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Environmental assessment of the valorisation and recycling of selected food production side flows

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ABSTRACT

Residues from the food manufacturing industry require management options with the best overall environmental outcome. The identification of sustainable solutions depends however, on many influencing factors such as energy input, transport distance, and substituted product. This study shows the influence of the choice of substituted products on the overall greenhouse gas (GHG) emissions for three specific food side-flows and their treatment in the European Union: animal blood, apple pomace and brewers' spent grain (BSG). In a direct comparison of possible treatment options, it is notable that the conversion to food ingredients (valorisation) does not always result in reduced environmental net impacts (GHG savings), which means that other options at lower levels of the waste hierarchy might be more beneficial to the environment. The further use of apple pomace or BSG for the production of food ingredients is only advantageous if the processing emissions are smaller than the emissions from the substituted products. The use of food side-flows as animal feed shows environmental advantages in all scenarios, as the use of conventional feed, such as soybean meal or hay, is reduced and so are the GHG emissions. The anaerobic digestion of food side-flows is associated with significant GHG emissions, but alternative energy also display a high GHG factor when based on fossil resources. The measuring of circularity in the food sector is a challenge in itself due to the complexity of renewable materials. This study shall help to understand the interwoven influences of certain parameters to the results.

1. Introduction

Food security will be of increasingly significant importance in the upcoming years. By 2030 worldwide food demand will be at least 20% higher than in 2015 (Klytchnikova et al., 2015). At the same time, a progressively negative impact of climate change on global crop yields is expected from the 2030s onwards (Challinor et al., 2014). It is therefore imperative to treat food as a precious resource, and to limit impacts on the environment globally to preserve land and ecosystems for future generations. However, it is estimated that up to 129.2 million tonnes of food waste is generated in the European Union (Caldeira et al., 2019) while one third of food produced for human consumption is lost or wasted globally (FAO, 2011 updates available in FAO, 2019). The production of food demands a lot of resources and energy and results in greenhouse gas (GHG) emissions, especially in the form of methane and nitrous oxide emissions from livestock farming and the use of fertilizers. Scherhaufer et al. (2018) estimated the environmental impacts from food waste throughout the food supply chain including food waste management. They concluded that 186 million tonnes of CO_2-equivalents (CO_2e) can be related to food wastage in the European Union, that accounts for 4% of the overall European Global Warming Impact. Emissions at food production are the determining factors for the overall environmental impacts of food (Bernstad Saraiva Schott and Cánovas, 2015). Improved tailoring of food systems is thus essential for food waste prevention, efficient use of food as a resource, and consequent global warming mitigation.

The reduction of food waste is addressed in the EU action plan for the Circular Economy (European Commission, 2015) which adopted the target of the Sustainable Development Goal (SDG) 12.3 of halving per capita food waste at the retail and consumer level by 2030 and reducing

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food waste further up the supply chain. Prevention has the highest priority in the waste hierarchy of the Waste Framework Directive (European Commission, 2008) and also in the food waste hierarchy (Garcia-Garcia et al., 2017; Papargyropoulou et al., 2014; WRAP 2018). However, not all side flows of the food supply chain (FSC) can be prevented. Besides the main product, food processing gives rise to various by-products and residues which are not fully valorised for various reasons. Food waste can be categorized into edible and inedible components of food as well as into avoidable and unavoidable food waste (Lebersorger and Schneider, 2011). A distinction between these types is crucial in the process of identifying the most appropriate options for addressing the food waste challenge (Papargyropoulou et al., 2014), and is also recommended for practitioners of Life Cycle Assessment (LCA) as it is essential for decision-makers (Corrado et al., 2017).

So far, the environmental impacts of food waste have been addressed focusing on the food supply chain (FAO, 2013; Monier et al., 2010; Scherhaufer et al., 2018) and also on food waste management (Bernstad Saraiva Schott et al., 2016; Eriksson and Spångberg, 2017; Padeyanda et al., 2016; Vandermeersch et al., 2014; Zhao and Deng, 2014) or food waste reduction (Hanssen et al., 2012). Life cycle costing (LCC) in connection with food waste has only been addressed in a limited amount of research (De Menna et al., 2018) or for specific scenarios within the value chain (e.g. logistic distribution from retailers in Bottani et al., 2019). Nonetheless, joint assessment of environmental and economic impacts through the integration of LCC with LCA would allow identifying burden shifting and possible trade-offs, as proposed by recent methodological advancement (De Menna et al., 2020). The use of unavoidable food waste (e.g. from peach processing in De Menna et al., 2015) and its conversion to other ingredients within the food industry, into food products (e.g. into chutneys in Eriksson and Spångberg, 2017), or into animal feed (Salemdeeb et al., 2017; van Zanten et al., 2013) is only addressed in a limited number of LCA papers. The reason for this restriction is often a matter of scope and boundaries (definition of food waste and classification) and a different focal point (crop cultivation, packaging solutions). However, the need for further investigation regarding the relevance of conversion and valorisation compared to other waste management strategies is recognized. Large quantities of waste are produced by the food industry, leading to a great loss of valuable materials (Mirabella et al., 2014), if not used appropriately. Food waste is recognized as having a great potential for conversion into high-value energy, fuel, and natural nutrients (Ingrao et al., 2018). The trend is to move up the waste-hierarchy from disposal (e.g. spreading onto land) to recycling (e.g. composting or anaerobic digestion) even up to using the resources in a bioeconomy (e.g. orange peels for bioplastic). By valorisation former food waste can be redirected to either food product, feed products or be converted to or extracted to food or feed ingredients. Valorisation has high potential in terms of value generation. In the sense of a circular economy, this trend should be supported. The market volumes for the high-value food ingredients are growing but are still limiting the potential, which make it necessary that other sustainable treatment options are used additionally. This paper shows the environmental performance of treatment options for food waste from the food industry by comparing different options in different settings (e.g. country, transporting distance). On top of the environmental relevance of processing unavoidable food waste, this study also demonstrates the complexity of using superseded products in the LCA of food waste management by system expansion and pinpoints crucial factors in the assessment.

