The circularity dashboard: Amsterdam kitchen waste case

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Preface

This report is the result of study carried out in the KB project "Circularity by Design". The author thanks project manager Hilke Bos-Brouwers for giving the opportunity to write this report. The project team is thanked for the fruitful discussions. The author gratefully acknowledges Willie van den Broek (AMS Institute) for information on the nature of Amsterdam kitchen waste and arranging samples. Aranka Dijkstra (AMS Institute) is acknowledged for making contact with design team for the Green Tower and Bajes Quarter. Maryia Mishyna (Wageningen University) is thanked for giving information on insect chitin production.

Summary

Within the Flagship project “Circularity by Design” (CbD) a (re)design process based on circularity will be applied within the Amsterdam metropolitan area with the aim to create a sustainable agri-food system. Various tools will be developed and tested within Living Labs to achieve high-end re-use of food and residual (organic) flows. One of the proposed tools is the Circularity Dashboard presented in this report. The case study of the Amsterdam based “Green Tower” or the more extended Bajes Kwartier urban development programme is one of the challenges in the CbD project. Facing the challenge of creating a new, circular neighbourhood, the developers of the Bajes Kwartier project in Amsterdam are expecting an annual production of 137 tonnes of source separated organics (SSO, or “GFT” in Dutch). In this densely populated area the SSO will not contain much garden residues but will be mainly kitchen waste (vegetable, fruit and meal residues; in Dutch “GFE”). For the Green Tower, seven options to valorize this GFE were identified. These were assessed using the Circularity Dashboard, including a set of indicators of circularity, economy, technology, environment and policy. For decision makers it is important that all information eventually is summarized on one page, table or infographic. The results can been seen in Table 1.

Table 1 The Circularity Dashboard: indicators of circularity, prerequisites and stimulating factors for seven applications of kitchen waste; green is favorable, orange is medium and red is unfavorable.

	Compost	Biogas	Chemicals (caproic acid)	Bioplastics (PHA)	Pig feed	Insect feed	Chitin
Product value (€/tonne)	15	1540 methane	3500 caproic	3500 PHA	40	40	4500
Mass conversion factor (kg product/tonne SSO)	150	64 methane 150 compost	100 caproic 150 compost	22 PHA 150 compost	1000	1000	1 chitin 185 compost
Maintaining functionality							
Regional utilization							
Matching volumes							
Legal							
Public opinion							
Government policy							
Opinion of the challenge owner							
Cost/benefit							
TRL	9	9	8	7	9	9	9
GHG emission reduction (kg CO_2-eq/tonne SSO	Low	176	63	78	92	92	1.5

The Circularity Dashboard seems to be a useful tool to discuss and select various valorization options for organic residues: it summarizes all information in one table. The dashboard used in this study provides an example. The setup of the tool allows for flexible inclusion of additional indicators, or different weighing factors (deciding on the relative importance of the indicators). The assignment of the three colors is based on a qualitative interpretation of available data and insights and preferences from the users of the tool. These user typically include experts and decision makers from relevant business and government stakeholders involved in the subject under study. The information can be used to discuss and select the most favorable valorization routes but it also shows promising alternative options that can become of interest if small bottlenecks related to technical or regulatory issues are solved.

1 Introduction

1.1 The Circularity by Design (CbD) Project

There is a growing need for circularity in currently disconnected food chains and materials segments (e.g. from agriculture, food processing, consumption, waste, chemicals and materials) and at various aggregation levels. Circularity addresses environmental and sustainability concerns. This requires knowledge on the synergies and trade-offs between individual circular systems, to design interconnected circular systems that cross segments and aggregation levels, aiming to ensure optimal use and valorisation of renewable biomass resources.

Within the Flagship project "Circularity by Design" (CbD) a (re)design process based on circularity will be applied within the Amsterdam metropolitan area with the aim to create a sustainable agri-food system. Various tools will be developed and tested within Living Labs to achieve high-end re-use of food and residual (organic) flows. The project is a collaboration between AMS Institute and 12 different scientific disciplines of Wageningen University & Research, and is joined by various local Amsterdam-based partners. Within four Urban Challenges, instruments are developed and tested in Living Labs in collaboration with different local stakeholders and at different levels. This allows us to make decisions on issues such as repurposing and processing within different scenarios. The following challenges have been identified: (1) Urban food systems, (2) Organic household waste, (3) Urban food production and (4) Circular way of living.

