nature of collecting food from multiple sites in congested areas is fuel and GHG intensive per tonne of food input.
4. Transport emissions. Processing sites are often long distances from the sources of food waste. The assessments considered processing sites 50km, 100km, 200km and 225km from source. Transport of finished product to end markets was not included in the assessment due to the low emission numbers and the unknown distances end uses.
5. Other emissions from processing. These are relatively minor for most technologies, with the greatest risk being fugitive emissions of nitrous oxide and methane from partially or fully anaerobic conditions during processing.

Factors that reduce net emissions for specific processing options are:

1. Biogas energy recovery. This can result in reduced net GHG emissions where biogas energy substitutes for fossil fuel energy.
2. Protein substitution. Use of food waste to cultivate insect protein could have significant benefit where the protein substitutes for mammalian protein and reduces production of mammalian protein. This is uncertain as the replaced product is often a by-product. A fall in demand for that by-product may not strongly influence overall mammalian protein production.
3. Soil carbon sequestration and potentially fertiliser substitution. These benefits are modest per wet tonne of food because most food waste has relatively low levels of organic carbon and nutrients, and most carbon and some nutrients are lost to the atmosphere during management and processing. The proportion of soil carbon that will persist in soil per tonne of food is low. Avoided emissions from substitution of fertilisers are also low.

The average performance of different scenarios is shown in Figure *6*, Figure *7* and Figure *8*. Figure *6* shows all scenarios, Figure *7* shows scenarios without protein farming and Figure *8* compares the remaining non-landfill options.

Figure 6 Comparison of organic management options - average expected scenarios (kg CO_2-e/wet tonne food input)

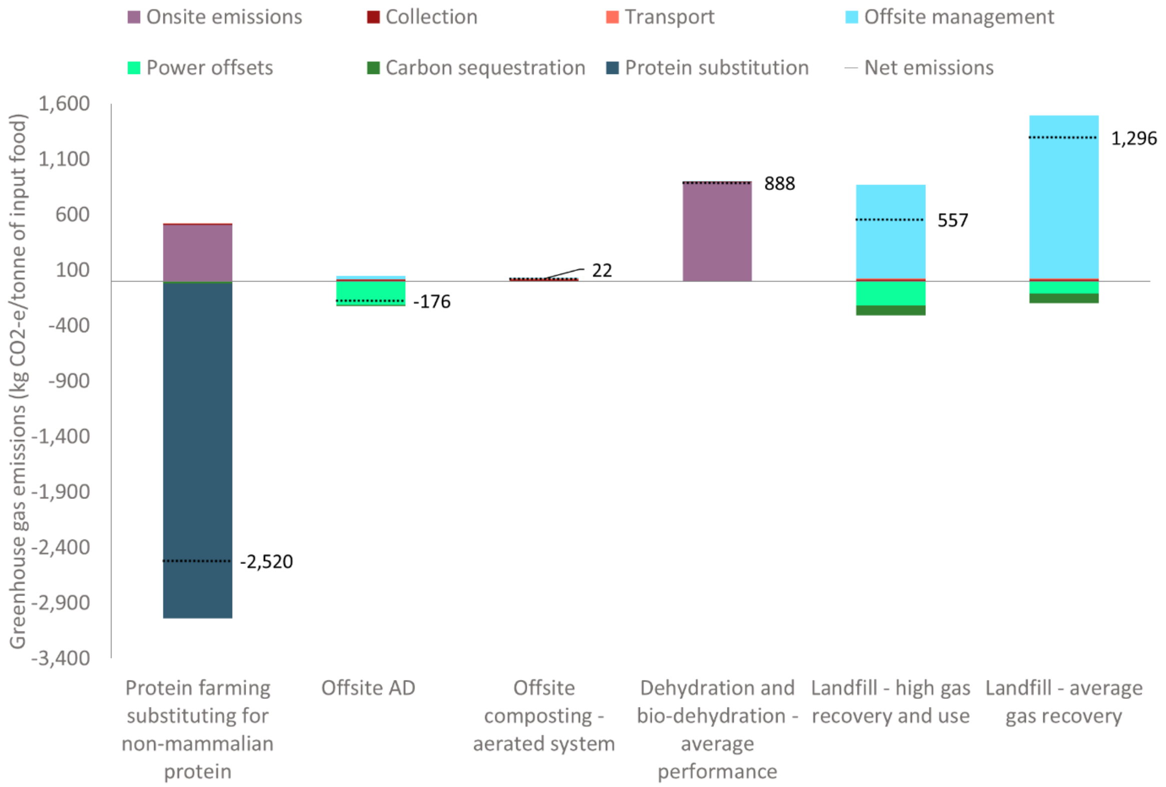


Figure 7 Comparison of organic management options - scenarios without protein farming (kg CO_2-e/wet tonne food input)