2. Methods

2.1. Goal and scope

2.1.1. Selected food side-flows

Food production creates organic residues and waste, which are only avoidable to a limited extent. In this study these organic material flows from food production are called food side-flows and are defined as a material flow of food and inedible parts of food from the food supply chain (FSC) of the driving product (e.g. apple pomace from apple juice production). The stakeholder in the FSC producing a side flow which is currently handled as waste tries to have as little as possible of it (Davis et al., 2017), or monetise it by turning it into a marketable product. The goal of this study was to quantify GHG emissions for valorisation and recycling of specific food side-flows which can be allocated to the unavoidable but edible part of food waste and which each have a relevant market in the European Union (EU). The corresponding functional unit is one tonne of food side-flow being valorised/recycled/disposed to a given secondary good.

Firstly, apple pomace is chosen as a major food side-flow, as it is the most important waste product in the apple manufacturing industry having great potential for use in the biotechnology industry, and being available in large quantities (Mirabella et al., 2014); 0.7 million tonnes of apple pomace are generated each year in the EU. Another relevant area is meat consumption, which is increasing globally whereas the demand for less valuable products such as blood, entrails or some muscles is decreasing (Mirabella et al., 2014). In the EU 2 million tonnes of animal blood is generated each year. Finally, residues from the brewery industry constitute another major flow in Europe with an estimated 4 million tonnes of brewers' spent grain (BSG) generated in Europe's breweries annually (Metcalfe et al., 2018). Consequently, this study addresses the following residues of the food industry: apple pomace, animal blood, and BSG

2.1.2. Treatment and disposal options for food side-flows

Options for the treatment or disposal of these food side-flows are based on the waste hierarchy (European Commission, 2008) but with extended focus on valorisation options such as redirecting food as food ingredient or the conversion to animal feed. In the view of a food use hierarchy as introduced in Wunder et al. (2018) the focus is on the safe use of resources rather than on the best way to manage waste.

Suitable options for the treatment and disposal of food side-flows were selected based on their market applicability (Technology Readiness Level 9), data availability, and the relevant combination of options illustrating the influence of origin (type of raw material), degree of processing (e.g. AD vs. pectin production) and degree of utilization (full utilization or only parts are utilized). Options shall be applicable in the member states of the EU, therefore EU average data and technology which represents the current practices in the EU were used in the assessment. Inventory data for all considered processes are documented and provided in the supplementary information.

The conversion of food side-flows into a food ingredient (valorisation) is represented in the assessment by the following examples: production of blood products out of slaughterhouse derived blood (Table S1), pectin production out of apple pomace (Table S2), and the production of wheat flour-like ingredients out of BSG (Table S3). Blood proteins for use in food applications was modelled by centrifugation, membrane concentration and ball drying. The assessment of pectic production includes first a drying step followed by several processing steps at the pectin plant e.g. mixing with hot water and processing acids (mineral acid), concentration by removing water and precipitation and further purification by mixing with aqueous alcohol. Mainly commercial scale process data was applied in those options. The situation was different for BSG flour, which is still a niche market for use in traditional bread recipes and food snacks (e.g. in Germany). In this case, a theoretical model was considered based on investigations in Metcalfe et al. (2018) including dewatering, drying and milling.

After valorisation for human consumption, valorisation for animal consumption is the next best option within the food use hierarchy. During this study, conversion into animal feed was considered for apple pomace and BSG (Table S5). Recycling into fertiliser meal was considered for animal blood (Table S4).

As recycling and recovery options, anaerobic digestion (AD) using

Table 1

Management options for selected food side-flows and assumed scenarios for substituted products.

	Animal blood	Apple pomace	Brewers' spent grain
Food ingredient	Blood products	Pectin and fibre	Cereal ingredient
Alternative -min	*Pork meat + ammonium nitrate*	*Gelatine and hay*	*Wheat flour, SE*
Alternative -med	*Beef + ammonium nitrate*	*Pectin and hay, EU avg.*	-
Alternative -max		*Modified starch from corn and hay*	-
Animal feed/Fertilizer*	Blood meal*	Animal feed	Animal feed
Alternative -min	*Ammonium nitrate*	*Hay, extensive*	*Rape seed meal, Sweden*
Alternative -max	*Poultry manure*	*Hay, intensive*	*Soy bean meal, Brazil*
Anaerobic digestion with CHP	●	●	●
EU electr. + heat	●	●	●
EU electr. + heat + fertilizer	●	●	●
NO Electr. + heat	●	●	●
EE Electr. + heat	●	●	●
Incineration with heat recovery (incl. drying)	-	-	●
Alternative - min	-	-	Wood chips
Alternative - med	-	-	Natural gas
Disposal	Waste water treatment	Land spread	Incineration