The aim of the CbD program is to demonstrate the feasibility of "Circularity by design" within the context of the greater Amsterdam metropolitan area. During the project, circular (re)design principles will be applied to create designs for urban circular agri-food systems. The ultimate goals of the project are at:

1. Urban scale: (1) to enable optimal resource exchange among sectors to realise connected circularity among sectors, and (2) to create a tool for evaluating & monitoring circularity & its contribution to city goals (connecting circularity to sustainability).
2. Challenge/case scale: co-design circularity for specific challenge case (connecting science & technology to practice for circularity).

1.2 Goal of this report

This report is based on research within WP2 " Food & biobased Products" of the CbD Project. One of the underlying problems studied in WP2 is how to generate options for the utilization of organic residues and how to select and rank the best options. The aim of WP2 was product-to-feedstock reverse engineering conceptualisation, and matching of products and processes within innovative food systems, including insect production & consumption and the potential of vertical farming. This reports contributes to the specific objective to establish design principles for CbD, based on the CbD Framework, and to integrate these in the designs for the Challenges. Research questions were (1) which organic residue is important for the Bajes Kwartier and for the Amsterdam Metropolitan Area, (2) which valorisation options can be identified for this residue and (3) and how to select the best routes. Another task of WP2 was to explore the possibilities for urban insect farming. One of the research questions in that task was to find a local residue that could be used as insect feed.

In this report options for the valorisation of SSO are presented as well as the indicators used to assess the circularity, prerequisites and stimulating factors (section 1.3). The result is shown in the Circularity Dashboard (section 2.1). The dashboard is filled with data/values and these are explained in section 2.2. The ease of use and versatility of the dashboard is discussed in section 3.

1.3 The Green Tower as example for the CbD Circularity Dashboard

The Green Tower or the more extended Bajes Kwartier are one of the challenges in the project "Circularity by Design". The designers of the Bajes Kwartier in Amsterdam expect an annual production of 137 tonnes SSO (source separated organics; Dutch: GFT-afval) by 1209 households and 71 tonnes SSO from companies. In this densely populated area the SSO will not contain much garden residues (like in other parts of the Netherlands) but will be mainly kitchen waste (vegetable, fruit and meal residues; in Dutch GFE). In Amsterdam seven options to valorize this SSO were identified:

1. Conversion into compost
2. Conversion into biogas, the residue is converted into compost
3. Chemistry (production of caproic acid by the Amsterdam company ChainCraft)
4. Production of bioplastics (PHA: poly-hydroxy-alkanoate)
5. Feed for pigs
6. Feed for insects
7. Conversion into insect chitin

Choosing between various options for residue valorization is common practice in the biobased economy. Mostly economic considerations and technological feasibility prevail in the selection process. However, selection based on the degree of circularity is a new trend. Such degree of circularity is composed of several circularity indicators. An example is given in a recent report by Elbersen *et al.* (2022) in which different options of agro-residue valorisation were compared using indicators for circularity, socio-economic impact, environmental impact and implementability. The circularity indicators were (1) functionality used, (2) biomass utilization efficiency, (3) possibility of reuse and (4) land sparing. In the study two options per case were presented in spider web diagrams.

In our study we would like to have all aspects of seven options in one glance. For that we will use a matrix (seven options against 12 indicators), which looks like a dashboard: the Circularity Dashboard. The Amsterdam SSO case is the first using this dashboard, as a try-out.

The seven options were assessed on aspects that are indicators of circularity:

- Product value
- Mass conversion factor
- Maintaining functionality
- Regional utilization

Prerequisites:

- Matching volumes
- Legal
- Public opinion
- Government policy
- Opinion of the challenge owner

Other stimulation factors:

- Cost/benefit
- Technological Readiness Level (TRL)
- Extent of reduction of Greenhouse gas (GHG) when using this application

2 Results

2.1 The dashboard

The result can been seen in Table 2 and the information leading to the values presented in the dashboard can be found in section 2.2.

