Biorefinery concepts for Amsterdam Metropolitan Region

Part of MEBICO project (Metropolitan Biorefinery Concepts)

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WAGENINGEN
UNIVERSITY & RESEARCH

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Summary

In 2050, 70% of the world's population lives in cities. As a result, issues surrounding sustainability are becoming increasingly urgent for cities. This concerns food supply, bio-based products, logistics, raw materials and waste flows in and out of the city. New techniques for the valorisation of raw materials and residual streams will lead to new chain concepts in urban areas. As part of the MEBICO project (Metropolitan Biorefinery Concepts) new biorefinery concepts were suggested for the most important organic waste/residues streams in the Amsterdam Metropolitan Region (AMR). An inventory was made of the organic waste/residues streams, four important streams were identified and their current processing was described. Residual waste from households and offices is currently subjected to post-separation and incineration, which mainly yields electricity and heat. Source separated organics (SSO, or in Dutch: GFT) is anaerobically digested and composted, which yields biogas and compost. Swill, supermarket waste and residues from food industry is subjected to anaerobic digestion as well and manure is mainly used as fertilizer on the land. The performance of these current conversion processes was described using performance indicators: (1) the amount of energy recovered from the stream, (2) added value and (3) the amount of CO_2-equivalents that can be avoided compared to a reference in which all organics in the waste are completely degraded and mineralized without the production of any useful/valuable energy, chemicals or materials. The conversion of four important organic waste streams in AMR are all characterized by low economic efficiencies. They are primarily waste destruction methods and the costs are paid by the owners of the residues. The processes that produce biogas have better energy conversion efficiencies and avoid more fossil CO_2-eq. emission than incineration and spreading over land.

Subsequently alternative processing options were suggested, all based on biorefinery principles. The processes were described and economically analysed. In addition the effect on the emission of fossil CO_2-eq. was estimated.

Three biorefining options for SSO were suggested:

1. Production of furfural and levulinic acid
2. Production of bioplastics (PHA) via volatile acids
3. Separate collection of (a) vegetable/fruit and (b) yard waste; conversion of vegetable/fruit into caproic acid and yard waste into fermentable sugars

Options 3a and 3b can be designed as separate biorefineries or as a combined biorefinery in which 3b is used for the production of bioethanol of which a part can be used as auxiliary material in the production of caproic acid. In such combined biorefinery seven products are produced: caproic acid, ethanol, lignin, biogas, minerals, sand and water. In the AMR not all household waste is separated at the source. A better separation will yield larger amounts of SSO which will be beneficial to reach economy of scale of the biorefinery and produce more added value.

Swill, supermarket waste and residues from food industry can be used to produce caproic acid as well or to produce larvae from the black soldier fly. Compounds from these larvae can be use as feed or as raw material for the production of chemicals.

Manure can be used to produce biogas and the digestate can be fractionated to produce a phosphate fertilizer, potassium fertilizer, an ammonia solution (used in flue gas treatment) and clean water that can be discharged. One more step is the use of the organic compounds from manure for the production of chemical building blocks such as furfural and levulinic acid.

Key performance parameters were used to asses these new ideas: the GWP (global warming potential) expressed as kg CO_2-eq. avoided per tonne dry matter and economic efficiency ((product value minus costs)/tonne dry matter). Several proposed biorefinery concepts perform better on these key parameters than the current best practice (anaerobic digestion and post-composting). A large positive effect on decreasing greenhouse gas emissions while improving the economy can be gained by the conversion of SSO and a co-substrate into levulinic acid and furfural. Several waste processing companies are already involved in development of this technology. PHA production does not give a real improvement, however, this may change by technology development in particular in

recovery/extraction of PHA from the bacterial cells. There is a great chance that the production of caproic acid is much more profitable than anaerobic digestion, but details on the costs are lacking. A drawback is the poor performance in reduction of greenhouse gas emissions. This may improve by further process development and the use of renewable instead of fossil energy. The biorefinery that combines various waste streams and conversion technologies gives an economically attractive alternative to current practice. The effect on greenhouse gas emissions is low, due to the same problems connected to caproic acid production.

1 Introduction

In 2050, 70% of the world's population lives in cities. As a result, issues surrounding sustainability are becoming increasingly urgent for cities. This concerns food supply, bio-based products, logistics, raw materials and waste flows in and out of the city. New techniques for the valorisation of raw materials and residual streams will lead to new chain concepts in urban areas.

Flexible and efficient (circular) metropolitan biomass and food supply, collection and processing networks are needed to create Resource Efficient Cities. In the increasingly expanding metropoles sufficient food and resource efficiency converge into concepts that address the zero-waste approach of efficient use of resources in metropolitan areas. Concepts like urban metabolism connect with the circularity of chains within the metropolitan boundaries in general, and with urban (food) waste and agricultural production in particular. Here transition towards a bio-economy is connected with the decrease of the sensitivity for disturbances in the supply of the urban society by strengthening circular chain networks of local processing and production units.

Delivered products reach a consumer (households, industry) in individual or bulk orders to a variety of places, where orders are decided on in the last possible moment. Food waste and biomass waste should be reduced or used as a feedstock for new products or for other purposes (e.g. bioenergy). A changing ordering process with the decoupling of customer, retail/wholesale and catering orders in combination with flexibility (i.e. e-commerce and home delivery) and the returning of food and biobased waste flows has a large impact on processing and packaging, logistical concepts and metropolitan logistic streams. This requires specific locations near the boundaries or in cities where those activities can be integrated Biomass waste streams from households and the food processing industries will be a valuable feedstock in the near future for several biobased products such as biochemicals, bioplastics, biofuels and bioenergy. Centralized integrated logistical centres that combine food and non-food value chains will enable to solve issues like (rapidly decreasing) quality, availability and costs of these new feedstocks (Figure 1).

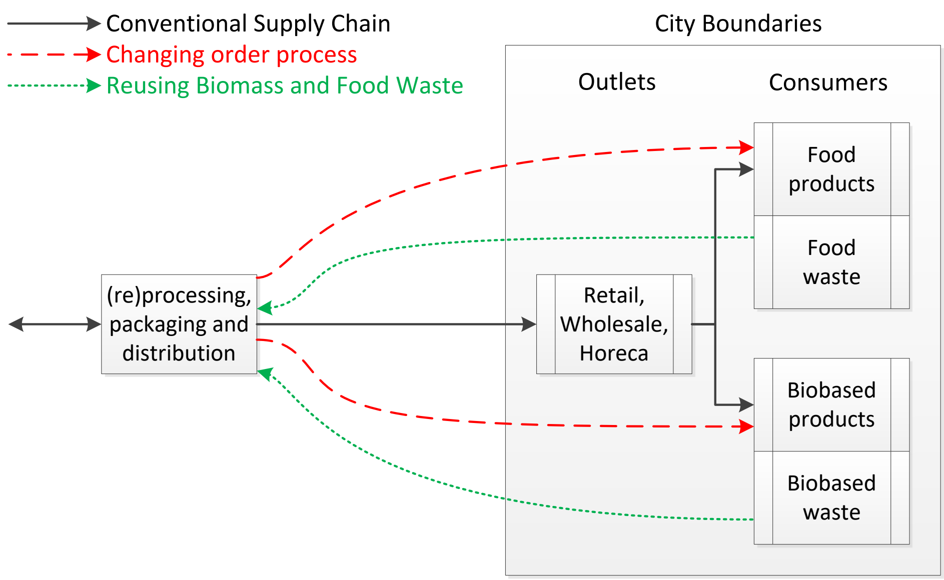

Figure 1 Focus area of the food and biomass supply network for Metropolitan Biorefinery Concepts

So the flow of food and biobased products into the city and waste flows out of the city should not be considered separately, but in conjunction with each other and other flows of goods that will have the same transport problems to reach the consumer. Of course they may differ in transport conditions such as processing, packing and/or transport conditions related to quality and therefore finding optimal ways of combining these different streams is essential.

The project Metropolitan Biorefinery Concepts (MEBICO) is dedicated to the valorisation of residues of organic matter in the Amsterdam Metropolitan Region (MRA). The project is carried out by WUR/WFBR and runs from 2015 to 2019. The main deliverables are:

- Vision on metropolitan Biorefinery concepts and the accompanying logistical challenges in the (re)processing of organic flows for metropoles;
- A plugin for a system dynamics model of adaptive chains that can be used to guide and optimise the logistics in food and biobased chains;
- Scientific publication of the model plugin for metropolitan biorefinery concepts.

The current report deals with a part of the project and was carried out in 2018 for the Netherlands Ministry of Economic Affairs and Climate Policy. The focus was on:

- Selection of streams and description of volumes and availability (case MRA).
- First Design Biorefinery Concepts – selection of potential biorefining routes and description of alternative (new) chain concepts (case MRA).

The research questions were:

- Which streams of organic residues in AMR are important and can be used as feedstock in a biorefinery?
- Which new biorefinery concepts are possible and will create a better performance on energy recovery and/or added value and/or reduction of greenhouse gas emission compared to current processing practices?

The study carried out contributed to selected activities planned in the larger MEBICO project:

- Choose the most appropriate/suitable biorefinery concepts for various resources and residues to produce new high value resources;
- Design integrated circular value chains that contain these biorefinery concepts and that are dedicated to the metropolitan situation;
- Calculate the effects of a design to assess its value on some key performance indicators (technical, economic, environmental, social, etc.).

The study starts with an estimation of quantities of organic waste/residues in AMR. The most important streams were identified and a description of the current processing was given. Subsequently, novel biorefining options were suggested. The current and new biorefining methods were compared using performance indictors on energy recovery, added value and reduction of greenhouse gas emission.

WFBR has carried out the study independently.

From the study the conclusion could be made that the conversion of four important organic waste streams in AMR are all characterized by low economic efficiencies. They are primarily waste destruction methods and the costs are paid by the owners of the residues. The processes that produce biogas have better energy conversion efficiencies and avoid more fossil CO2-eq. emission than incineration and spreading over land. Key performance parameters were used to asses new biorefinery options, such as production of furfural, levulinic acid, caproic acid, fermentable sugars, lignin and PHA from SSO and swill: the GWP (global warming potential) expressed as kg CO_2-eq. avoided per tonne dry matter and economic efficiency ((product value minus costs)/tonne dry matter). It appeared that several proposed biorefinery concepts perform better on these key parameters than the current best practice (anaerobic digestion and post-composting). These conclusions may be further extrapolated to other biorefineries in which chemical building blocks are produced and in which the residue is valorised as well.

This report is confidential and for WFBR employees only. A second version of this report is public. In this second version information from confidential project has been deleted.

2 Quantities of organic waste in AMR

2.1 Organic waste

Organic waste is derived from biomass. It includes waste from food, garden, paper, textile, wood, biomass from agriculture and nature, but also sludge produced from sewage. It excludes plastics and other petrochemical products.