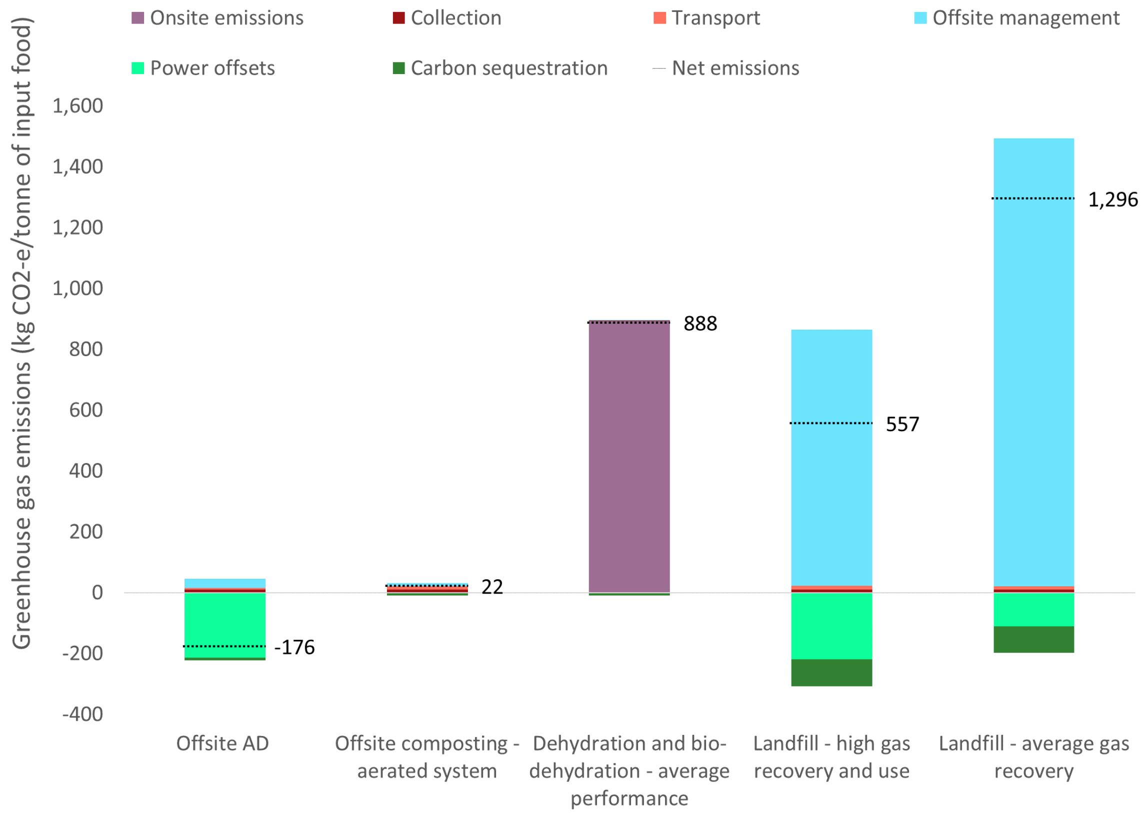
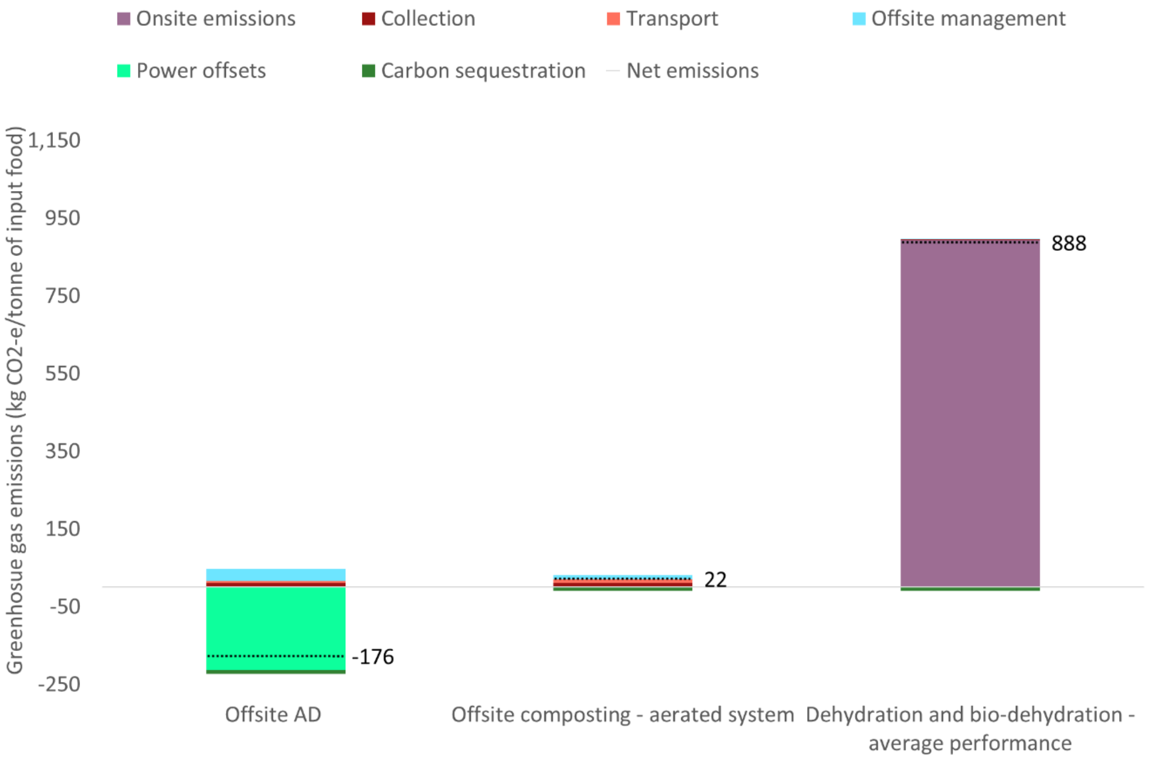