Table 2 The circularity dashboard: indicators of circularity, prerequisites and stimulating factors for seven applications of kitchen waste; green is favorable, orange is medium and red is unfavorable.

	Compost	Biogas	Chemicals (caproic acid)	Bioplastics (PHA)	Pig feed	Insect feed	Chitin
Product value (€/tonne)	15	1540 methane	3500 caproic	3500 PHA	40	40	4500
Mass conversion factor (kg product/tonne SSO)	150	64 methane 150 compost	100 caproic 150 compost	22 PHA 150 compost	1000	1000	1 chitin 185 compost
Maintaining functionality	[red]	[red]	[orange]	[orange]	[green]	[green]	[green]
Regional utilization	[green]	[green]	[orange]	[orange]	[green]	[green]	[green]
Matching volumes	[green]	[green]	[green]	[green]	[green]	[green]	[green]
Legal	[green]	[green]	[green]	[green]	[red]	[red]	[green]
Public opinion	[green]	[green]	[green]	[green]	[green]	[green]	[green]
Government policy	[orange]	[green]	[green]	[green]	[red]	[green]	[green]
Opinion of the challenge owner	[orange]	[green]	[green]	[green]	[red]	[green]	[green]
Cost/benefit	[orange]	[orange]	[green]	[orange]	[green]	[green]	[green]
TRL	9	9	8	7	9	9	9
GHG emission reduction (kg CO_2-eq/tonne SSO)	Low	176	63	78	92	92	1.5

2.2 The values of the indicators

2.2.1 Product values and conversion factors

Product value tells something about the reuse of value, and the mass conversion factor is important for the reuse of mass. We don’t want to lose much mass in each cycle. We can estimate product values and the conversion factor in each of the seven possible applications of SSO.

We have collected SSO from IJburg, a residential area in Amsterdam in which households collect kitchen waste in plastic bags and dispose the bags in containers in the street. We analysed the material: it contained per tonne 259 kg dry matter, of which 237 kg organic matter, of which 38 kg crude protein, 24 kg crude fat/oil and 22 kg crude fibre.

SSO can be composted or first digested to produce biogas and subsequently compost the solid residue. It is known from SSO composting that the compost yield is independent of a prior anaerobic digestion (www.rova.nl). The compost yield on SSO is 0.29 tonnes from 1 tonne of SSO (www.meerlanden.nl). The compost yield on the Amsterdam type of SSO is unknown, but because of lack of garden residues the digestibility will be higher, therefore, the compost residue will be lower. That is estimated 0.15 tonnes compost per tonne SSO. The value of compost is € 15/tonne (Reterra Tarievenlijst 2021).
It can be expected that SSO is highly digestible in anaerobic digestion. The author’s estimation is that 80% of the organic matter is converted into biogas. A tonne of SSO contains 237 kg organic matter (with a gross calorific value 18.7 MJ per kg (Groenestijn, 2018)) this represents an amount of energy of 4,432 MJ. If 85% of this energy ends up in methane (gross calorific value of 55.5 MJ/kg (www.hydrocarbonengineering.com)) then 64 kg methane can be produced.

The trend in biogas plants is to produce 'green gas', which is almost similar to natural gas and can be introduced in the gas grid. It contains about 90% (v/v) methane. The long term value (not the current high prices) of green gas is € 1/Nm^3 (personal communication with HoSt, a Dutch digester supplier). This translates to € 1.10/Nm^3 methane. One Nm^3 methane contains 714 g methane, therefore the value of methane is € 1,540/tonne.

SSO can be used by the Amsterdam based ChainCraft to first produce volatile fatty acids and subsequently caproic acid. These are biological processes, carried out by bacteria, in which short chain fatty acids such as acetic acid are elongated using ethanol into medium chain fatty acids such as caproic acid. Caproic acid can be used to produce antimicrobials, plant growth promoters and as precursor to various commodities including lubricants, fragrances and paint additives. The value is estimated € 3,500/tonne (Groenestijn, 2018). To produce caproic acid: one tonne SSO contains 237 organic matter and the author estimates that this organic matter can be converted into 120 kg volatile fatty acids and subsequently to 100 kg weight contribution to caproic acid. The other half, about 100 kg as well, is delivered by the second feedstock, ethanol, to produce the total 200 kg caproic acid. But the relevant part of the yield is 100 kg caproic acid per tonne of SSO.