2.2 Collection

Household waste from MRA is collected by four companies and sewage is collected by four water boards. The most important waste collectors are AEB, Meerlanden and HVC. These companies not only collect but also process the waste streams. In table 1 the parts of AMR in which these companies are active are shown. GAD Gooi en Vechtstreek collects the municipal waste from Blaricum, Gooise Meren, Hilversum, Huizen, Laren, Weesp and Wijdemeren. The processing of this waste is carried out by other companies such as Indaver.

In most municipalities source separated organics (SSO; Dutch: GFT) is collected separately, but not in Amsterdam and Diemen. In Amsterdam the separate collection of other waste types at the source is underdeveloped as well. Instead Amsterdam fully relies on separation technology located at central waste collection centres. The highest degrees of source separation can be found in municipalities in which DIFTAR (differentiated tariffs) is introduced (Table 2). In this system households only have to pay for the numbers of bins filled with residual waste they offer to the waste collectors. This way they are motivated to take out SSO, paper, plastic and other categories.

Waternet is the most important water board in the AMR. Besides Waternet, HHR Hollands Noorderkwartier gives service to the AMR municipalities north of Amsterdam, HHR van Rijnland collects the sewage in areas west of Amsterdam and Waterschap Zuiderzeeland is active in Almere and Lelystad.

Table 1 Municipalities, number of inhabitants, introduction of DIFTAR and service area of four important waste and wastewater processing companies.

Municipality	Number of Inhabitants 2017	DIFTAR	AEB	Meerlanden	HVC	Waternet
Aalsmeer	31,436	X	X	X		X
Almere	202,452				X	
Amstelveen	89,582		X			X
Amsterdam	849,497		X			X
Beemster	9,378		X		X	
Beverwijk	40,893				X	
Blaricum	10,498					X
Bloemendaal	23,017	X	X	X		
Diemen	27,697		X	X		X
Edam-Volendam	35,877		X		X	
Gooise Meren	57,136					X
Haarlem	159,469		X			
Haarlemmerliede & Spaarnwoude	5,766		X	X		X
Haarlemmermeer	146,643	X	X	X		
Heemskerk	39,159		X		X	
Heemstede	27,008	X		X		
Hilversum	89,205					X
Huizen	41,376					X
Landsmeer	11,355		X			
Laren	11,117					X
Lelystad	77,163				X	
Oostzaan	9,694		X			
Ouder-Amstel	13,458	X	X			X
Purmerend	79,956				X	
Uitgeest	13,493				X	
Uithoorn	26,323		X			X
Velsen	67,725				X	
Waterland	17,275		X			
Weesp	18,949					X
Wijdemeren	23,553					X
Wormerland	15,908				X	
Zaanstad	154,272				X	
Zandvoort	16,935		X			
TOTAL	2,443,265					
Service outside the MRA			Hillegom Katwijk Lisse Noordwijk Teylingen Zeevang	Hillegom Lisse Noordwijkerhout	35 other municipalities and 6 water boards in the Netherlands	Nieuwkoop De Ronde Venen Stichtse Veld De Bildt Utrecht

2.3 Amounts of organic waste generated in MRA

The amounts of the organic fractions of municipal waste collected in MRA are given in Table 2.

Table 2 Organic municipal waste collected in Metropolitan Region Amsterdam (CBS).

	Tonnes/year (2016)
Total household waste	1,127,712
Household residual waste	564,729
Coarse household residual waste	96,393
Source separated organic waste (Dutch: GFT)	108,821
Waste paper and card-board	97,698
Textile	10,366
Drinks cartons	7
Diapers	11
Frying fat and oil	147
Coarse garden waste	25,685
A and B waste wood	50,097
C waste wood	4,460

Besides waste from households, AMR annually produces the following streams from businesses (Metropool regio Amsterdam: Grondstoffen Atlas, 2018):

- 1135 ktonnes liquid manure
- 49 ktonnes solid manure
- 43 ktonnes residual waste from offices
- 20 ktonnes paper and cardboard waste from offices
- 5 ktonnes organic waste from offices
- 60 ktonnes residual waste from the tourism sector
- 5 ktonnes organic waste an swill from the tourism sector
- 3 ktonnes frying fat from the tourism sector
- 600 ktonnes organic waste from the food industry

In addition, biomass residues are harvested from arable land and are harvested as a result of the maintenance of nature areas, woods, parks, roadsides, sport/recreation areas and waterways. No data in this category could be found for MRA. However, detailed and recent information on these types of biomass streams is generated by Jutte *et al.* (2018) for Flevoland Province. These data will be used to estimate the amounts of MRA proportionally to the land area of MRA and Flevoland (Table 3). This may give an overestimation in the amounts of biomass from arable land.

Table 3 Estimation of biomass residues from arable land and land/water maintenance in AMR using the data from Flevoland Province.

	Flevoland Province	AMR
Land area (km^2)	1412	1602
Water plants (ktonnes/year)	65	74
Verge grass (ktonnes/year)	4	5
Pruning wood (ktonnes/year)	90	102
Grass (ktonnes/year)	93	106
Ash wood (or other wood) (ktonnes/year)	35	40
Biomass residues from arable land (ktonnes/year)	845	960

In AMR sewage contains wastewater from households, public buildings, (small) companies and storm water. This sewage is treated in municipal wastewater treatment plants and as a result clean water and residual sludge is produced. In this treatment process three types of sludge can be distinguished:

1. primary sludge: suspended particles from the sewer (faeces, toilet paper, food)
2. secondary sludge: the bacterial mass that is created in the biological treatment process
3. digested sludge: the residue after primary and secondary sludge are anaerobically digested in a sludge digester (to produce biogas).

Waternet is the most important water board in the MRA and treats the sewage of 1.2 million inhabitants. In 2013 it produced 37,745 tonnes sludge dry matter (sum of primary and secondary sludge) (Buijzer *et al.*, 2015). This amount was anaerobically digested and the residue sludge amounted 26,283 tonnes sludge dry matter, which was about 100 ktonnes wet sludge. However, MRA has 2.4 million inhabitants, which means that other water boards are active as well. These use more or less the same type of treatment processes. Therefore, the amounts of sludge for the complete MRA are estimated by extrapolation:
75 ktonnes (dry matter) primary and secondary sludge annually, which is converted into 49 ktonnes (dry matter) digested sludge. In addition, the water boards annually collect 4 ktonnes grease from sewer lift stations and the sewage treatment plants.

In addition, sludge is generated by wastewater treatment plants of large companies in MRA. No detailed data are available for MRA, but an estimation can be made. According to CBS in the Netherlands in 2016 1266 ktonnes wet sludge or 205 ktonnes sludge dry matter was transferred from industry to sludge processing companies. Proportional with the number of inhabitants MRA would produce 181 ktonnes wet matter or 29 ktonnes dry matter industrial organic sludge.
Specialist companies collect grease and frying fat from hotels, restaurants and pubs. The order of magnitude in MRA probably is 1-10 ktonnes/year.

2.4 Import and export of waste

Next to the waste generated by activities in MRA, waste can be imported and exported as well. One of the reasons is the large waste processing capacity in MRA, e.g. in form of incineration and biogas plants.
Important streams crossing the MRA borders are (Circular Amsterdam, 2015):

- Import organic waste: 2000 ktonnes/year
- Export organic waste: 300 ktonnes/year

Interesting is to realize that the metropolitan region is highly dependent on imports of resources. In the metropolitan region, 10 million tonnes of material are consumed annually, of which 60% is imported from abroad (Circular Amsterdam, 2015). More than 50% of the import consists of fossil fuels, used mainly in the petroleum industry for the production of plastic and transport fuels. Forty percent is biomass feedstock, mainly for industry and food industry.

2.5 Current methods to process organic waste of MRA

Currently a large part of the organic waste is used for the production of various energy carriers.
In 2016 AEB incinerated 1483 ktonnes waste (Rijkswaterstaat, 2017; AEB Annual Report 2016), of which:

- 540 ktonnes municipal waste
- 102 ktonnes sludge
- 493 ktonnes company waste
- 348 ktonnes waste imported from the UK

This incineration produced heat and a part of the heat was used to generate electricity. In 2016 as much as 1024 GWh electricity was produced and 185 GWh heat. The electricity was delivered to the net and the heat to Waternet and WPW city heating (aebamsterdam.nl). The cooperation between AEB and Waternet is a fine example of synergy. Residual sludge and biogas produced by sludge digestion from a neighbouring Waternet wastewater treatment plant is delivered to AEB. The sludge is incinerated and the biogas is used to improve the efficiency of the waste-to-energy power plant. In return AEB delivers heat and electricity to the wastewater treatment plant. AEB used 9.4 million Nm^3 biogas and the energy produced already is included in the electricity and heat data presented above. Next to energy, in 2016 AEB produced 300 ktonnes construction materials, 22 ktonnes iron, 4 ktonnes other metals and 6 ktonnes gypsum.

In 2017 Meerlanden processed 55 ktonnes SSO (www.meerlanden.nl), of which:

- 35 ktonnes was anaerobically digested, which yielded 2.6 million m^3 green gas, 12,000 L citrus fuel and 34 ktonnes digestate. The citrus oil was used as biobased herbicide.
- This 34,000 tonnes digestate and 18 ktonnes fresh SSO was composted, which yielded 20 ktonnes compost, 10 GWh residual heat extracted from the composting process and 4.5 million condensate water. A part of the heat was used in horticulture greenhouses and the condensate was used for city street cleaning and producing brine for city street ice control.
- 2 ktonnes heavily polluted SSO was incinerated in the waste-to-energy power plant in Wijster.

In addition, 7 ktonnes wasted bread, swill and verge grass was converted into green gas and compost as well.
Besides that, Meerlanden collects 190 ktonnes highly recyclable waste such as wood, glass, paper, materials from electrical devices and small batches of chemical waste.
In 2016 70% of the textile collected by Meerlanden was reused and 18% was recycled in form of new products.

At its location in Middenmeer HVC annually processes 114 ktonnes SSO: 76 ktonnes is digested and converted into biogas and the other part is composted (Rijkswaterstaat, 2017). More SSO (43 ktonnes/annum) is composted at HVC Purmerend, while at HVC Alkmaar annually 671 ktonnes waste is incinerated to yield 396 GWh electricity and 43 GWh heat. This heat is used in the city heating system.

In 2016 Orgaworld in Lelystad converted 34 ktonnes SSO in the Biocel anaerobic digester and 33 ktonnes SSO in the composting plant (Rijkswaterstaat, 2017). The biogas was used to produce electricity and heat (together 4200 GWh annually) in a combined power and heat plant. In addition, 43 ktonnes waste from food companies, industrial organic sludges and green biomass waste was composted. In total 40 ktonnes of compost was produced in Lelystad (www.orgaworld.nl).
Greenmills is the largest ecological industrial production estate in Europe. It is located in Amsterdam and exploited by Simadan (www.simadan.nl). It comprises companies for storage of biodiesel and edible oil and fats and production of oil/fat compounds. Important parts are:

- Orgaworld anaerobic digester: conversion of 120 ktonnes swill, supermarket waste, other organic waste and 350,000 m^3 polluted water into 20 million m^3 biogas (annually) (orgaworld.nl; simadan.nl). The biogas is used to produce 48 GWh electricity and 53 GWh heat. The digestate is used to produce 3.5 ktonnes fertilizer.
- Rotie collects used frying oil and organic waste from companies
- Biodiesel Amsterdam uses the waste oils and produces 125,000 m^3 biodiesel annually.