(- stands for: option is not considered, ● stands for: option is considered for this specific side-flow)

combined heat and power plant was considered for selected food side-flows with a high moisture content, and incineration with heat recovery for food side-flows with a high dry matter content. The model covers biogas to produce energy in a CHP (combined heat and power) unit, as this reflects the current situation in Europe. The methane content, which depends on the substrate used in the fermenter, is calculated based on a theoretical biogas yield (Table S6). Digestate after fermentation was considered to be stored in open tanks. Open storage is a significant source of ammonia and methane emissions. Closed digestate storage could effectively reduce emissions, but is still rare in Europe. In the case of BSG, two recovery options were considered, as AD is a common option for recycling, but dewatering and incineration is an additional commercially practiced possibility (Table S9). Disposal on land, in this case spreading on agricultural land, is a common disposal option for many food side-flows within the processing industry. Direct N_2O emissions caused by microbial nitrification and denitrification of nitrogen through the side flow as well as indirect N_2O emissions associated with volatilisation, leaching and runoff from soils are calculated based on the nitrogen content of the side flow and IPCC (2006) (see Table S7). As another disposal option, incineration without energy recovery was considered for BSG. In this case, it was assumed that BSG was used in a municipal waste incineration plant generating emissions by using auxiliary fuel to burn fresh matter BSG (see Table S10). For animal blood, a disposal option via the waste water stream of slaughterhouses and an external waste water treatment plant (WWTP) was assumed (see Table S8) as side flows of slaughterhouses, such as fat, faeces, and also blood may enter waste water. Slaughterhouses can be divided into those which treat their waste water on-site and discharge directly to the local water course, and those which discharge their waste water to the local WWTP. For waste water discharge to a local WWTP, slaughterhouses must comply with specified conditions in trade effluent discharge consents in line with legislative requirements (European Commission, 2005). Here it was assumed that the latter is a possible disposal route for small slaughterhouses or butchers.

Food waste prevention at source and redistribution (e.g. food donations) are options of first priority in the waste hierarchy, but are targeted for avoidable food waste. The focus in this study is on side-flows of the food supply chain which are generated during the food production process but which are not or are only partially avoidable. That is why food waste prevention at source is out of the scope of this investigation.

2.1.3. Transport

The influence of the transport vehicle and transport distance is only possible to predict to a limited extent in practice. Blood that is further processed into ingredients for human consumption or for animal feed needs to be cooled. Transport systems equipped with cooling devices are therefore necessary and considered in the assessment with a distance of 200 km. For other materials, cooling is not essential. For dried apple pomace a transportation distance to the pectin plant of 200 km was assumed. However, a short transportation period is required to avoid mould growth especially when used for animal feeding. Thus, for animal feeding a transport distance of only 20 km was assumed. For moist BSG the maximum distance coverable is reported as 80 km. In the assessment 30 km was assumed in the valorisation option. The transport distance to anaerobic digestion plants was considered with 20 km. Variations in the distance and the influence on the overall results are discussed in the results section.

2.1.4. Substituted products

Valorisation, recycling and recovery options typically produce a valuable product; a secondary good (e.g. pectin, animal feed, electricity, heat), which can be further used as a food ingredient or as an energy source. This secondary good can replace/substitute another product on the market, this is called substituted product. The actual superseded product is based on plausible scenarios. The data collected refer to the average GHG emissions generated in the EU, or in a specific country within Europe for the comparison products, considering current knowledge, infrastructure, and market conditions in the year 2017. The substituted products represent a combination of market alternative products providing the same specific function (functional equivalence) as well as high and low impact alternatives (Alternative max, Alternative min). In the case of anaerobic digestion, alternative scenarios were built for different combinations of output products (electricity, heat, digestate) as well as country electricity mixes (e.g. Norway as the greenest electricity mix in Europe and Estonia as the least green electricity mix in Europe). The functional equivalence is determined case by case either on the protein or energy content, or in the case of equal nutrient equivalent on mass basis. The selection is however limited to the commercial production of a comparison product, and to a sufficiently good standard of data quality. The identified substituted products for each food side-flow is shown in Table 1. The GHG data, data sources and equivalent amounts are described in the supplementary materials (Table S11 – S22). For the land spread option, no comparison products were considered. There may be some benefits as a soil conditioner and recovery of some trace nutrients, but these are not the principle reason for this option.

2.2. Methodological framework for the assessment

2.2.1. Attributional modelling with substitution approach

A footprint approach (attributional approach) was used to

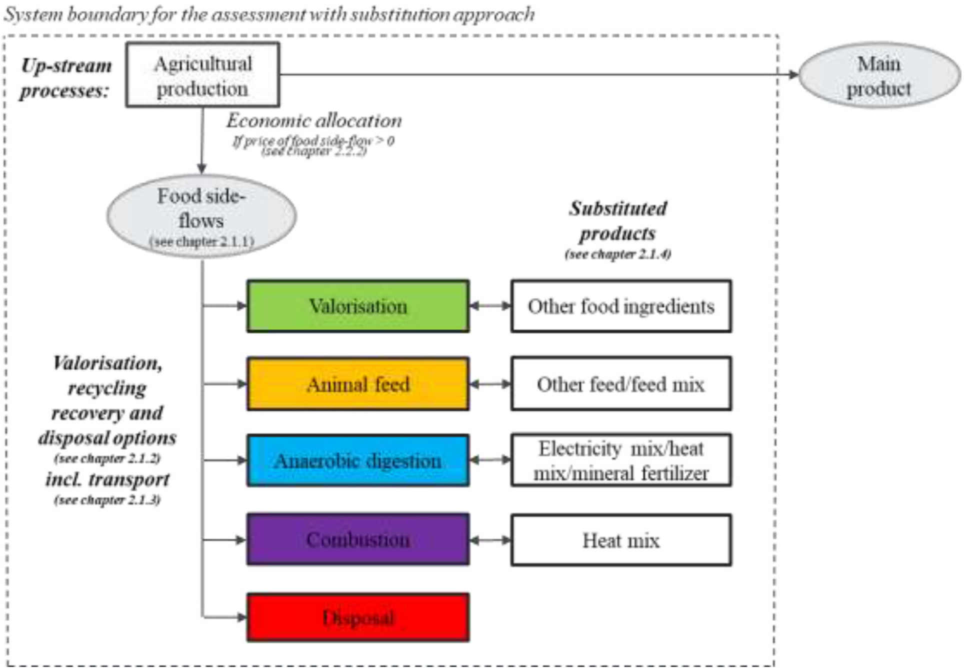

Fig. 1. Process flow diagram.