The volatile fatty acids can also be converted into a bioplastic, e.g. polyhydroxyalkanoate (PHA). PHA is accumulated in granules inside bacteria that consume volatile fatty acids. PHA is biobased and biodegradable. The most important pilot plant project on PHA production in the Netherlands was the PHARIO project, which is now followed up by the demo project PHA2USE in Dordrecht. The PHARIO team estimated the value of PHA at € 3,500/tonne and the yield on volatile fatty acids found in the project was 0.18 tonnes of PHA per tonne of volatile fatty acids (Bengtsson *et al.*, 2017). One tonne of SSO can be converted into 120 kg volatile fatty acids and subsequently into 21.6 kg PHA. When producing caproic acid or PHA a solid residue will remain. These are compounds originating from SSO that can't be easily biodegraded, mostly fibres and insoluble minerals. These are stabilized by composting. The amount of compost created this way is comparable to the amount of compost that is produced in a compost-only process.

Kitchen waste cannot serve as animal feed due to the presence of meat in the kitchen waste that can contain germs and due to the lack of control over the composition of kitchen waste (https://www.wur.nl/nl/project/stimulans-voor-stadsvarkens.htm). But suppose it is allowed: what is the value of SSO? Vleesvarkensbrok has a value of € 278/tonne (May 2021; www.pigbusiness.nl) and it contains barley, wheat, rapeseed meal, maize, palm kernel expeller, molasses soy, beet pulp, vegetable fat, premix, vegetable oils, chalk/limestone, lysin, minerals and vitamins, phytase, monocal, DL-methionin and threonin. The amounts of important constituents are 15% crude protein, 4.7% crude fat and 5.3% crude fibres (www.junai.nl/vleesvarkensbrok).

According to Erik Schaap, from Schaap Holland, a potato processing company, the potato peel pulp is sold as pig feed for € 40/ton wet matter. The wet matter contains 14% dry matter and 4% protein.
SSO from Amsterdam contains 3.8% crude protein, 2.4% crude fat and 2.2% crude fibre on basis of wet mass, but also minerals, carbohydrates, vitamins. What does that mean for the value? It contains 4 times less crude protein than vleesvarkensbrok, moreover it does not contain added amino acids and phytase, and the handling and storage of SSO is more challenging than that of vleesvarkensbrok. SSO is closer to potato peel pulp. Therefore, the value of SSO as feed may not be more than € 40/tonne. The value of SSO for insect feed may be comparable: € 40/tonne.

The use of SSO for insects that serve as food or feed is not yet allowed due to safety issues, but a production of insect chitin for non-food/feed applications must be possible. According to Ravi *et al.* (2020) 125 grams of black soldier fly larvae can be produced from one tonne of vegetable/fruit waste (composition near to the SSO we have been collected). Frass (compost) is a coproduct and 185 kg can be produced from one tonne of SSO. According to Maryia Mishyna (WUR) 125 grams of black soldier fly larvae yields 40 kg dried larvae. From that amount 1 kg chitin can be produced. The residue (larvae protein, fat) is a co-product.
Chitin can be deacetylated to chitosan, a polymer that is soluble in water. Chitosan has a wider range of application than chitin. The value of chitin and chitosan depends on the application. Chitin as a food ingredient may have a value near € 30,000/tonne, but the purification is costly as well. In our study we focus on non-feed/food applications that has value in sustainability and circularity, e.g. in case it can replace fossil

based chemicals. An example is the use of chitosan as a flocculant for sludge from wastewater treatment plants. The chitosan can replace polyacrylamide derivates which are normally used in sludge flocculation. The price of flocculant polyacrylamides is about € 5,600 /tonne (information from Robert Kras; Waterschap Aa en Maas). Suppose a same value for chitosan in flocculant quality and 1.26 kg chitin is required to produce 1 kg of chitosan, then the chitin has a value of about € 4,500/tonne.