- Noba Vital Lipids uses vegetable oil (e.g. palm oil) to annually produce 180 ktonnes innovative fatty products for animal feed, for example C6-C12 medium chain fatty acids.

These companies show a strong interdependence and synergy with respect to feedstock, residue streams and utilities.

The SSO collected by GAD Gooi en Vechtstreek is transferred to Indaver, transported to Alphen a/d Rijn and converted into biogas by anaerobic digestion (www.gad.nl).

The main part of sewage sludge produced in sewage treatment plants are anaerobically digested to produce biogas. The residue sludge (after digestion) is incinerated to produce electricity and/or heat. Water plants, verge grass, pruning wood, grass, ash wood (or other wood) are currently composted or harvested but left at the site. E.g. Waternet harvest 20,000 tonnes of water plants (wet weight) annually of which the largest part is left at the waterside and a small part is transferred to a composting plant (STOWA, 2018).

A large part of biomass residues from arable land is not utilized and stays on the land. Straw is collected and used for various applications, e.g. in stables. Other residues, e.g. from greenhouses, are mainly composted. In the Netherlands compost companies are organized in the BVOR. According to the BVOR Annual report (BVOR Jaarverslag 2017) a share of 80% of the Dutch biomass residues and SSO is processed by its members. That includes 2900 ktonnes of biomass. In the annual report of 2014 (BVOR Jaarverslag 2014) more details are given: 400 ktonnes biomass from arable land and horticulture, 15 ktonnes from forestry and 2400 ktonnes biomass from parks, fields and road sides from municipalities. Interpolating these numbers to AMR (surface area AMR/Netherlands*0.8) about 24 ktonnes of biomass from arable land/ horticulture must be composted.

According to Schulze *et al.* (2017) only slightly more than 2% of the manure (wet weight) in the Netherlands is anaerobically digested, 9% is incinerated (mainly poultry manure, because that is sufficiently dry) and the largest part is spread over the agricultural land. Three manure codigesters can be found in the east part of MRA. In MRA a relatively low number of poultry farms can be found. Therefore, in MRA about 28 ktonnes manure may be digested annually and 1156 ktonnes is used on the land.

2.6 Overview

In Table 4 an overview is given of the current practices for important streams of organic solid waste/residues in MRA.

Table 4 The largest organic solid waste streams in MRA and the way these are processed.

Nature of the waste stream	Annual amount (ktonnes)	Processing
Municipal residue streams	565	Separation in waste separation stations for recycling (construction materials, metals). Largest part is incinerated.
Municipal coarse residue streams	96	
Residual waste from offices	43	
Residual waste from tourism sector including swill	60	Biogas production (swill), incineration
Municipal SSO	109	50% biogas, 50% composting
Waste from food industry	600	Large part biogas
Waste paper and cardboard from households	98	Recycled in cardboard mills
Waste paper and cardboard from offices	20	Recycled in cardboard mills
Export paper waste	<30	
A and B wood from households	50	Recycling e.g. in pallets and fiberboard (larger part), fuel for power plants
Sludge from municipal sewage treatment plants	75 (dry matter)	Biogas, residue (49 ktonnes) is incinerated
Sludge from industrial wastewater treatment plants	29 (dry matter)	Incinerated
Water plants	74	Composted, left on the waterside
Biomass from forests and park (pruning)	142	Composted (large part), fuel for homes and power plants
Grass	106	composted
Biomass from arable land	960	Largest part stays on the land, straw is used for stables and a small part is composted.
Manure	1184	1156 ktonnes used on the land, 28 ktonnes for biogas production (digestate again used on the land)
Import organic waste	2000	Incineration, biodiesel, biogas
Export organic waste	300	

3 Efficiencies and costs current organic residue conversion methods

3.1 Residual waste from households and offices: post-separation and incineration

Residual waste is the largest stream in AMR in which organic material is present. Currently this stream is incinerated coupled to the generation of electricity. AEB, the main actor in AMR in this field, incinerates various types of waste, but municipal waste is the largest part. AEB operates two incinerators: the AEC and the newer, more efficient HRC. Based on the data from AEB Jaarverslag 2016 and 2017 it can be concluded that the AEC has an energy efficiency of 25% and the HRC 30.4%. 3686 TJ electricity and 66 TJ heat was produced from 1438 ktonne waste plus 9 million m^3 biogas. That is 2.5 GJ/tonne after substraction of the energy derived from biogas. The HVC incinerator in Alkmaar produced 2.4 GJ electricity and waste heat per tonne waste. Furthermore, based on the amounts of waste and biogas processed and electricity and heat produced by AEB, it can be estimated that the original energy content of the waste is 11 GJ/tonne (wet) waste. The estimated dry matter content is 54% and organic matter is 70% (w/w) of dry matter.

According to WISE 54% of the energy produced by waste incineration is derived from renewable sources (biomass) and 46% from fossil sources (e.g. plastics) (www.wisenederland.nl). Plastic waste has a higher heating value (HHV) of 42 GJ/tonne and biomass (e.g. wood) 23 GJ/tonne dry matter (www.phyllis.nl). Combining all data it can be concluded that municipal waste contains two times more biomass than it contains fossil organic matter and that a tonne of (wet) municipal waste contains 0.38 tonnes of biomass plus fossil based dry matter.

If fossil based matter can be represented as $(CH_2)_n$ and biomass as $(C_6H_{10}O_5)_n$, the expected amounts of CO_2 produced per tonne municipal waste can be calculated. That should be near 0.87 tonne CO_2/tonne (as is) municipal waste.

In 2016 AEB has incinerated 1483 ktonnes waste and, therefore, a CO_2 emission of 1290 ktonnes could be expected. This CO_2 is a mixture of CO_2 from a long-term and a short-term carbon cycle. Besides that, the waste has to be transported and the by-products such as ash have to be processed, which leads to CO_2 emissions as well. Politiek and Kupfernagel (2016) have studied the CO_2 emissions of (other types of) waste incineration plants and concluded that the emissions of the incineration plant are two orders of magnitude larger than the emissions for transport and by-product processing. Therefore, for now, only the plant emissions are considered.
According to AEB in 2016 the amount of potentially avoided CO_2 emission was 183.900 tonnes (AEB Jaarverslag 2016, 2017). That is the amount of CO_2 emitted in case the same amount of electricity (3686 TJ) would have been produced in a power plant on natural gas.

AEB produces CO_2 but also avoids the emission of CO_2. Furthermore, the feedstock of AEB contains fossil based materials and biobased materials. How to express the effect of AEB's operation on greenhouse gas emission abatement, and how to compare it with alternative waste processing operations? It depends on the reference system. It is proposed to take a reference in which all organics in the waste are completely degraded and mineralized without the production of any useful/valuable energy, chemicals or materials. In that case the avoided CO_2 emission is 183.900 tonnes, or 0.12 tonne CO_2 per tonne residual waste.

In 2016 AEB produced 3752 TJ energy (mainly electricity), which is 1042 GWh, and 332 ktonnes recyclable materials. With a value of € 0.038/kWh and € 50/tonne recyclable materials the yield is about 56 million euro. The value of the products is summarized in Table 5.

Table 5 The value of the products per tonne of residual municipal waste.

	Price per unit	Amount	Yield
Electricity	€ 0.038/kWh	694 kWh	€ 26.3
Fertilizer	€ 50/tonne	0.23 tonne	€ 11.5

AEB's yearly costs amount 159 million euro (= turnover minus EBITDA plus earnings from product sales), which is € 107/tonne residual waste. That includes the separation process, which yields 0.23 tonne recyclable materials per tonne residual waste. The EBITDA is 37% of the turnover.

Summary:
- Residual municipal waste energy content: 11 GJ/tonne (as is)
- Content: 0.38 tonne biomass and fossil based matter/tonne
- Content: 0.24 tonne biomass/tonne
- Yield post-separation and incineration: 2.5 GJ and 0.23 tonne recyclable materials/tonne
- Avoids 120 kg CO_2 emission/tonne
- Cost: € 107/tonne
- Product yield: € 38/tonne

3.2 SSO: anaerobic digestion and post composting

SSO can be converted into biogas and the biogas can be processed to green gas. The residue after digestion, the digestate, can be composted. Meerlanden has given a detailed description of the products made from SSO in a chain in which citrus oil is extracted (from orange peels), green gas is produced, compost is produced and a part of the heat that is generated in the composting process is used in horticulture. Even the condensate that is produced during the recovery of that heat is used for street washing and de-icing.

A tonne of SSO contains about 38% dry matter and 65% of the dry matter is organic matter, although strong variations occur during the year (Milieuverslag GFT-afval 2009, 2010; author's own determination). The inorganic part mainly comprises sand and clay. The calorific value (HHV) of SSO is estimated 5.0 GJ/tonne (www.phyllis.nl).
Meerlanden produces 10,000 L citrus oil, 2.6 million m^3 green gas, 10,000 tonnes of compost and 5 GWh heat from 35,000 tonnes SSO (www.meerlanden.nl).

The energy contained in 2.6 million m^3 green gas (88% v/v methane; 55 MJ/kg methane) is estimated 88.6 TJ. The heat recovered in the composting process is 5 GWh, which is 18 TJ (www.meerlanden.nl). Therefore, the energy recovered from a tonne SSO is 3.0 GJ/tonne. It should be realized that this high energy recovery is mainly in form of gas. In case this gas has to be converted into electricity and heat, the efficiency may be 78% of this: 2.3 GJ/tonne SSO (Dumont, 2008).

The avoided CO_2 emission, roughly estimated solely on the basis of avoided use of natural gas, can be calculated from the biogas and heat produced and amounts 0.15 tonne CO_2/tonne SSO.

The value of compost is about € 18/tonne (Bruins en Kwast, 2017, www.grondwerkentrikikoen.be). The author's own estimation of the value of unpure citrus oil is € 1000/tonne.

Table 6 shows the values of the products. In total: € 19/tonne SSO, without SDE (government) subsidy.

The costs of the operation can be estimated using the fact that in the Netherlands SSO has a negative value: the gate fee is € -25/tonne. The cost can be estimated by € 25 + € 19 minus profit. Meerlanden has a 15 % profit (EBITDA) (De Meerlanden Jaarverslag 2016), therefore, the SSO processing costs may be near € 37/tonne SSO.

Table 6 The value of the products from anaerobic digestion and post-composting per tonne SSO.