summarize all GHG emissions associated with the processing emissions to treat and manage food side-flows as well as its transport. Data was collected within the EU project REFRESH and is documented in Östergren et al. (2018) and Metcalfe et al. (2018) as well as for selected side-flows in the supplementary material. A helping tool, FORKLIFT was created within the mentioned project, which covers the Life Cycle Assessment (LCA) and environmental Life Cycle Costing (LCC) of the management of food side-flows and the different superseded products as well as for different parameters (e.g. fuel, transport vehicle, transport distance, market value, energy input) (Davis et al., 2019). This tool was used in this study to calculate GHG results for different scenarios. Although the tool follows a generic approach to assess both the environmental and cost dimensions of a system (as recommended in Davis et al. (2017)), this study focuses only on the GHG emissions, due to limited availability of open access cost data for investment and labour.

The system boundary of the assessment is shown in Fig. 1. The high recyclability or valorisation option is assessed analogously to the 'recyclability substitution approach' in (European Commission, 2010), where the recycled content is rewarded when it would be otherwise unused/landfilled. To solve multi-functionality at this end-of-life stage, system expansion with substitution was chosen. Thus, the emissions of production of substituted products are subtracted from the total emissions based on equivalent units (e.g. protein equivalents in case of valorising animal blood, mass equivalent in case of valorising apple pomace and BSG, energy equivalents in case of anaerobic digestion or combustion).

2.2.2. *Consideration of the market value of food side-flows above zero*

The starting position of this assessment is that holders have a side flow of their production line, which they intend or are required to dispose of. According to the definition of ISO 14044, such side flows can be considered a waste, thus no allocation of up-stream processes is required. However, if the waste is further used or treated, which is the case in the valorisation options, the situation changes. The market value of the waste may increase and is consequently above zero. From an LCA perspective, it then becomes a co-product and the multi-functionality needs to be solved (European Commission, 2010).

The extraction of food ingredients out of food side-flows may gain importance in the future following the trend of circular economy and resource efficiency. Furthermore, side-flows such as the dewatered BSG, which can be used in boilers to produce heat and replace fossil fuel generated heat, may become more important with regards to the planned energy transition, decarbonisation and bio-economy. Conflicting interests of the food, feed, and fuel industries may be reflected in price (price at selling point). For example, fiscal incentives for food side-flows used in anaerobic digestion may influence the price, and may stipulate this treatment instead of redirecting it to feed animals. For this reason, it is even more important to integrate a possible shift of market value in the environmental assessment. The situation changes if the market value of the side-flow is considered with economic allocation of up-stream emissions.

Economic allocation was identified as the most feasible method to distribute the environmental burden between one or more co-products. The relative value of a side-flow with respect to the product portfolio of the given product being processed (e.g. apples) at the point of sale is used for economic allocation of up-stream emissions. The impact of the main product at the farm gate was used as a proxy for the total GHG up-stream emissions. The allocation factor (AF) was calculated based on (FAO, 2016, 2018; International Dairy Federation, 2015) using the following formula:

$$\mathrm{AF}_{\mathrm{SF1}} = \frac{\mathrm{P}_{\mathrm{SF1}}{*}m_{\mathrm{SF1}}}{(\mathrm{P}_{\mathrm{SF1}}{*}m_{\mathrm{SF1}} + \mathrm{P}_{\mathrm{SF2}}{*}m_{\mathrm{SF2}} + \ldots\mathrm{P}_{\mathrm{DP}}{*}m_{\mathrm{DP}})}$$

With $\mathrm{AF}_{\mathrm{SF1}}$ = allocation factor (for economic allocation) for side-flow 1, $\mathrm{P}_{\mathrm{SF1}}$ = price of the side-flow 1, $\mathrm{m}_{\mathrm{SF1}}$ = mass of the side-flow 1, P_{DP} = price of the driving product and m_{DP} = mass of the driving product. A driving product can have several side-flows (co-products or driving products), and these can be incorporated as well (side flow 2 …).

In this study, results are primarily shown for a baseline with an AF of zero to enable a more streamlined comparison. However, the influence of price ratios on the overall results (growth of impacts) is discussed with a hypothetical value of 20% (meaning that the price of the side-flow is 20% of the price of the main product) in the results section. The environmental thresholds represent the point at which the emissions of the management options are on the same level as the emissions of the comparison products. Next to the price, the physical causality is

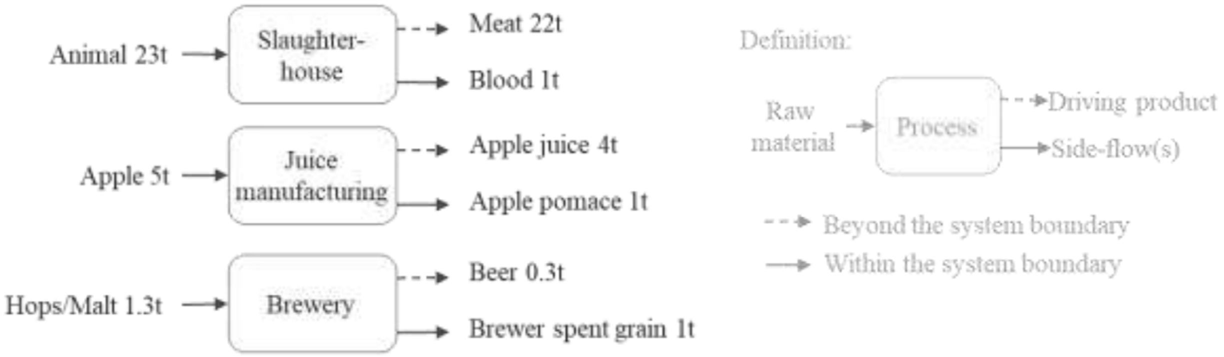

Fig. 2. Mass balance per tonne of selected food side-flows.