2.2.2 Functionality

Maintaining as much of the original functionality of an organic residue is paramount in circularity. Applying SSO as feed for pigs or insects is using the full functionality of the constituents. Proteins, starch, vitamins and fats are used as such, although a part of these functional compounds are degraded into organic acids during collection and storage of SSO by fermentation. In the conversion of SSO into chitin (a polymer of glucose) a large part of the functionality is maintained as well. That is also true for the other insect components (protein, fat). However, the insects are using the SSO as an energy source as well, which means oxidizing it into CO_2, H_2O and minerals. Therefore, a part of the SSO is losing its functionality.

For an application as feedstock for the production of medium chain fatty acids or PHA, the complex compounds in SSO should first be converted into simpler compounds: volatile fatty acids. By this conversion a large part of the original functionality is lost. The molecular weight, molecular variety and the degree of information is reduced. Even more functionality is lost when producing biogas: methane molecules are even smaller and simpler than volatile fatty acids. At least you can make new polymers from volatile fatty acids; this is not possible/easy when using methane: another step in the loss of functionality.

In the composting process most of the matter is oxidized into CO_2 and H_2O: an enormous loss of functionality. But the residue, the compost itself has a medium functionality: the plant fibers have a water absorption capacity and structure properties. Please note that such compost is produced as a by-product in biogas, PHA and medium chain fatty acid production as well.

2.2.3 Regionality

To limit the use of fuels and material for transport, a short distance between the place of origin of SSO and the conversion/production site is favorable and it is even better if the product can be sold in the region as well. Besides that, regional connections stimulate the social coherence of the local community and reduces the dependency of the supply chains on geopolitics.

However, the amount of SSO produced by the Bajes Kwartier is small and some utilization types need an economy of scale, which means transport of the SSO to a collection hub or to a decentral processing unit. The logistic strategy also depends on how SSO collection will develop in Amsterdam. Separate collection must increase, but there is a choice in collection in plastic bags or via a kitchen grinder.

In Amsterdam large composting plants and biogas plants are available and ChainCraft is based in Amsterdam as well. The compost and biogas can be totally used in the region as well. The utilization of medium chain fatty acids may not necessarily in Amsterdam, but all over the Netherlands. Having only one plant in the Netherlands makes the supply chain vulnerable. Composting and biogas production in principle can be carried out in the Bajes Kwartier on small scale as well, but the operation costs per tonne will be higher than that of large scale central processing and odour issues should be solved when working in the vicinity of residents.

With respect to bioplastic production (PHA) it is important to realize that at the moment there is no production capacity in the Netherlands, but if this type of utilization will be a success, it can be expected that each province will have a PHA production plant, to keep the transport effort of the bulky SSO matter low.

SSO utilization as pig feed probably can be realized within boundaries of the metropolitan region (if it was allowed). Insect cultivation can be done even in the Green Tower, but again, the economy of scale and the odour issues are a challenge in that situation.

2.2.4 Matching volumes

If an amount of SSO is available for conversion into a product with a much smaller annual volume, the owners of the SSO have to find additional outlets and communicate and adjust with other nearby owners of SSO. If the need for a product is orders of magnitude higher than the amount of SSO feedstock, the producers of that product should have a special reason to use SSO as a small part of a much larger feedstock intake. The creation of a value chain will be easier if the annual volumes of utilized SSO matches with the annual product volumes required.

It is expected that the Bajes Kwartier is going to produce more than 200 tonnes SSO annually. In future the Metropolitan Region Amsterdam may produce more. Suppose 80 kg SSO per inhabitant per year (personal communication with CirkelWaarde) and 2.5 million inhabitants in the MRA, the maximum is 200,000 tonnes per year. The reality will be much lower.

For the composting application a good match between amounts of feedstocks and product exist in the Netherlands with a volume of a few millions of tonnes of compost annually (Groenestijn *et al.*, 2019). Compost is produced from leaves, prunings, grass, SSO, certain types of sludge and food industry residues.