	Price per unit	Amount	Yield
Green gas	€ 0.016/kWh	703 kWh	€ 11.26
Compost	€ 18/tonne	0.29 tonnes	€ 51.42
Citrus oil	€ 1,000/m^3	0.00029 m^3	€ 0.29
Heat from composting	€ 0.016/kWh	143 kWh	€ 2.29

Summary:

- SSO energy content: 5.0 GJ/tonne (as is)
- Content: 0.38 tonne dry matter/tonne SSO of which 65% organic matter
- Yield anaerobic digestion and composting: 3.0 GJ (mainly green gas), 0.29 tonne compost and 0.3 L citrus oil/tonne
- Avoids 150 kg CO_2 emission/tonne
- Cost: € 37/tonne
- Product yield: € 19/tonne

3.3 Swill, supermarket waste and residues from food industry: anaerobic digestion

In AMR swill, supermarket waste and residues from food industry are anaerobically digested. The biomass is converted into biogas, which is used in the production of electricity and heat. The residue after digestion, the digestate, is dried and sold as a NPK fertilizer. A tonne of swill contains 0.20 tonne dry matter and 80% of the dry matter is organic matter (www.fao.org). The calorific value of swill is estimated 3.1 GJ/tonne. The properties of supermarket waste and waste from food industry will not differ much from those of swill.

It is known that a tonne of swill yields 111 m^3 biogas with 60% (v/v) methane (www.jcarels.be). This means that the digestion yields 2.6 GJ/tonne swill. As stated before, conversion into electricity and heat will be carried out with a certain efficiency and will yield to a lower energy yield. Orgaworld in Amsterdam produces 20 million m^3 biogas annually (465 TJ), which is converted into 48 GWh electricity, 53 GWh heat and 3.500 tonnes fertilizer. The energy contained in electricity and heat is 364 TJ. Per tonne of swill and related products 268 kWh electricity and 296 kWh heat is produced.

The avoided CO_2 emission, again roughly estimated solely on the basis of avoided use of natural gas, can be calculated from the biogas produced and amounts 0.13 tonne CO_2/tonne swill and related residues.

Table 7 gives the value of the products. In total about € 24/tonne swill and related residues, without SDE (government) subsidy. The values of electricity and heat are from Lensink (2016) and the value of fertilizer from Brummelaar (2018).

Table 7 The value of the products per tonne of swill.

	Price per unit	Amount	Yield
Electricity	€ 0.038/kWh	268 kWh	€ 10.18
Heat	€ 0.0335/kWh	296 kWh	€ 9.92
Fertilizer	€ 200/tonne	20 kg	€ 4.00

The costs of the operation can be estimated again by using the gate fee for swill (€ 37/tonne) (www.refman.energytransitionmodel.com) and assuming a profit of 15%. The costs are € 37 + € 24 - € 9 = € 52/tonne swill and related residues.

Summary:

- Swill and related residues energy content: 3.1 GJ/tonne (as is)
- Content: 0.20 tonne dry matter/tonne swill of which 80% organic matter
- Yield anaerobic digestion and production of electricity and heat: 2.0 GJ/tonne swill and related residues and 20 kg fertilizer/tonne.
- Avoids 130 kg CO_2 emission/tonne
- Cost: € 52/tonne
- Product yield: € 24/tonne

3.4 Manure used as fertilizer on the land

The largest part of the manure produced in the MRA is spread over meadows and arable land. The fibres improve the soil structure and the minerals (e.g. N, P and K) can be used for crop growth. However, the easily biodegradable organic matter in manure is mineralized rapidly when introduced in the soil. These compounds are lost for a destination with a higher value and/or fossil-based greenhouse gas emission saving potential. The most important way this method avoids the use of fossil resources is the recycling of N, P and K. Nitrogen is the most important. Ammonia and derived products such as urea are normally produced from mineral gas (methane) and the production cost a lot of additional energy. In one tonne of manure about 6 kg N is present. The production of this same amount of NH_4-N costs 168 MJ methane (energy and building block) and as a result of this production process 8.4 kg CO_2 is produced (own calculations using information from www.wikipedia.org/wiki/Haber_process).

The addition of nitrogen fertilizer to the soil leads to the emission of N_2O, a potent greenhouse gas: 1 kg N_2O represents 298 kg CO_2 equivalents (www.climatechangeconnection.org). However, by the use of synthetic fertilizer more N_2O (0.013 kg N_2O-N/kg added N) is produced than by manure incorporation (injection) into the soil (0.009 kg N_2O-N/kg added N) (Coenen *et al.*, 2018). It can be calculated that the replacement of synthetic fertilizer by manure saves the emission 11.4 kg CO_2-equivalent per tonne manure.

A negative aspect of spreading manure on the land is the emission of methane. No information is available on that. Studies are in progress to quantify the emission of methane from ditches that are polluted with the run-off of manure from meadows.
Transportation of manure (10 km, diesel truck) leads to an emission of 0.88 kg CO_2 per tonne manure (BioGrace).

The total fossil-based greenhouse gas emission reduction of manure spreading on the land compared to the use of synthetic fertilizer on the land amounts to about 19 kg CO_2-equivalents per tonne manure. Cattle and pig farmers pay € 18- € 25 per tonne of manure to the company that collects the manure (www.boerderij.nl). Crop farmers get € 11 - € 15 per tonne for spreading it on the land. This can be translated to about € 9 processing costs and a product value of € -13 per tonne manure.
The calorific value (HHV) of (pig) manure with a dry matter content of 8% amounts to 1.4 GJ/tonne (www.phyllis.nl). The organic matter of cattle and pig manure on average is 85% of dry matter.

Summary:

- Manure energy content: 1.4 GJ/tonne (as is) (www.phyllis.nl)
- Content: 0.08 tonne dry matter/tonne SSO of which 85% organic matter (www.phyllis.nl)
- Avoids 19 kg CO_2 emission/tonne
- Processing cost: € 9/tonne
- Product yield: € -13/tonne

3.5 Overview

Characteristics and performance indicators for current conversion methods are summarized in Table 8.

Table 8 Efficiencies and costs of current conversion methods for important organic residue streams in MRA.

	Residual waste: post separation and incineration	SSO: anaerobic digestion and post-composting	Swill and related residues: anaerobic digestion	Manure on the land
Dry matter content % (w/w)	54	38	20	8
Organic matter (% of dry matter)	70	65	80	85
Calorific value (GJ/tonne as is)	11	5.0 (HHV)	3.1	1.4 (HHV)
Energy product yield (GJ/tonne as is)	2.5	3.0 (biogas) or 2.3 (electricity and heat)	2.0 (electricity and heat)	0
Energy conversion efficiency (%)	23	46	65	0
Other product yield (kg/tonne as is)	230 (recyclable materials)	290 (compost) 0.3 (citrus oil)	20 (fertilizer)	-
Kg CO_2-eq. avoided per tonne as is	120	150	130	19
Kg CO_2-eq. avoided per tonne dry matter	222	394	650	238
Processing costs (€/tonne as is)	107	37	52	9
Product value (€/tonne as is)	38	19	24	-13
Economic efficiency: (product value minus costs)/tonne dry matter	-128	-47	-140	-275
Cost (€)/tonne CO_2-eq. avoided	892	246	400	474

The conversion of four important organic waste streams in AMR are all characterized by low economic efficiencies. They are primarily waste destruction methods and the costs are paid by the owners of the residues. The processes that produce biogas have better energy conversion efficiencies and avoid more fossil CO_2-eq emission than incineration and spreading over land.

4 Biorefining options

4.1 Selection strategy

According to Cramer (2014) the best opportunity for municipalities to make a transition to a circular city is the end of a chain: the waste/residue stage. Step 1 is to select the most important waste streams: those with high volumes and high environmental pressure. The next step is to find options for a better circularity.

The largest streams organic residues in AMR are heterogeneous: residual household waste, source separated organics (SSO), swill and related residues and manure. Current technology for these types of residues are composting, anaerobic digestion, incineration, aerobic biological treatment (wastewater), drying and recycling. In our previous (WFBR) reports new technologies to process such type of residues are discussed in detail (Meesters *et al.*, 2015; Annevelink, 2016). These are:

- Technology for upgrading biogas to Bio-LNG
- Torwash upgrading
- Gasification
- Pyrolysis
- Hydrothermal upgrading (HTU)
- Technology for production of fermentable sugars
- Technology for production of organic acids and fatty acids
- Technology for production of furans and bioaromatics
- Technology for production of PHA

Now more novel technologies can be added:

- Production of medium chain fatty acids (caproic acid)
- Production of larvae of the black soldier fly
- Renescience process (enzymatic liquefaction)

Some of these technologies are running on small commercial scale in the Netherlands, e.g. the pyrolysis plant of BTG and Friesland Campina in Borculo (about 7,000 tonnes of pyrolysis oil annually) (www.bioenergyinternational.com) and the caproic acid production plant of ChainCraft in Amsterdam (1,000 tonnes/year) (www.chaincraft.nl). Other technologies are running on full scale but using homogeneous feedstock (production of fermentable sugars from corn stover) and most other technologies are still in a laboratory or pilot plant stage.

The study 'Circular Amsterdam' (2016), carried out by Circle Economy, TNO and Fabric for Amsterdam Municipality, recommends high value processing of organic residues and source separation of organics. In this study a production of protein, biogas and chemical buildings blocks (and eventually bioplastics) are foreseen. A report has been produced. However, no details on feedstock requirements, product yield and conversion costs are given. According to the authors four important measures that contribute to circularity of organic residual streams in Amsterdam are:

1. Central hubs for biorefinery. Already such hubs exists: the Greenmills cluster and the AEB/Waternet/Port of Amsterdam cluster.
2. Waste separation and return logistics, e.g. smart street containers, pick-up and delivery service and codes bags for households.
3. Cascading of organic flows: recover valuable material first and use the residue for further refining and secondary products.
4. Retrieving nutrients: nutrients such as N, P and K should be recovered and reused in agriculture.

4.2 SSO

In the AMR SSO is currently processed via composting and via anaerobic digestion and subsequent composting. These are the two most practised methods for conversion of this feedstock in the Netherlands and actually all over the world. Soest and Schwencke (2009) have explained well why separate collection of SSO followed by anaerobic digestion, post-composting and utilization of the compost produced is superior to SSO complete composting and the incineration or composting of integral household waste. It has ecological (greenhouse gas emission reduction, soil improvement) and economic advantages. According to Soest and Schwencke thermal conversion processes such as gasification, hydrothermal upgrading and pyrolysis are less suitable because of the high mineral content of SSO. Home composting is not considered as realistic as well because of a low willingness amongst the people and a low process efficiency.

Nevertheless, the waste processing companies in the Netherlands are exploring biorefining options for SSO to create higher product values compared to biogas. In addition, waste collection companies are running pilots with higher degrees of separation, e.g. the collection of vegetable/fruit waste from households and a separate collection of garden waste.
The composition of SSO varies from region to region and depends on the season (in winter less garden waste). Own determination of 2015 autumn SSO from Northern Netherlands (Table 9) reveals that the mineral content is high (27% of dry matter) and the organic matter contains 40-45% carbohydrates. It is known that sometimes the mineral content can approach 50%. The organic material is slightly acidified, but not as much as silage.

Table 9 Chemical and physical characterization of SSO; carbohydrates after chemical hydrolysis.