Figure 8 Comparison of organic management options – remaining non-landfill options (kg CO_2-e/wet tonne food input)



The most favourable management options based on the assessed GHG emissions, in declining order, are:

1. Onsite protein farming if the protein substitutes for other sources of protein, and if renewable energy is used to power sites.
2. Food to AD with biogas energy recovery and digestate to fertiliser.
3. Onsite dehydration and bio-dehydration units if renewable energy is used to power units, with dehydrated outputs composted offsite.
4. Offsite composting using aerated systems, particularly if renewable energy is used to power sites.
5. Offsite composting using turned windrow systems provided piles are well managed.
6. Onsite dehydration and bio-dehydration units if non-renewable energy is used to power units, with dehydrated outputs composted offsite.

Onsite composting vermicomposting systems can have a low emissions profile if materials are well-managed, but many sites generating large amounts of food will find these systems impractical.

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Appendix A Register of key input data and assumptions

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	Key input data and assumptions	Used in model	Source
1.	NSW electricity emissions factor (kg CO2-e/kWh)	0.89	National Greenhouse Accounts Factors 2020
2.	Transport emissions factor (rigid truck) (kg CO2-e/t.km)	0.129	NSW Government (2017) Carbon Estimate & Reporting Tool
3.	Transport emissions factor for collection and transport (kg CO2-e/L of fuel)	2.717	National Greenhouse Accounts Factors 2020
4.	Fuel consumption per tonne of FO for stop start collection in urban area (L/tonne)	3.000	Diesel_consumption_in_waste_collection_and_transport_and_its_environmental_significance
5.	GHG emissions from road collection (kg CO2-e/tonne of collected material)	8.152	derived from data
6.	Fuel consumption per m for FO for small 8t load vehicle (L/km)	0.286	derived from data
7.	Fuel consumption per tonne km for FO for small 8t load vehicle (L/t.km)	0.036	derived from data
8.	Emissions from small 8t load vehicle kg CO2-e/t.km	0.097	derived from data
9.	Fuel consumption per km for large 25t load vehicle (L/km)	0.530	derived from data
10.	Fuel consumption per tonne km for FO for large 25t load vehicle (L/t. km)	0.021	derived from data
11.	Emissions from large 25t load vehicle kg CO2-e/t.km	0.058	derived from data
12.	Emissions from rail transport CO2-e/t.km	0.026	derived from data
13.	Global warming potential of methane (CO2-equivalents)	28	National Greenhouse Accounts Factors 2020
14.	DOC of food	0.15	National Greenhouse Accounts Factors 2020
15.	DOCf of food	0.84	National Greenhouse Accounts Factors 2020