required to generate the AF. For this, it is necessary to understand the mass balance and consequently the mass ratio between the driving product and the side-flow shown in Fig. 2. Aligning the mass ratio to the functional unit of one tonne food side-flow, it results in mass ratios of 1:22 (in case of animal blood vs meat), 1: 4 (apple pomace vs apple juice) and 1: 0.3 (BSG vs. beer).

2.2.3. Impact assessment

Global warming potential (GWP 100) is assessed as a proxy of environmental impacts from the management of food side-flows of manufacturing processes. The IPCC 2014 characterisation factors from the fifth assessment report are applied (e.g. CH_4: 28 times CO_2, N_2O: 265 times CO_2 global warming potentials over a 100-year period). Emission data (Carbon dioxide equivalents CO_2e) for energy and resources were primarily sourced from scientific literature, which are cited in the supplementary materials. Current electricity mixes were sourced from GaBi database. Transport was sourced with permission from the Network of Transport Emissions (NTME). Additionally, emission data of some specific comparison products such as hay or modified starch were sourced from Ecoinvent 3.6. Biogenic carbon fluxes are omitted from the assessment, because carbon neutrality is assumed on the basis that the CO_2 release is equal to the CO_2 sequestration from biomass growth, regardless of the difference in timing of uptake and release.

Results are shown for the GHG emissions during processing of the food side-flow including their transport, as well as for the production of the substituted products (credits). The net emissions result from subtracting the emissions from the substituted products by the emissions from the food side-flow processing and transport. Negative net emissions imply GHG savings and positive net emissions GHG burdens.

3. Results

3.1. Animal blood

Blood can be processed into plasma and haemoglobin. Plasma can be used as a feed or food additive. The latter is considered in the assessment. GHG emissions associated with the production of comparison products for food additives, such as pork or beef are higher than the emissions generated during plasma processing. No alternative valorisation option for haemoglobin was included in the assessment. It may be used for example as colourant in pet feed, but a suitable comparison product could not be identified. By far the highest GHG savings are made through the use of animal blood as food ingredients (Fig. 3), as it can substitute meat, whose production is emission intensive.

Blood meal can be used as nitrogen fertiliser. Blood meal fertiliser is associated with slightly more GHG emissions compared to mineral fertiliser (plus 45 kg CO_2e) and slightly less to poultry manure (minus 62 kg CO_2e).

The GHG emissions associated with AD and digestate application, and the emissions associated with average European energy and fertiliser are almost the same. When changing the country grid mix to a country with high grid mix emissions like Estonia, AD saves about 40 kg of CO_2e per tonne of blood. When changing the grid mix to a country with low grid mix emissions like Norway, the emissions from AD are substantially higher.

Blood leaving the abattoir through the effluent is treated in a wastewater treatment plant. In the biological treatment step of the wastewater, some gaseous nitrous oxide (N_2O) can be formed which is a relevant GHG. No further functions are produced in this scenario.

Even though the emissions from transportation are influenced by using trucks with cooling equipment, the overall transport emissions have a lower relevance on the total emissions compared to the processing emissions in the valorisation and fertilizing options. Consequently, a change in the distance doesn't influence the results of the net impacts. The situation is different in case of anaerobic digestion. The default transport distance is defined as 20 km. An increase of the transport distance from 20 km to 200 km results in an increase of emissions from 58 to 82 kg CO_2e/t animal blood, which largely influences the net emissions. In this case, transport distance becomes a key factor for the net emissions.

A massive increase in impacts is recognized, when animal blood becomes a market value due to enhanced high-value valorisation. If a hypothetical price of 20% of the main product (meat) is accounted, the impacts of valorisation increase with a factor of 8. Although the AF of blood is very low (only 0.01 with a relative price of 20%) the effect on the overall GHG emissions is enormous. This is due to the high GHG emission of the main product, in this case meat (livestock farming produces approx. 5770 kg CO_2e/t carcass weight (Cederberg et al., 2009). However, the point at which the emissions of the management options are on the same level as the emissions of the comparison products is only reached, when a hypothetical price of 77% is assumed.

3.2. Apple pomace

The production of pectin from apple pomace (Fig. 4) results in higher GHG emissions compared to the average emissions generated in the EU during pectin production, and also compared to the emissions generated during modification of corn to starch or gelatine. This is due to the quantity and type of heat used for drying the apple pomace, and in the pectin production process. If the fuel type is changed, for example from light fuel oil to wood chips from forests, the GHG emissions decrease from 106 kg CO_2e/t apple pomace to only 17 kg CO_2-eq./t apple pomace. The production of pectin then becomes considerably lower in emissions than the comparison products. However, the electricity mix does not have a significant impact on the GHG emissions. Indeed, compared to the thermal energy use of the process, the electricity use is very low. The key parameters are therefore the fuel used for drying apple pomace and the heat used in the processing step.