Dry weight (%)	38
Ash content (% DW)	27
Ca in Ash (g/kg DM)	15.3
Mg in Ash (g/kg DM)	2.0
Organic matter (% DW)	73
pH	5.7
Carbohydrates	
Glucose (g/100 g DW)	22.2
Xylose (g/100 g DW)	5.9
Arabinose (g/ 100 g DW)	1.8
Galactose (g/ 100 g DW)	1.8
Rhamnose (g/100 g DW)	0
mannose (g/ 100 g DW)	0.8
Fructose (g/ g DW)	0
Water absorption capacity (kg/kg DW)	3.8
Volatile fatty acids	
Acetic acid	1.4
Propionic acid	0.9
Butyric acid	0.7
Valeric acid	0
Lactic acid	1

The amounts (see previous chapters), composition, variation and waste status of SSO determine the choice of processing and connected products. The products cannot be used in feed or food because of the waste status of SSO and the product market should be at least 20 ktonnes annually and preferably

more than 100 ktonnes worldwide. Conversion processes that are hampered by the presence of minerals (gasification, pyrolysis and hydrothermal upgrading) are not suitable.
Three biorefining options are suggested:

1. Production of furfural and levulinic acid
2. Production of bioplastics (PHA) via volatile acids
3. Separate collection of (a) vegetable/fruit and (b) yard waste; conversion of vegetable/fruit into caproic acid and yard waste into fermentable sugars

4.2.1 Production of furfural and levulinic acid

Aromatics are an important raw material for the production of, among other things, polystyrene and ABS rubber. There is increasing interest in the chemical industry in the production of aromatics from biomass. The reason is twofold. Aromatics are now produced from a fraction of crude oil in oil refineries, but due to the switch to gases (natural gas, shale gas) as raw material, less and less oil is being refined. This induces a shortage of aromatics. In addition, producers want to switch because of sustainability considerations and a need for more security of supply to renewable raw materials such as biomass. Bioaromatics can be produced from carbohydrates, lignin and protein. However, a production from the carbohydrate fraction is obvious for SSO.

In the production of bioaromatics from carbohydrates, furans are an intermediate product. These furans (furfural and hydroxy-methylfurfural (5-HMF)) can also be used in other markets. Furfural is now produced worldwide by at least 48 companies (mainly from bagasse) in a total quantity of 250,000 tonnes per year. The value is € 750 / tonne and the applications are solvent, lubricating oil and raw material for furfuryl alcohol. The production of 5-HMF (by 11 companies) is small, but the compound is one of the possible raw materials for polyethylene furanoate, an alternative to PET. Depending on the process used for the production of furans from biomass, levulinic acid (which is no furan) can also be produced. Levulinic acid is in the top 12 of the US Department of Energy for promising chemicals that can be produced from biomass carbohydrates. Now production is still more than 2,000 tonnes / year (by 18 companies). The current value amounts to € 2000 / tonne, but the market is expected to expand strongly and the value then falls to € 1200 / tonne. Levulinic acid can be used for the production of polycarbonate, aminolevulinic acid (herbicide), acrylates and methyltetrahydrofuran (gasoline additive and solvent).

Work is being done in various places around the world on the improvement of processes for the production of furfural, 5-HMF and levulinic acid and also for the production of bioaromatics. In the Benelux the Biorizon program is the largest (www.biorizon.eu). This is a program from TNO, VITO (Belgium), the Green Chemistry Campus (Bergen op Zoom) and 200 companies and organizations. Waste processors such as Orgaworld, Twence and AEB participate in the projects, but also chemical companies such as SABIC.

The production of bioaromatics from biomass is carried out by first converting the carbohydrates to furans and levulinic acid at high temperatures in the presence of a strong acid. In a next unit operation the furans are converted into aromatics. This occurs with Diels-Alder reactions in special reactors.

The process for the production of furans, levulinic acid and bioaromatics from heterogeneous residues is still in the development phase. Experience has been gained with the use of GFT in the production of furfural and levulinic acid. Furfural can be used to produce aromatic compounds or be sold as such in a large existing market. The current market for levulinic acid is small, but expected to grow if low priced levulinic acid (as produced from SSO) is entering the market.

A possible process for the production of furfural and levulinic acid consists of the soaking of the biomass with an acid solution, followed by the passage of the biomass with steam, in a pressure reactor. The steam treatment has two functions: (1) heating the biomass and (2) taking in and discharging formed furfural (steam stripping). Because furfural is quickly removed from the reaction mixture, it does not react further to tar products (humines). This furfural is formed from the C5 sugars that mainly occur in hemicellulose. The C6 sugars (from cellulose and starch) are converted into levulinic acid, which accumulates in the wet biomass. The furfural is then extracted from the steam and the levulinic acid is extracted from the biomass. The remaining biomass can be composted or incinerated, but in principle it can also be used as a raw material for other biobased production processes. For example lignin and humins can be extracted and used as a high value fuel for ships. Because steam has to flow through the biomass in this process, this is particularly suitable for the somewhat drier and porous biomass streams with a dry matter content of at least 25%.

For now (in this study) the biorefinery is limited to the production of furfural and levulinic acid, the used acid is recovered and recycled and the minerals are recovered as well (Figure 2). The remaining organics are converted into compost. The project Waste-to-Aromatics in which WFBR is participating has generated information on the yields and costs. In this public report no details can be given on these confidential data, only a position in the ranking between alternative biorefineries.

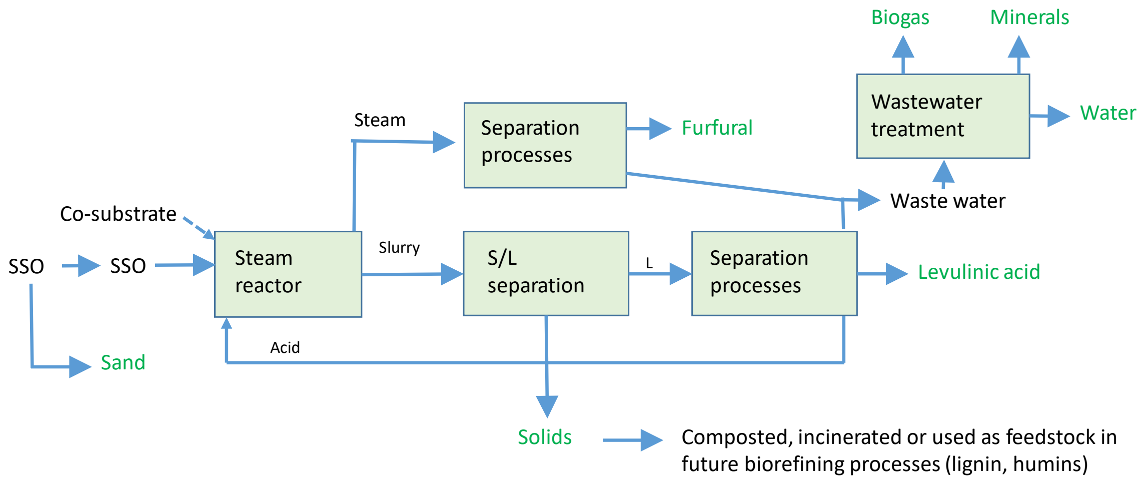

Figure 2 Biorefinery for production of furfural and levulinic acid from SSO

CO_2 emission can be saved per tonne SSO when comparing production of furanics from SSO with production of xylene from oil (including emissions from production process and end-of-life). The biogas produced contributes with avoided CO_2 emission per tonne SSO as well.

Summary:

- Content: 0.38 tonne dry matter/tonne SSO
- Yield: levulinic acid, furfural, compost, green gas and minerals
- Avoids an amount of CO_2 emission/tonne SSO that is comparable to complete anaerobic digestion
- Cost: same level as PHA production
- Product yield: same level as the production costs

4.2.2 Production of bioplastics (PHA) via volatile acids

Polyhydroxyalkanoate is a natural biobased polyester that is produced by bacteria. The bacteria store this substance as a carbon and energy reserve inside the cells in form of granules. Most occurring forms are polyhydroxybutyrate (PHB), polyhydroxyvalerate (PHV) or mixtures of these (PHBV). Bacteria can produce these compounds from volatile fatty acids (VFA): such as acetic acid, propionic acid, butyric acid and valeric acid. The VFA can be produced from many organic compounds such as carbohydrates, lipids and protein. In anaerobic biological digestion processes organic compounds are normally first converted into VFA, CO_2 and hydrogen gas before methane is produced from these intermediates. Worldwide a lot of experience has been gained on production of bacterial PHA from mixtures of VFA or wastewater containing organic compounds. However, the experience is mainly based on laboratory or pilot plant research. In addition, knowledge and experience can be found on the production of VFA from wastewater, sludges, and other organic solid residues. In the Netherlands companies such as Orgaworld, Attero and HVC have gained experience using SSO. No full scale operations has been realized so far. One of the bottle necks are the high costs for extraction and purification of the PHA from the bacterial mass.

A possible biorefinery is the anaerobic biological acidification of SSO in a reactor. The liquid phase of such a reactor contains the VFA and is fed to a second biological reactor for PHA production. The solids from the first reactor can be composted. The second reactor is aerobic and uses special bacteria that accumulates PHA. The bacterial mass is harvested and extracted using an organic solvent (e.g. butanol). The PHA in the solvent is further purified and the solvent is reused (Figure 3).
The PHA-accumulating bacteria in the second reactor can be pure cultures or mixed cultures. Pure cultures can accumulate more PHA and show higher PHA yield factors on the VFA substrate. However, costs have to be made to keep the cultures pure or at least dominant in the reactor. Mixed cultures show lower yields but are easier to maintain.