The match with biogas is good as well. Biogas currently is only a small part of all gas used or all energy used (few percent). The Netherlands can use much more biogas and much more organic feedstocks. The market is the renewable energy market. The energy companies have a good reason to utilize organic feedstocks: to produce renewable energy.

ChainCraft is still small. It is now producing 1,000 tonnes caproic or related acids per year and it is preparing to produce 10-20 times more. Then 100,000 to 200,000 tonnes feedstock would be required annually, but SSO will only be used for medium chain fatty acids for non-feed/food applications, which will be only a part of the total production capacity. It may absorb the amount of SSO produced in Amsterdam in future.

Plastics represent a very large market. In 2020, 367 million tons of plastics were produced (https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/), the majority from petroleum. In 2020, the bioplastics market was 9.17 billion US dollars, which will correspond to approximately 3 million tons of plastics, and is expected to grow at an average annual rate of 17.1% until 2028 (https://www.grandviewresearch .com/industry-analysis/bioplastics-industry). The PHA market was less than 1% of this. For 2020 it is estimated to be USD 62 million and is expected to grow on average by 14.2% per year until 2025 (i.e. USD 121 million in 2025, equivalent to approximately 30,000 tons of plastics) (https://www. marketsandmarkets.com/Market-Reports/pha-market-395.html).

In the EU project RES URBIS the researchers are more optimistic. The project team states that PHA has the potential to replace 1% of petrochemical plastics. That is about 3-4 Mton per year (Fantinel, 2020). The Markets and Markets study is likely to be cautious and extrapolate strongly from the present, while the RES URBIS study assumes expected changes that could greatly enlarge the market. The market share depends on uncertain factors (production costs, usable quality, regulations and customer behaviour). For the Netherlands it can be imagined that the production in 2025 may be 3,000 tons of PHA (14,000 tonnes SSO needed) annually and in long term 40,000 tonnes (180,000 tonnes SSO required). The PHA plant will also use other feedstocks, but the order of magnitude of SSO and PHA in the Netherlands are matching.

Pigs around Amsterdam can eat all SSO produced in Amsterdam (if it was allowed). When we realize that the amount of feed dry matter consumed in the Netherlands is an order of magnitude larger than the amount of food dry matter consumed by humans (Groenestijn *et al.*, 2019), the food residues produced can be used to mix with other feed types and feed our animals.

SSO as insect feed: it is not unrealistic to state that the development of the SSO collection will match the development of insect rearing. Both activities will strongly increase from now on.

The world chitin market was US$ 1.5 billion in 2021 (www.futuremarketinsights.com), which may represent 100,000 to 200,000 tonnes chitin/year. Since 1 kg chitin can be produced from one tonne of SSO and MRA can annually produce 200,000 tonnes SSO, MRA can deliver 1-2 ‰ of the world requirement. The reality will be much lower, therefore, it seems a good match.

2.2.5 Legal aspects

Just like SSO (GFT-afval) kitchen waste has a legal status as waste. Moreover, it contains meat and therefore it is classified by the European Animal By-Products Regulation (Regulation (EC) No. 1069/2009). This classification is based on the risk to public and animal health. SSO is category 1, the mildest category (while 2 and 3 material is more dangerous).

Production of compost and biogas from SSO already are allowed. The use of SSO for the production of medium chain fatty acids is only possible when these fatty acids are not used for food or feed (personal information from ChainCraft). It can be expected that this is also true for the production of bioplastic (PHA). The use of SSO for husbandry animal feed is not allowed due to the risk on diseases e.g. BSE and due to the lack of control for the presence of pollutants in SSO. This may change in future for certain safe sources of SSO in combination with a pretreatment for the inactivation of microbes, viruses and prions. The same is true for SSO as insect feed, but projects are running to identify the risks and generate ideas to reduce the risks. There is a chance that in future SSO may be allowed as insect feed if the insects are used for certain restricted applications.

The use of chitin from insects grown on SSO in wastewater treatment applications should not yield legal problems.