	Key input data and assumptions	Used in model	Source
16.	% of degraded DOCf converted to methane	50%	National Greenhouse Accounts Factors 2020
17.	% of gas oxidised through landfill cap	10%	National Greenhouse Accounts Factors 2020
18.	C to CH4 conversion rate	1.336	National Greenhouse Accounts Factors 2020
19.	Methane to CO2-e conversion	3.67	National Greenhouse Accounts Factors 2020
20.	GWP of methane potential from food in landfill without gas capture and oxidisation (tonnes CO2-e/t of food)	2.1	Derived from data
21.	Moisture content of food	75%	Blue Environment estimate
22.	Moisture content of dried food	20%	Blue Environment estimate
23.	GWP of dried organics CO2-e/tonne	4.7	Derived from data
24.	GWP of stabilised organics CO2-e/tonne	0.2	Derived from data
25.	% DOC lost to atmosphere through dehydration/biodrying	10%	Blue Environment estimate
26.	% DOC lost to atmosphere through anaerobic composting	84%	Blue Environment estimate based on degradability of DOC
27.	% DOC lost to atmosphere through AD	84%	Blue Environment estimate based on degradability of DOC
28.	Food waste emissions in landfill (t CO2-e/t food)	2.1	National Greenhouse Accounts Factors 2020
29.	Est dry weight of organic carbon from 1 tonne food in hydrated/biodehydrated food	0.14	Derived from data
30.	Est dry weight of organic carbon from 1 tonne food in compost	0.02	Derived from data
31.	Est dry weight of organic carbon from 1 tonne food in digestate	0.02	Derived from data

	Key input data and assumptions	Used in model	Source
32.	GHG emissions from AD of food (t CO2-e/ t waste treated)	0.028	National Greenhouse Accounts Factors 2020
33.	GHG emissions from wastewater treatment (no AD gas recovery) kg CO2-e/tonne of food	3.192	NGERS Wastewater calculator missions Factors
34.	Garden waste emissions in landfill (t CO2-e/t garden)	1.6	National Greenhouse Accounts Factors 2020
35.	Composting emissions factor (t CO2-e/ t waste treated)	0.05	NGER (Measurement) Determination 2008 (July 2020)
36.	GHG emissions from composting of food (t CO2-e/t waste treated)	0.02	National Greenhouse Accounts Factors: 2020
37.	Landfill gas capture rate, food (%) - average	30%	Blue Environment approximation based on gas recovery practices and rate of degradation of food in landfill
38.	Landfill gas capture fate, garden (%)	60%	Blue Environment approximation based on gas recovery practices and rate of degradation of food in landfill
39.	AD energy gen. rate (kWh/tonne of food)	300	https://www.biogas-info.co.uk/about/faqs/
40.	% of AD power exported	80%	Based on EarthPower's reported performance (when the facility is operational)
41.	Offsets from AD kg CO2-e/tonne of food	214	Derived from data
42.	Offset emissions from soil carbon sequestration in compost - in soil over a 100 year period (t CO2-e/t compost)	0.008	Blue Environment estimate based on assumption that 10% of organic carbon from food in compost will persist in soil for 100 years

Appendix B Summary tables for modelled scenarios

Appendix B Summary tables for modelled scenarios

Appendix table 1 Modelling of landfill emissions used to produce Figure 1, kg CO2-e/wet tonne of input food

Landfill location	Large metropolitan	Large metropolitan	Regional landfill 100km from source	Rural landfill 50km from source	Rural landfill 50km from source
Management components	**Lower emissions landfill - rail transport 225km**	**Average practice - road transport 200km**	**Average practice**	**Average practice**	**No gas capture**
Collection	10.7	10.7	10.7	10.7	10.7
Transport	11.25	10	5	5.5	5.5
Fuel use	2.97	2.97	2.97	2.97	2.97
Power use	0	0	0	0	0
Landfill emissions	840	1,470	1,470	1,470	2,100
Power offsets	-220	-110	-110	-110	0
Carbon sequestration	-88	-88	-88	-88	-88
Net emissions	557	1,296	1,291	1,291	2,031

Appendix table 2 Modelling of emissions from offsite composting used to produce Figure 2, kg CO2-e/wet tonne of input food