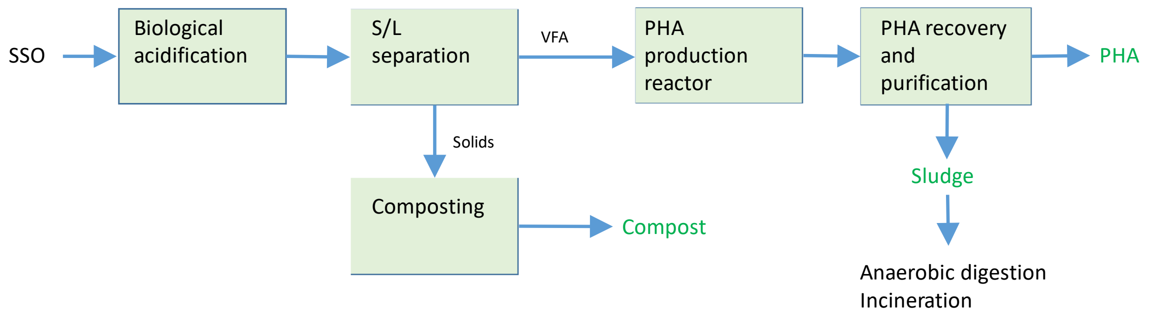

Figure 3 Biorefinery for the production of PHA from SSO

The PHARIO project (Bengtsson *et al.*, 2017) as carried out by VEOLIA and Dutch water boards used the route with mixed cultures. Activated sludge from a sewage treatment plant was used because of its natural potential to accumulate PHA. This activated sludge (produced in a wastewater treatment plant) was added to a special reactor dedicated to aerobic PHA production. A pilot plant was operated using VFA from the acidification of primary sludge and wastewater from a candy factory. It was found that 0.19 g PHA was produced from a gram COD (chemical oxygen demand). Since acetic acid, the dominant VFA, has a COD of 1.07 kg per kg acetic acid, the yield can be translated as 0.18 g PHA/VFA (as acetic acid). In the project it was found that the sludge dry matter contained 41% PHA. The residue sludge may be processed the same way as other activated sludge from wastewater treatment plants: anaerobic digestion followed by incineration.
In case SSO has to be used for VFA production an estimation of the yield can be made by assuming that all methane produced in SSO anaerobic digestion has been produced via acetic acid:

$CH_3COOH \text{ --> } CO_2 + 3\ CH_4$

This is not completely correct as a small part of the methane produced is from H_2 and CO_2. However, based on the methane production observed by Meerlanden when digesting SSO, it can be estimated that 173 g VFA can be produced from one tonne of SSO. In a second reactor, designed and operated in the PHARIO project, 31 kg PHA can be produced from this VFA.
The amount of compost produced from the solids that remain in the first reactor can be estimated as follows. Normally SSO contains 380 kg solids. By the VFA production process 173 kg is solubilized and removed as VFA and an estimated amount of 40 kg may be solubilised as well (minerals, soluble organics). The amount of solids left may be 167 kg, from which 84 kg compost can be produced.
The PHARIO project included an estimation of the production costs and the value of PHA. According to the project team the costs for production of PHA using organic residues and activated sludge amount € 3.4 per kg PHA, of which € 0.2 for the production of VFA, on a scale of 5,000 tonnes PHA annually. The expected market price in 2015 was estimated to be € 3.5/kg PHA. However, it will be a challenge to find a large market for PHA at this high price. When SSO is used, the production costs can be expressed as € 105/tonne SSO. The composting of 167 kg solids (dry matter), which may actually be 0.5 tonne wet filter cake, will cost another € 13/tonne SSO.

The cost for taking activated sludge and processing it after use is left out, because this is part of the normal operation of a wastewater treatment plant.

The value of the products is summarized in Table 10. In total € 110 product value can be generated per tonne SSO.

Table 10 The product value per tonne SSO.

	Price per unit	Amount	Yield
PHA	€ 3.5/kg	31 kg	€ 109
compost	€ 18/tonne	84 kg	€ 1.5

To estimate the avoided carbon dioxide emission by producing PHA instead of a fossil based plastic, it is proposed to compare PHA with PET (polyethylene terephthalate) similar as the approach of Fernandez-Dacosta *et al.* (2015). Differences are created by the different production processes and by the end-of-life treatment. In this end-of-life process the plastics are oxidized (burned) and converted into CO_2 and H_2O, however, the CO_2 emitted by degradation of PET is fossil based and contributes to greenhouse gas emission.

According to Fernandez-Dacosta *et al.* (2015) three processes for the production of PHA from waste water (not SSO) had global warming potentials ranging from 2.4 to 4.3 kg CO_2-eq./kg PHA, while the production of PET had a potential of 2.2 kg CO_2-eq./kg PET. The end-of-life CO_2 production of PET is 2.3 kg CO_2/kg PET. In this stage it is assumed that the values for SSO will be near the values of waste water. The overall result is an avoided CO_2-eq. emission ranging from 6 to 78 kg CO_2-eq./tonne SSO.

Summary:
- Content: 0.38 tonne dry matter/tonne SSO
- Yield: 31 kg PHA and 84 kg compost per tonne SSO.
- Avoids 40±30 kg CO_2-eq. emission/tonne SSO
- Cost: € 118/tonne SSO
- Product yield: € 110/tonne SSO

4.2.3 Separate collection of (a) vegetable/fruit and (b) yard waste; conversion of vegetable/fruit into caproic acid and yard waste into fermentable sugars

SSO is a mixture of kitchen waste (mainly vegetable and fruit residues) and yard waste from households. The exact composition has been studied in the UK and the Netherlands. Seventy percent of the weight (as is) is yard waste and 30% is kitchen waste (City of Surrey, 2013; Milieuverslag GFT-afval 2009, 2010). In winter the percentage of yard waste is lowest. Yard waste is mainly composed of grass and leaves.
Experiments on separate collection of vegetable/fruit waste and yard waste have been carried out by waste company Circulus-Berkel (Apeldoorn and Deventer and surroundings) and by Meerlanden on Java-eiland (Amsterdam). Analyses of the Deventer vegetable/fruit waste revealed that it contained 20% dry matter and the dry matter contained 36% carbohydrates, 22% organic acids and 2% minerals.
Once separated, vegetable/fruit waste should get an application with a higher value compared to the current anaerobic digestion and composting (of SSO). One interesting option is the production of caproic acid.

If kitchen waste is taken out of the SSO, the yard waste will be left. This yard waste in principle can be composted (current practice for grass and leaves). New technologies may be pretreatment (breaking the lignocellulosic complex) followed by anaerobic digestion or by production of fermentable sugars. In this study we consider the production of fermentable sugars.

4.2.3.1 Vegetable/fruit into caproic acid

The Amsterdam biotechnology company ChainCraft has developed a technology in which medium-chain fatty acids can be made from organic residual flows (www.chaincraft.nl). The technology originally was developed at Wageningen University (Chen *et al.*, 2016). The process is based on biological acidification of the residual stream, in which acetic acid is the main product. This acetic acid is produced from the sugars present, other acids,proteins and fats. This acetic acid is then used to produce medium-chain fatty acids in a second biological reactor in which chain elongation takes place. This requires ethanol as a second raw material. One of the possible products is caproic acid (Figure 4). ChainCraft has successfully completed the research with a pilot plant and is now running a demonstration plant in which 1,000 tonnes of product have to be produced per year. In couple of years the production will be scaled up 10 to 20 times.

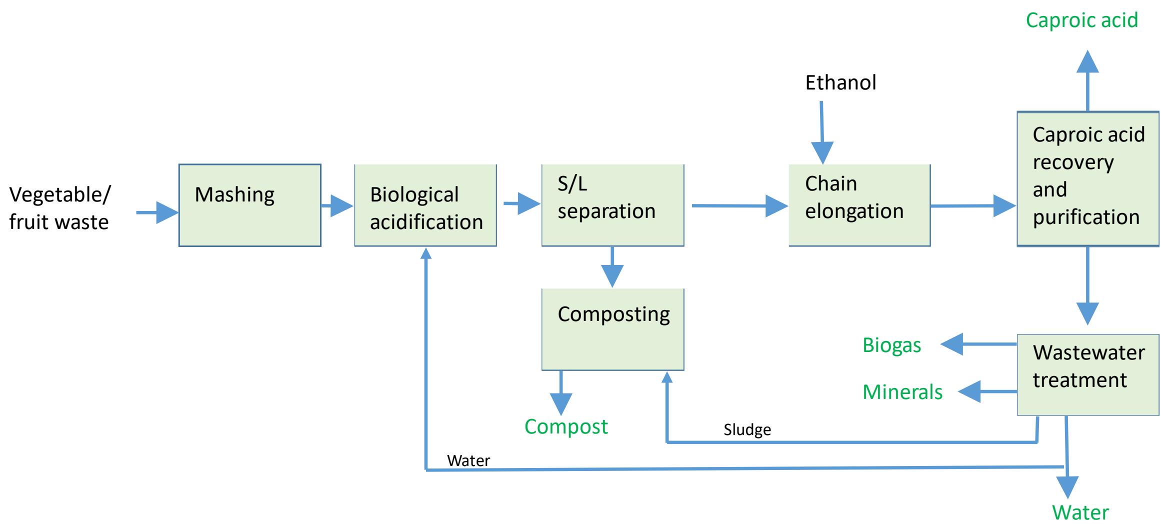

Figure 4 Biorefinery for the production of caproic acid from vegetable/fruit waste

Precisely because the vegetable/fruit waste is already quite acidified and contains a lot of organic matter, the production of medium-chain fatty acids is interesting. ChainCraft already has experience with the processing of fruit and vegetable waste streams. It is estimated that vegetable/fruit waste could yield at least 1,200 kg of product per tonne of dry matter, with half of the product weight coming from added ethanol. This amounts to 240 kg of product / tonne of wet weight.
One of the products ChainCraft can produce is caproic acid. The market for this organic acid can be connected to feed or chemistry. Since household vegetable/fruit waste has a waste status, the product can only be used in the chemistry market. Caproic acid is worth about € 3,500 / tonne (www.iowabio.org; www.alibaba.com. Approximately 0.8 tonnes of ethanol (value € 550 / tonne; www.icis.com) will have to be used for the production of one tonne of caproic acid. The remaining production costs, including the purification of the fatty acids, are unknown to the author. The total production costs are roughly estimated at € 700±150/tonne vegetable/fruit.
The product yield (caproic acid) is about € 840 per tonne vegetable/fruit. Compost hardly contributes to the income.

Chen *et al.* (2017) have made a LCA of the caproic production process described above. The production of caproic acid from supermarket food waste is estimated at 8.7 kg CO_2-eq. emission/kg caproic acid. This includes the use of ethanol produced from corn grains, which contributes with 2.5 kg CO_2-eq. emission/kg caproic acid. The production of corn grains accounts for 77% of this 2.5 kg. If ethanol is generated from organic waste (see section below) the contribution of ethanol will be decreased to 0.6 kg CO_2-eq. emission/kg caproic acid. The total GWP will be 6.8 kg CO_2-eq. emission/kg caproic acid.

If caproic acid is a raw material to produce jet fuel (it can be converted into decane) the GWP of the biobased caproic acid production process should be compared to the production process of kerosene. Extraction, refining and transportation has a GWP of 0.016 kg CO_2-eq. emission/kg kerosene. Moreover, the combustion of this fossil-based fuel yields 3.1 kg CO_2-eq. emission/kg kerosene (Koroneos *et al.*, 2005).

The overall difference is 6.8 – 3.1 – 0.016 = 3.7 kg CO_2-eq. emission/kg caproic acid. The fact that this biotechnological and biobased process gives a higher GWP than the fossil alternative is due to the high energy use of the process and the assumption that this energy is generated from fossil sources. However, in a world in which energy is generated from biomass, wind or solar radiation, the difference can become lower or even negative.

Summary vegetable and fruit waste:

- Content: 0.20 tonne dry matter/tonne vegetable and fruit waste
- Yield: 240 kg caproic acid and 84 kg compost per tonne vegetable and fruit waste.
- Avoids -888 kg CO_2-eq. emission/tonne vegetable and fruit waste (it has a higher GWP than the fossil alternative).
- Cost: € 700±150/tonne vegetable and fruit waste.
- Product yield: € 840/tonne vegetable and fruit waste.