2.2.6 Public opinion government policy and opinion of the challenge owner

The public generally supports all ideas in which organic residues are used to make various products, without knowing the technical, legal and economic bottle necks. The Dutch ministries, provinces and municipalities have policies to create products with higher values. They all use the scale of Lansink or value pyramids. That is why composting is less popular. Moreover, the valorisation options should be legal. That is why the use of SSO as pig feed is blocked. That should also be true for the use of SSO as insect feed, but the government has funded projects in which the safety of this application is studied. According to the government this application may have a chance in the future.

2.2.7 Cost/benefit

Composting has been made a profitable process by the negative value (gate fee) of the residue. For Dutch SSO this is about € -25/tonne and for the Amsterdam type of SSO (kitchen waste) this may even be lower. In the Netherlands this gate fee has been calculated using the compost value and the compost production costs. In the case of composting as the route for utilization SSO will never get a positive value.

Producing biogas and compost creates a higher value, but the production costs for biogas are high as well. The gate fee still is required to make the production running. This can change in future when the green gas gets a higher value. Then the negative gate fee can slowly develop towards € 0/tonne SSO. The production of medium chain fatty acids has the potential to accept higher prices for the feedstocks. Current PHA production technologies rely on negative values for SSO. The production costs were estimated near to the value of PHA (both € 3,500/tonne PHA) (Bengtsson *et al.*, 2017). € 3,500 is still too high to compete with fossil based plastics. The problematic cost/benefit ratio is the reason why the introduction of this utilization route proceeds slowly.

SSO can have a positive value (at the gate of a farm) when applied as feed e.g. for insects. But handling and transport may reduce the benefit for the owner of SSO, but at least a negative fee can be avoided. Chitin production from black soldier fly larvae already is practiced on industrial scale (but not yet using SSO), therefore the cost/benefit ratio may be favorable (www.alpha-chitin.com).

2.2.8 Technology Readiness Levels (TRL)

When selecting a utilization option, the technology readiness level plays a role. Nine different levels can be defined:

- TRL 1 – Basic principles observed
- TRL 2 – Technology concept formulated
- TRL 3 – Experimental proof of concept
- TRL 4 – Technology validated in lab
- TRL 5 – Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – System prototype demonstration in operational environment
- TRL 8 – System complete and qualified
- TRL 9 – Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Composting has a TRL of 9, although the experience with kitchen waste is limited. Kitchen waste should be mixed with larger pieces of fibrous biomass.

Biogas production of kitchen waste, swill, SSO (GFT) has a TRL of 9. Production of medium chain fatty acids from residues of vegetables and fruit processing is now demonstrated at a smaller size, maybe too small to make profit. Moreover, the Amsterdam type of SSO as a feedstock may need process modifications. Therefore the TRL is 8.

Production of PHA has been running on pilot scale (but not yet with kitchen waste) and in May 2022 a larger demo plant was inaugurated. Therefore TRL is 7.

Kitchen waste was used as a feed for pigs long time ago before it was forbidden. So, technically the TRL is 9. Mealworm and black soldier fly are now reared on mixtures in which vegetables and fruit residues are common. That is TRL 9. However, the use of SSO is not allowed yet. That is a legal problem, not a problem of technology readiness. The recovery of chitin (and conversion to chitosan) from black soldier fly larvae is carried out on industrial scale (TRL 9) (www.alpha-chitin.com).

2.2.9 Greenhouse gas emission reduction

In this chapter we focus on the large effects only. It is not a detailed LCA study

SSO is biobased and at the end of life, when it is digested, degraded or incinerated, if that is done in a proper way, it produces short-chain CO_2, which is not counted as a greenhouse gas (GHG). Greenhouse gases can be emitted in the conversion/production process if fossil based energy is used or chemicals are used that have been produced in processes with GHG as by-product. However, in future, fossil based energy will be phased out, allowing production processes to use energy without a connected GHG emission.
GHG emission can be prevented by using SSO as a substitute for a fossil based raw material. This is a large effect. In addition, if it is a substitute for crops such as wheat, corn and soy, it also saves energy and fertilizers that have been used to produce these crops, and as a consequence GHG emission.

The use of SSO to produce compost is almost neutral with respect to GHG emission. Compost is not replacing any fossil based alternative, so there is no gain. The composting process needs some energy and only if this energy is produced from fossil based fuels, a slight GHG emission will occur.