If wet apple pomace is used as animal feed, only the emissions produced during transportation are directly linked to this process,

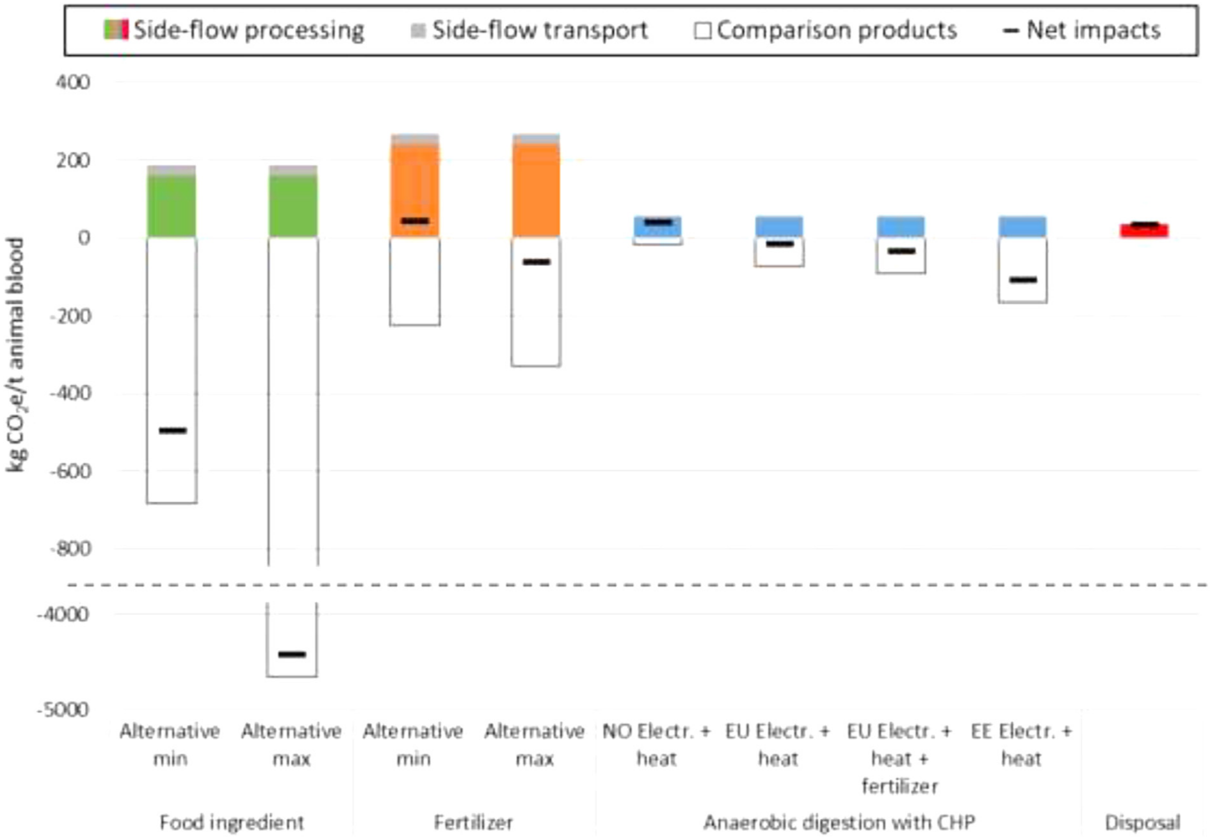

Fig. 3. GHG emissions of several options for the valorisation, recycling and disposal of animal blood including credits for comparison products (no market value of the food side-flow considered, AF = 0).