4.2.3.2 Yard waste into fermentable sugars

Yard waste is mainly composed of leaves and grass and these contain cellulose or lignocellulose, a complex consisting of cellulose, hemicellulose and lignin. Cellulose and hemicellulose are polysaccharides and can be converted into their monomers: monosaccharides such as glucose, xylose and arabinose. Worldwide the use of lignocellulosic materials to produce fermentable sugars is studied in hundreds of laboratories, pilot plants and a few full scale factories. In the Netherlands for example at WUR, TUD and DSM. Most research has been carried out with wheat straw, corn stover and sugar cane bagasse. An example of a full scale plant is the joint venture of DSM and Poet in the USA, called Poet-DSM Advanced Biofuels LLC, in which corn stover is used to produce bioethanol, via fermentable sugars. Although plants are running at full scale, the technology is still in development to make the process more reliable and profitable. Even at a full scale, temporary production stops had to be made to solve technical or commercial problems.

Most processes for the production of fermentable sugars from lignocellulose are based on pretreatment (to break the lignocellulose complex) followed by hydrolysis of (hemi)cellulose. Pretreatment can be based on high temperatures, low pH, high pH, mechanical forces, advance oxidation or the action of fungi. Hydrolysis can be catalysed by enzymes or acids. After the hydrolysis the water fraction with the soluble monosaccharides can be separated from the solids (Figure 5). The solids mainly contain lignin and sand. The lignin can be used as a feedstock for the biobased economy as well (e.g. production of asphalt). The liquid can be used in a fermentation process. Well studied processes in which cellulosic substrates are used are the production of ethanol and lactic acid.
Since yard waste is mainly composed from grass and leaves it is expected to contain 40% dry matter (author’s own experience) and the dry matter may contain 30% inorganic substances and 70% organics. Based on information from the phyllis2 database the organic matter of a grass/leaves mixture may contain 34% cellulose, 30% hemicellulose and 19% lignin. It is proposed to separate the sand from the yard waste first. Technology for such separation is available, e.g. at WUR and Twence. The cleaned product will have a composition not far away from sugar cane bagasse. TNO has made an estimation of the costs of a plant for the production of a monosaccharide solution from sugar cane bagasse (unpublished data; the project team is transferred to WUR/FBR). The expected yield amounts to 0.62 tonnes of monosaccharides per tonne of biomass dry matter. The production costs are estimated at € 220 per tonne of monosaccharide, excluding the feedstock costs and excluding lignin sales. Such a plant produces 100,000 tonne monosaccharides annually based on a pretreatment process that uses steam and acid, a hydrolysis using enzymes, a solid/liquid separation and drying of the lignin. 27,500 tonnes of dry lignin is produced.

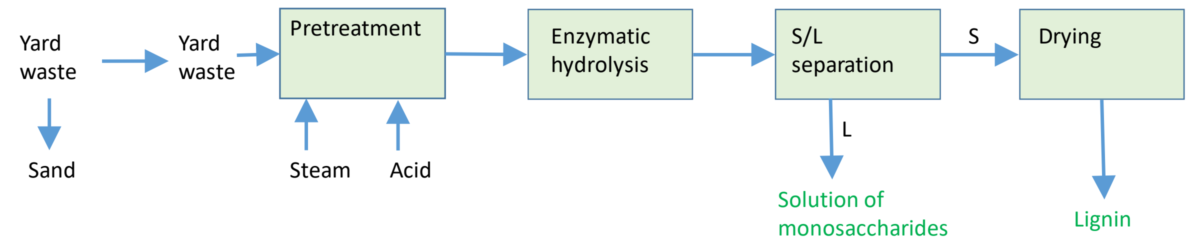

Figure 5 Biorefinery for the production of fermentable sugars and lignin from yard waste

Per tonne of yard waste 0.92 tonne cleaned yard waste and 0.08 tonne sand can be produced. From the amount of cleaned yard waste 0.20 tonne monosaccharides can be produced and 0.053 tonne lignin. The value is summarized in Table 11: in total € 57 product value per tonne yard waste.

Table 11 The product value per tonne yard waste.

	Price per unit	Amount	Yield
monosaccharides	€ 180/tonne	0.20 tonne	€ 36
lignin	€ 400/tonne	0.053 tonne	€ 21.2

The production costs per tonne of yard waste can be derived from the earlier study on sugar production from bagasse; the scale in Amsterdam can be half of that of the bagasse case but will be sufficiently large to keep the same production costs per tonne of sugar. This way the production costs of fermentable sugars and lignin from yard waste is estimated at € 44/tonne yard waste (0.20 x 220). The sand removal and disposal is estimated at € 10/tonne yard waste. The gate fee for yard waste is € 25/tonne (negative value).
Summary yard waste:

- Content: 0.40 tonne dry matter/tonne yard waste
- Yield: 200 kg fermentable sugars and 53 kg lignin per tonne yard waste.
- Production cost: € 54/tonne yard waste.
- Product yield: € 57/tonne yard waste.

4.2.3.3 Combining vegetable/fruit and yard waste processing in one biorefinery

The production of caproic acid needs ethanol as a raw material. For a better sustainability second generation bioethanol would be ideal. First generation bioethanol is produced from food crops such as wheat, corn and cane sugar, and can interfere with food prices and involves a high GWP connected to crop cultivation. Second generation bioethanol is produced from biomass residues, which does not have these two disadvantages (depends on the method of allocation of energy/chemicals/fuel to different crop parts). Therefore, the fermentable sugars produced from yard waste may be used for the production of bioethanol. A part of the bioethanol produced can be used for caproic acid production. For that purpose bioethanol does not have to be distilled and dewatered like this is required for an application as a biofuel. The beer (6-15% ethanol) can be used as well, which saves money and energy (Figure 6).

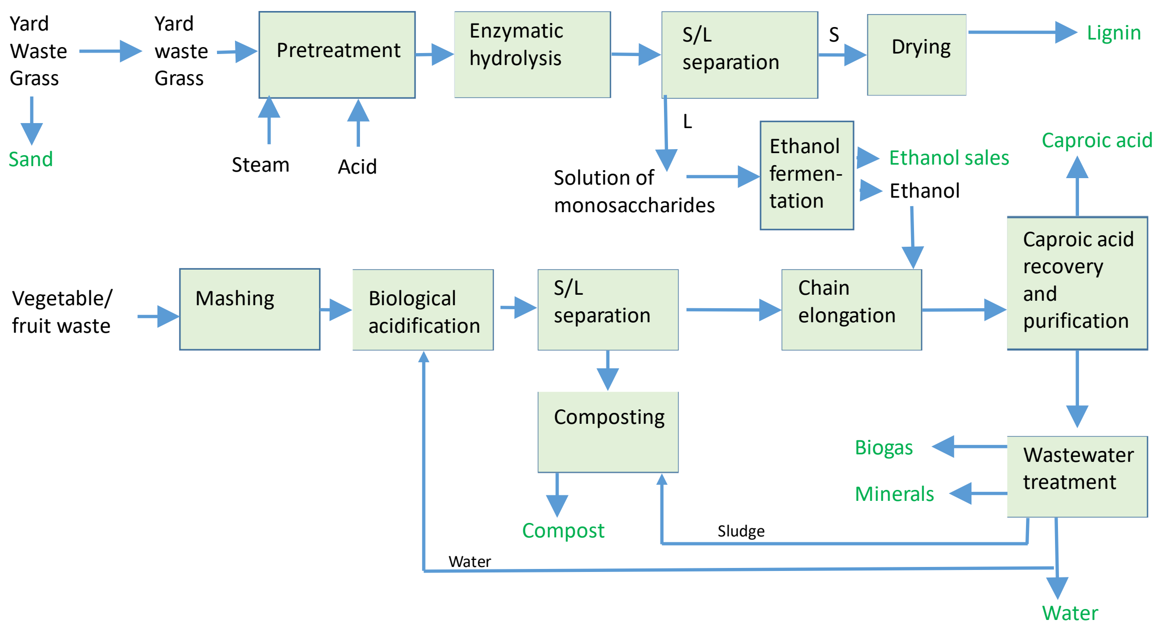

Figure 6 Biorefinery for yard waste, grass and vegetable/fruit waste

The potential size of such biorefinery can be calculated from earlier disclosed quantities of organic residues in the AMR. The AMR annually produces 109 ktonnes SSO, 106 ktonnes grass and 600 ktonnes municipal residues. The municipal residues contain large quantities of kitchen and yard waste. The trend is source separation, even in the AMR. In principle 90 kg SSO can be collected per person per year (situation in Amstelveen; www.cbs.nl). AMR has 2.4 million inhabitants, therefore, the amount of SSO can increase to 216 ktonnes. This can be further split up into 65 ktonnes vegetable/fruit waste and 151 ktonnes yard waste. These 65 ktonnes vegetable/fruit waste can be used to produce 13 ktonnes caproic acid. For this production process 10.4 ktonnes ethanol is required.

The 151 ktonnes yard waste plus 106 ktonnes grass can be used to produce 27.4 ktonnes bioethanol plus 16 ktonnes lignin. A part of this ethanol can be used in caproic acid production. Important co-products of the combined biorefinery are 4.6 ktonnes compost and 12 ktonnes sand. Table 12 shows the values of the products. The total product value amounts to more than M€ 61/year.

Table 12 The amount and value of the products annually generated by a biorefinery for the processing of 65 ktonnes vegetable/fruit waste, 151 ktonnes yard waste and 106 ktonnes grass.

	Price per unit	Amount	Yield
Caproic acid	€ 3,500/tonne	13,000 tonnes	M€ 45.5
Bioethanol	€ 550/tonne	17,000 tonnes	M€ 9.4
Lignin	€ 400/tonne	16,000 tonnes	M€ 6.4
Compost	€ 18/tonne	4,600 tonnes	M€ 0.08

The production costs:

The production of first generation bioethanol is a marginal business: the production costs are near to the sales value of bioethanol (dominant in value) and residues such as DDGS (dried distillers grains and solubles). The production costs will be near € 550/tonne bioethanol. In the production of second generation bioethanol, sugars derived from biomass residues are used. However, these sugars are less pure. According to the fermentation industry in the Netherlands similar production costs can be reached if the price of the sugars produced from biomass residues is € 180/tonne. However, the production costs of such sugars are € 220/tonne, which makes the bioethanol (yield ethanol/sugar is 0.45) € 89/tonne more expensive. This leads to production costs of € 639/tonne bioethanol. From earlier experiences the author knows that distillation and rectification costs about € 110/tonne bioethanol. In our biorefinery 38% of the ethanol does not require a distillation since the beer from the fermenter can be used as such in caproic acid production. That makes the production costs connected to the bioethanol factory € 597/tonne bioethanol or M€ 16.4 per year.

Using the data above, and the fact that ethanol already is delivered by the biorefinery, the conversion of 65 ktonnes vegetable/fruit waste per year into caproic acid and compost may cost M€ 39 annually. The annual costs of the complete biorefinery will be near M€ 55.

The GWP of the complete biorefinery can be compared with a reference system in which the organic residues are completely mineralized/oxidized, kerosene is used instead of caproic acid, gasoline instead of bioethanol and phenol-formaldehyde resin instead of lignin.
In the caproic acid section (above) it was concluded that the production and use of caproic acid instead of production and use of kerosene (decane) yielded and additional 3.7 kg CO_2-eq. emission/kg caproic acid. It had a higher GWP than the fossil alternative and that was due to the use of fossil energy in the production process.