The use SSO for the production of biogas (green gas) and compost has the benefit that the green gas can be used to replace natural gas. Per tonne of SSO 64 kg methane can be produced, saving 176 kg CO_2. That is a maximum since biogas plants can leak some methane, which has a 25 stronger GHG potential than CO_2 and in the worst cases can reduce half of the emission saving. We should do our best to prevent such leakage.

Emissions of greenhouse gases can be avoided to produce medium chain fatty acids, under which caproic acid, from SSO instead of palm oil. According to ChainCraft greenhouse gas emission is reduced by 70% compared to the oleochemical process (www.Chaincraft.nl).

The production of caproic acid from SSO is an alternative to production of caproic acid from palm kernel oil (in which it is present in small amounts). SSO and fresh fruits from oil palm are both renewable bioresources. It is proposed to focus on the differences in GHG emission in the extraction or conversion from fresh oil palm fruits or from SSO to caproic acid. Ramirez-Contreras *et al.* (2020) described all GHG emissions in different stages of the palm-to-oil chain: from cultivation to the crude palm oil. For our study the part in the oil mill is relevant. Greenhouse gases are emitted by the oil mill in form of methane from the effluent treatment plant and as a result of the use of diesel and electricity. According to the authors this amounts 900 kg CO_2-eq. per tonne of crude palm oil. Most oil is extracted from the fruit, but caproic acid is extracted from the oil from the kernel. We assume GHG emission of caproic acid is also near 900 kg CO_2-eq. per tonne. According to ChainCraft the emission is reduced by 70% compared to the oleochemical process: this is a reduction of 630 kg CO_2-eq. per tonne caproic acid, which is 63 kg CO_2-eq. per tonne SSO.

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 (average is 3.3), 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 of (2.2 + 2.3 – 3.3) or 3.6 kg CO_2-eq./kg PHA. One tonne of SSO can yield 21.6 kg PHA, therefore in this route SSO can save about 78 kg CO_2-eq per tonne SSO.

Does SSO as feed save any GHG emission compared to regular feed for animals? Not if the production of SSO is regarded as food production that consumes fertilizers and energy for farm and factory operations and transport as well. But if SSO is regarded as lost in a regular situation, then it can replace feed and save GHG emission (if it is legally allowed). One tonne SSO may replace 308 kg corn (same dry matter) and according to Jayasundara *et al.* (2014) cultivation and drying of corn in Canada lead to a GHG emission of 243-353 kg CO_2-eq. per tonne corn (with 84.5% dry matter). This is on average 92 kg CO_2-eq. for 308 kg corn. A similar effect will be gained when using SSO for insect rearing instead of a grain.

If chitosan can be used to replace fossil-based polyacrylamide, it saves the emission of fossil-based CO_2 when polyacrylamide is incinerated (e.g. in a sewage sludge incinerator). Polyacrylamide has a chemical formulae as $[C_3H_5ON]_n$. In an incinerator 3 moles CO_2 will be produced from one mole of polyacrylamide monomer. Knowing that 1.26 kg chitin is required to produce 1 kg chitosan and that 1 kg chitin can be produced from a tonne of SSO, assuming that 1 kg polyacrylamide can be replaced by 1 kg chitosan, and using all molecular weights involved, it can be calculated that 1.5 kg CO_2-eq. can be saved per tonne of SSO. Furthermore, differences may exist with regard to the CO_2 emission in the production processes for polyacrylamide and chitin, but for now these are not incorporated in our study yet.

3 Discussion and conclusion

The Circularity Dashboard seems to be a useful tool to select and discuss various valorization options for organic residues: it summarizes all information in one table. The dashboard used in the study provides an example. The setup of the tool allows for flexible inclusion of additional indicators, or different weighing factors (to decide on the relative importance of indicators). The assignment of the three colors is based on a qualitative interpretation of available data and insights and preferences from the users of the tool. These user typically include experts and decision makers from relevant business and government stakeholders involved in the subject under study. The information can be used to select the most favorable valorization routes but it also shows promising alternative options that can become of interest if small bottlenecks related to technical or regulatory issues become solved.

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