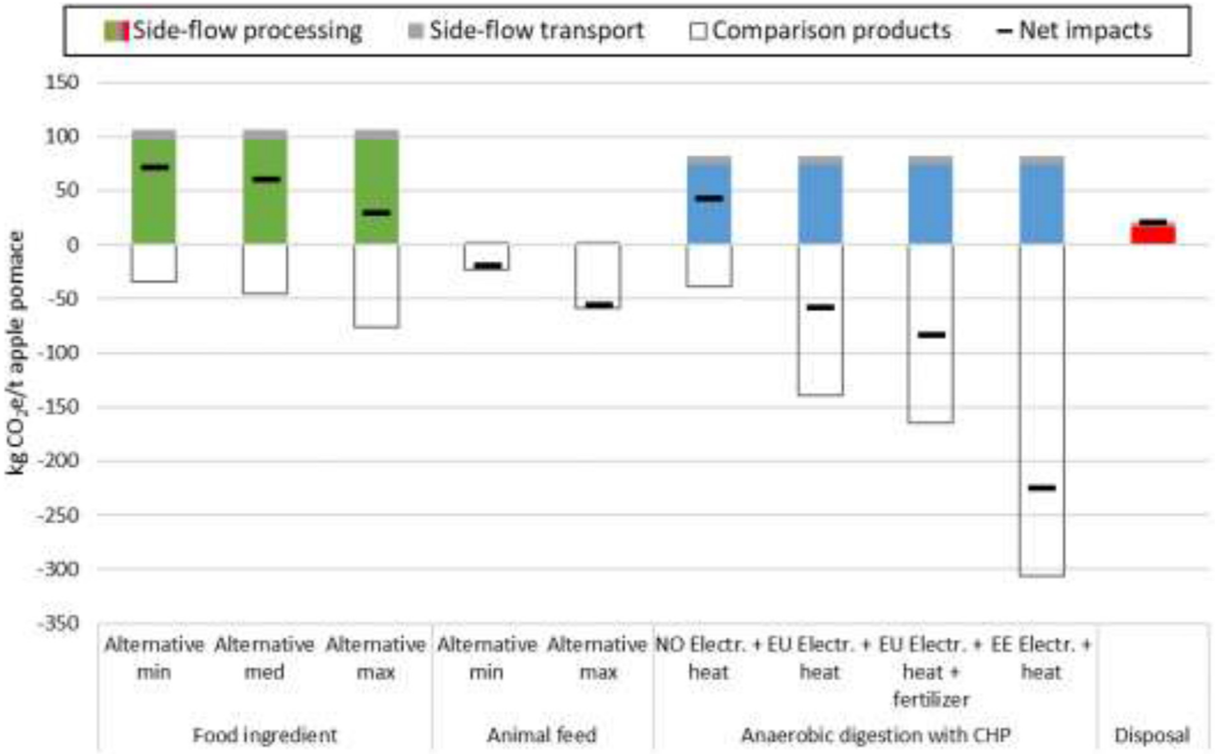

Fig. 4. GHG emissions of several options for the valorisation, recycling and disposal of apple pomace including credits for comparison products (no market value of the food side-flow considered, AF = 0).

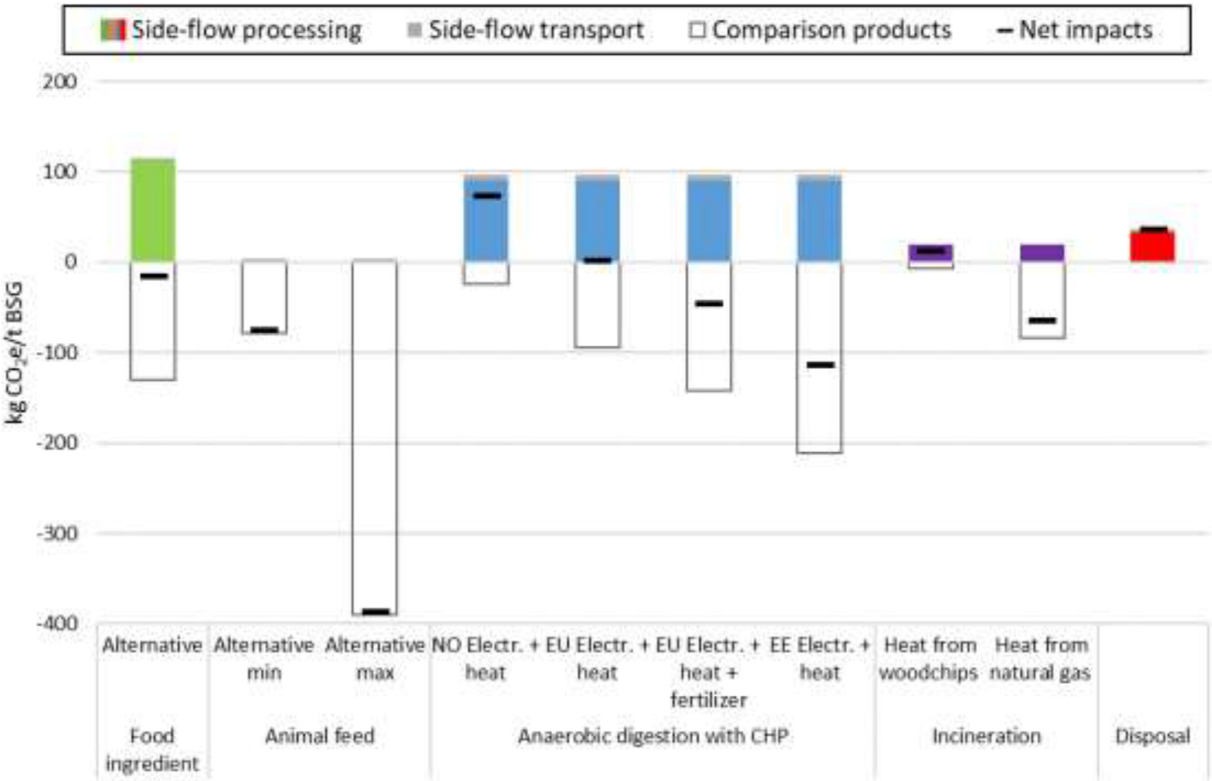

Fig. 5. GHG emissions of several options for the valorisation, recycling and disposal of BSG including credits for comparison products (no market value of the food side-flow considered, AF = 0).

resulting in 4 kg CO_2e/t apple pomace when a transport distance of only 20 km in a single trailer tractor is assumed (Fig. 4). However, if apple pomace is dried then a longer transport distance may be appropriate. In this case GHG emissions increase substantially. If the drying of apple pomace is assumed to require 2.8 kWh/t electricity and 281 kWh/t heat from light fuel oil, and if a 100 km transport distance in a rigid truck (Euro 4) is added, then GHG emissions increase to 107 kg CO_2e/t and surpass the comparison products (hay).

GHG savings can be observed in most scenarios of the AD process using apple pomace (Fig. 4). Although, if the Norwegian electricity mix is considered as substituted energy, then the emissions from AD using apple pomace are higher. A conclusion can be drawn, that if AD is used in a country where the national electricity mix already contains a high share of renewable energy then the environmental benefits of putting apple pomace through AD are not as high as they would be in a country with a higher share of fossil energy. The situation changes slightly if the digestate of the AD can be used as agricultural fertilizer, and additional savings of more than 20 kg CO_2e/t apple pomace can be made.

Finally, land spread is considered as an option to use up apple pomace (Fig. 4). In this scenario, transport to the land and distribution over the land create emissions due to fuel use, and due to application over the field which creates both direct and indirect N_2O emissions.