The production and use of bioethanol instead of energy-equivalent amounts of gasoline saves 2.0 kg CO_2-eq. emission/kg gasoline or 1.1 kg CO_2-eq. emission/kg bioethanol. This can be derived from the review of Wiloso *et al.* (2012) on LCA studies on second generation bioethanol production.
The destination of lignin is not decided yet. Lignin can be used to replace bitumen, phenol resins and other aromatic compounds and polymers. For now it is proposed to express the emission reduction achieved by production and use of lignin as mainly the end-of-life greenhouse gas emission of phenol-formaldehyde resin. The outcome is 2.7 kg CO_2-eq. emission/kg lignin, which is the CO_2 originating from the phenol-formaldehyde resin material. The total effect is summarized in Table 13.

Table 13 The effect of the complete biorefinery on greenhouse gas emission.

	Greenhouse gas emission reduction (kg CO_2-eq. emission/kg)	Amount produced (tonnes/year)	Greenhouse gas emission reduction (tonnes CO_2-eq. emission per year)
Caproic acid	-3.7	13,000	-48,100
Bioethanol	1.1	17,000	18,700
Lignin	2.7	16,000	43,200
TOTAL			13,800

Summary per tonne of mixture of vegetable/fruit waste, yard waste and grass as processed in a biorefinery:

- Content: 0.38 tonne dry matter/tonne
- Yield: 40 kg caproic acid, 53 kg bioethanol, 50 kg lignin and 14 kg compost per tonne
- Avoids 43 kg CO_2-eq. emission/tonne
- Cost: € 171/tonne
- Product yield: € 189/tonne

4.2.4 Overview and discussion

A comparison of current and future SSO conversion methods is presented in Table 14.

Table 14 Comparison of efficiencies and costs of one current and six future SSO conversion methods.

	SSO: anaerobic digestion and post-composting	SSO: conversion into furanics	SSO: conversion into PHA	Vegetable/ fruit conversion into caproic acid	Yard waste conversion into fermentable sugars	Vegetable/ fruit, yard waste and grass biorefinery
Dry matter content % (w/w)	38	38	38	20	40	38
Organic matter (% of dry matter)	65	65	65	98	70	
Calorific value (GJ/tonne as is)	5.0 (HHV)					
Energy product yield (GJ/tonne as is)	3.0 (biogas) or 2.3 (electricity and heat)	lower than complete anaerobic digestion (green gas)				
Energy conversion efficiency (%)	46					
Other product yield (kg/tonne as is)	290 (compost) 0.3 (citrus oil)		31 (PHA) 84 (compost)	240 (caproic acid) 84 (compost)	200 (fermentable sugars) 53 (lignin)	40 (caproic acid) 53 (bioethanol) 50 (lignin) 14 (compost)
Kg CO_2-eq. avoided per tonne as is	150	Comparable to anaerobic digestion	40±30	-888		43
Kg CO_2-eq. avoided per tonne dry matter	394	Comparable to anaerobic digestion	105±80	-4440		113
Processing costs (€/tonne as is)	37	Near to those of PHA production	118	700±150	54	171
Product value (€/tonne as is)	19	Near to processing costs	110	840	57	189
Economic efficiency: (product value minus costs)/tonne dry matter	-47	Near to zero	-21	700±750	8	47
Cost (€) per tonne CO_2-eq. avoided	25		3000	-	-	4000

The key performance parameters are the GWP (global warming potential) expressed as kg CO_2-eq. avoided per tonne dry matter and economic efficiency ((product value minus costs)/tonne dry matter). Several proposed biorefinery concepts perform better on these key parameters than the current best practice (anaerobic digestion and post-composting). Please note that SSO currently has a negative value which is not included in the processing costs shown above. This negative value is required to make the current processing economically possible. A large positive effect on decreasing greenhouse gas emissions while improving the economy can be gained by the conversion of SSO and a co-substrate into levulinic acid and furfural. Several waste processing companies are involved in development of this technology. A full scale realization may take five years since the TLR level still is 4 and the market for levulinic has to be developed. PHA production does not give a real improvement, however, this may change by technology development in particular in recovery/extraction of PHA from the bacterial cells. There is a great chance that the production of caproic acid is much more profitable than anaerobic digestion, but details on the costs are lacking. A drawback is the poor performance in reduction of greenhouse gas emissions. This may improve by further process development and the use of renewable instead of fossil energy. The biorefinery that combines various waste streams and conversion technologies gives an economically attractive alternative to current practice. The effect on greenhouse gas emissions is low, due to the same problems connected to caproic acid production. For the last three routes further source separation of SSO is required.

4.3 Swill, supermarket waste and residues from food industry

Swill, supermarket waste and residues from food industry contain more water than SSO and are acidified to a larger extent (by production of organic acids from carbohydrates during storage). It is comparable to vegetable/fruit waste from households, but it is safer (cleaner, more control possible). Biorefining options are:

- Production of caproic acid (similar as vegetable/fruit waste) with compost as a co-product
- Production of larvae of the black soldier fly: a source of protein that can be used as feed. The residue can be used as compost.

4.3.1 Caproic acid production

Swill and related materials have similar dry matter contents as vegetable/fruit waste (0.2 kg dry matter per kg biomass as is), but lower organic matter content (80% of dry matter). This means a production of only 980 kg of caproic acid / tonne of swill wet weight and more compost: 99 kg / tonne swill wet weight. This will slightly change the performance indicators:

Summary swill conversion into caproic acid:

- Content: 0.20 tonne dry matter/tonne
- Yield: 196 kg caproic acid and 99 kg compost per tonne
- Avoids -728 kg CO_2-eq. emission/tonne (it has a higher GWP than the fossil alternative).
- Cost: € 575±125/tonne
- Product yield: € 686/tonne

4.3.2 Larvae from the black soldier fly

Swill is in principle suitable for insect breeding. It will then have to be mixed with other feed components to compensate for the changing composition. This is common in the cattle feed sector. In this way you can obtain a standard mixture. The feed composition also determines the composition of the insect. Catering waste is favorable, because there is more protein in it. This also applies to supermarket waste. However, it is not yet known what the essential amino acids are for these insects. WUR/RIKILT investigates the accumulation of heavy metals and prions in insects and looks at whether that is a danger. Not only the composition is important, the supply of the substrate must be constant. The black soldier fly is most commonly used in insect breeding. Alternatives are mealworm (Protifarm), grasshoppers and crickets. The advantage of the black soldier fly is the lower demands on the substrate. The market introduction will also be faster. The larvae eat fungi as well, but no woody products (which are left over). Size reduction of the swill is required, but it should not be slurry. The larvae like to dig in porous airy material for protection against light. It should not be too dry as well. The cultivation conditions must be controlled well. A temperature of 28 °C is optimal. At a lower temperature everything runs slower, but a low pH is accepted. Purifying protein from the larvae is an option. Larvae drying is sufficient. Protix (company) separates everything because they started the business with larvae oil production at the time, and for oil production fractionation is required. So this company separates oil, protein and chitin. This is interesting since pure protein is more valuable than whole larvae.

The black soldier fly is cultivated worldwide. The largest producer is Agriprotein in South Africa (purified products: meal and oil). Companies can be found in Belgium (Millibeter: whole larvae), USA, Germany (Hermetica) and Poland (Hipromine). These are all small businesses.
It is now permitted to use certified substrates for the cultivation of seven insect species (list of approved farm animals) for fish feed and pet food. It is expected that the list will be extended next year with chicken feed and in two years with pig feed. Swill is not yet on the list but there is a chance that it will soon be allowed. The IPIFF is lobbying for that in Brussels.
Oil from larvae contains a lot of lauric acid and is now sold to Koppens Diervoeding: for weaned piglets.

Black soldier fly larvae are not yet used for food (but mealworm and cricket are). There are psychological factors prohibiting that. The chitin (still in the larva) and oil can also be used in chemistry but that is not yet operational. The residue probably can be used as a soil improver: the chitin-rich substrate residue (= frass) promotes soil health. That is subject of a running investigation (NWO project).

The legal obstacle is the waste status of swill. The expectation is that it will get a certified feedstock status. Prion problems (BSE legislation) will be a matter of concern. For financers such as the RABO bank, these matters are also important when assessing the financing. Good news is that the RABO bank and the NOM have co-financed a Protix project in Bergen op Zoom of 45 million euros, which means there is trust.

4.4 Manure

In MRA most manure is spread over the land, only a few farms use anaerobic digestion and production of biogas. After anaerobic digestion, the P, K and N rich digestate is used as a fertilizer. The difference is the biogas production: a part of the organic compounds (mainly the easily degradable part) is not lost in the fields but utilized as a renewable energy source. The digestate still contains fibres that can improve soil properties.

The effect per tonne of manure: 20 m^3 biogas or 14 m^3 green gas (88% methane) (Factsheet Mestverwerking, 2016). The effect is the recovery of 0.37 GJ/tonne in case the green gas is used to produce electricity and heat (to make it comparable to other biorefining options in our study). The avoided CO_2 emission, roughly estimated solely on the basis of avoided use of natural gas, can be calculated from the biogas and heat produced and amounts to 24 kg CO_2/tonne manure. Manure digestion is not economically feasible. It relies on government subsidies.
One step further is to fractionate the digestate. The digestate contains solid particles (e.g. undigested fibres) and dissolved minerals. An example can be found in the plans of Twence for a manure refinery (Factsheet Mestverwerking, 2016). The digestate of the mono-manure digester is separated into a solid fraction and a liquid fraction using a press or centrifuge. The solid fraction contains a major part of phosphate and is dried. This can be used as fertilizer. The liquid is fractionated by reverse osmoses

and evaporation. It yields a potassium fertilizer, an ammonia solution (used in flue gas treatment) and clean water that can be discharged.

One more step is the use of the organic compounds from manure for the production of chemical building blocks. The Waste-to-Aromatics consortium (see above) is developing a process to convert the carbohydrate fraction of manure into furfural and levulinic acid. Other research groups try to convert manure organics into other building blocks. It is too early to assess the yields and costs of these future alternatives, but it will contribute to reduction of greenhouse gas emission.

5 Conclusion

From the study the conclusion can be made that the conversion of four important organic waste streams in AMR are all characterized by low economic efficiencies. They are primarily waste destruction methods and the costs are paid by the owners of the residues. The processes that produce biogas have better energy conversion efficiencies and avoid more fossil CO2-eq. emission than incineration and spreading over land. Key performance parameters were used to asses new biorefinery options, such as production of furfural, levulinic acid, caproic acid, fermentable sugars, lignin and PHA from SSO and swill: the GWP (global warming potential) expressed as kg CO_2-eq. avoided per tonne dry matter and economic efficiency ((product value minus costs)/tonne dry matter). It appeared that several proposed biorefinery concepts perform better on these key parameters than the current best practice (anaerobic digestion and post-composting).

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