Location	50km from source	100km from source	100km from sources	200km from source	200 km from source, using renewable power
Management type	Turned windrow	Turned windrow	Aerated pile or vessel	Aerated pile or vessel	Aerated pile or vessel
Collection	10.7	10.7	10.7	10.7	10.7
Transport	5.5	5.00	5.00	10	5.5
Fuel use	15	15	1.4	1.4	1.4
Power use	0.1	0.1	8.9	8.9	0
Fugitive emissions	0.19	0.10	0.10	0.10	0.10
Power offsets	0.00	0.00	0.00	0.00	0.00
Sequestered carbon	-8.8	-8.8	-8.8	-8.8	-8.8
Net emissions	22.6	22.0	17.2	22.2	8.8

Appendix table 3 Modelling of emissions from anaerobic digestion used to produce Figure 3, kg CO2-e/wet tonne of input food

Management component	50km from source	100km from source	50km from source, no energy offset
Collection	10.7	10.7	10.7
Transport	5.5	5	5
Fuel use	2	2	2
Power use	0	0	0
Fugitive emissions	28.00	28.00	28.00
Power offsets	-213.60	-213.60	0.00
Sequestered carbon	-8.8	-8.8	-8.8
Net emissions	-176.3	-176.8	36.9

Appendix table 4 Modelling of emissions from dehydration and bio-dehydration options used to produce Figure 4, kg CO2-e/wet tonne of input food

Dehydration option	Bio-dehydration	Bio-dehydration	Bio-dehydration	Bio-dehydration	Dehydration	Dehydration	Dehydration	Dehydration	Bio-dehydration or dehydration
Energy efficiency	**Energy efficient**	**Average energy consumption**	**High energy consumption**	**Average energy consumption, management of outputs on site**	**Energy efficient**	**Average energy consumption**	**High energy consumption**	**Average energy consumption, management of outputs on site**	**with 100% renewable power**
Collection	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Transport	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Fuel use	-	-	-	-	-	-	-	-	-
Power use	504.3	893.5	1,199.7	893.5	84.3	517.1	1,281.6	517.1	-
Fugitive emissions	-	-	-	0.2	-	-	-	0.2	-
Offsite management emissions (composting)	1.7	1.7	1.7	-	1.7	1.7	1.7	-	-
Power offsets	-	-	-	-	-	-	-	-	-
Sequestered carbon	-8.8	-8.8	-8.8	-8.8	-8.8	-8.8	-8.8	-8.8	-8.8
Net emissions	498.8	888.0	1,194.2	886.5	78.8	511.6	1,276.1	510.1	-7.2

Appendix table 5 Modelling of protein farms options used to produce Figure 5, kg CO2-e/wet tonne of input food

	Onsite unit - mammalian protein substitution	Offsite management -mammalian protein substitution	Onsite unit - other protein substitution	Offsite management - other protein substitution	Onsite unit - without protein substitution	Offsite without protein substitution
Collection	3	11	3	11	3	11
Transport	2	6	2	6	2	6
Power use	504	504	504	504	504	504
Fugitive emissions	0	0	0	0	0	0
Sequestered carbon	-22	-22	-22	-22	-22	-22
Substitution for mammalian protein	-19,961	-19,961	-	-	-	-
Substitution for other protein	-	-	-3,019	-3,019	-	-
Net emissions	-19,474	-19,463	-2,531	-2,520	487	499

Appendix table 6 Modelling of comparison of organic management options used to produce Figure 6,Figure 7 and Figure 8, kg CO2-e/wet tonne of input food

	Landfill, average gas recovery	Lower emissions landfill	Offsite composting - aerated system	Offsite AD	Dehydration and bio-dehydration - average performance	Protein farming substituting for non-mammalian protein
Onsite processing	843.0	1,473.0	-	-	504.3	504
Collection	10.7	10.7	10.7	10.7	1.1	11
Transport	11.3	10.0	10.0	5.5	0.6	6
Offsite processing emissions (composting)	-	-	10.4	30.0	1.7	-
Power offsets	-220.0	-110.0	-	-213.6	-	
Carbon sequestration	-88.0	-88.0	-8.8	-8.8	-8.8	-22
Protein substitution	-	-	-	-	-	-3,019
Net emissions	556.9	1,295.6	22.2	-176.3	498.8	-2,520.2
% reduction of average landfill	57%	0%	98%	114%	61%	295%