If the market value of apple pomace for valorisation is above zero, the up-stream emissions doesn't affect much the overall result. Considering a hypothetical price of 20% of the main product (apple juice), only a slight increase of emissions can be observed from 106.2 to 106.9 kg CO_2e/t apple pomace in case of valorisation. This is due to the low AF (only 0.05 with a relative price of 20%) and the low up-stream emissions (0.3 kg CO_2e/kg apples). The situation is different in case of animal feeding. There the emissions increase from 4 to 17.2 kg CO_2e/t apple pomace. In this case, an environmental threshold is achieved by a hypothetical price of 6.5% (Alternative min) and 17.1% (Alternative max). Considering a market value for apple pomace used in anaerobic digestion, the influence doesn't affect much the overall results. At a hypothetical price of 20% the emissions increase only from 81.9 to 82.6 kg CO_2e/t.

3.3. Brewers' spent grain

The production of a food ingredient creates slightly less emissions compared to wheat flour (produced in Sweden) (Fig. 5), considering that it contains a crude protein content similar to BSG. The crucial factor is the amount of thermal energy used in the process for producing a food ingredient from BSG. If the fuel generating this thermal energy is changed to wood chips from forest, instead of light fuel oil, the emissions heavily decrease from 115 kg to only 30 kg CO_2e/t BSG. If the electricity mix is changed from the EU mix to a Norwegian mix than the emissions further decrease to 11 kg CO_2e/t BSG. The emissions of transport only play a minor role, considering the fact that the transport of fresh BSG is limited to avoid mould growth. So, larger transport distances (> 200 km) which would affect the results (at a distance of 200 km, the emissions would increase from 115 kg to 134 kg CO_2e/t) are not feasible.

BSG for animal feed is compared to soybean meal from Brazil and rapeseed meal from Sweden. Animal feed made from BSG has a lower environmental impact than rapeseed meal from Sweden and a far lower one than soybean meal from Brazil (Fig. 5). If drying is necessary for processing into animal feed, the GHG emissions increase. If energy for drying is assumed to be the same as that for the drying of apple pomace, the GHG emissions increase from 4 kg CO_2e/t to 101 kg CO_2e/t, which is slightly higher than rapeseed meal but still much lower than soybean meal from Brazil.

Anaerobic digestion of BSG produces higher emissions compared to energy produced with a green electricity mix (NO electricity mix) and nearly the same emissions as the EU average energy mix (Fig. 5). If the mineral fertilizer equivalent for digestate is considered, then GHG savings are apparent. So, the use of digestate as a mineral fertilizer, which covers more than 40 kg CO_2-eq./ t BSG, has a high impact on the overall results. This is due to the high nitrogen content of BSG, which on the one hand increase N_2O emissions during the application of digestate, but on the other hand also means that a higher quantity of ammonium nitrate fertilizer can be substituted. However, if Estonia, whose electricity is mainly produced from fossil fuels, is set as a chosen country, the AD emissions are lower.

The dewatering and incineration of BSG produces heat which can be used as thermal energy. Compared to European average heat, the emissions generated by dewatering and incineration are far lower, but compared to renewable energy, such as heat produced from woodchips, emissions are higher (Fig. 5). If the electricity mix is changed from the EU average to the Norwegian mix, emissions are below even the emissions produced from woodchips.

If BSG is incinerated without dewatering or drying in a municipal waste incineration plant, then energy cannot be recovered. No comparison product can be set as an alternative and therefore this option produces solely emissions (Fig. 5). Incineration of BSG has been modelled using a parametrised waste incineration plant model. Input parameters were set to represent BSG only (a mix or other fractions were not assumed to be included). As the model used to determine the inventory for this scenario is usually used to incinerate waste, all activities associated with handling, gas cleaning etc. are relatively high (emissions are caused by 40% auxiliary materials and chemicals used for exhaust gas cleaning, 42% auxiliary energy, 18% incomplete combustion). This is also reflected in the higher emissions of BSG used in a municipal waste incineration plant, than of BSG which is dried and incinerated in a boiler as in the previous scenario.

In contrast to animal blood and apple pomace, BSG has a relatively high AF (0.4 with a relative price of 20%), as the mass of the side-flow goes beyond the mass of the main product. That is why, the emissions of the valorisation increase from 115 to 325 kg CO_2e/t BSG, despite the relatively low up-stream emissions of the production of barley (0.5 kg CO_2e/kg barley). The environmental threshold is achieved at a hypothetical relative price of already 7%. In case of animal feeding, the emissions increase from 4 to even 214 kg CO_2e/t BSG at a hypothetical price of 20%, which is higher than the emissions of the substituted product rapeseed meal. Compared to soybean meal with 390 kg CO_2e/t, a large range of prices is still possible until it reaches the environmental threshold. More relevant is the consideration of a market value for BSG used in anaerobic digestion, the emission would increase from 97.3 to 307.4 kg CO_2e/t at a hypothetical price of 20%, which exceeds the GHG emission of the substituted products.

4. Discussion

4.1. Integration of LCC

The integration of LCC with LCA is recognized in De Menna et al. (2018) as a possible strategy to identify and avoid trade-offs between environmental and economic impacts. However, the availability of published data is often limited which hinders the implementation of LCC. While some data, e.g. for energy and fuels, can be sourced from open access databases, others such as specific investment costs and labour requirements are usually protected, due to their commercial sensitivity, or when they are available, they refer to rather different technologies or countries from those used in the LCI.

As far as the economic cost of animal blood treatment is regarded, a study on plasma and haemoglobin production reported an investment cost of EUR 900,000 for a plant treating 2,322 tonnes of animal blood per year, and a labour cost of more than 12,000 person hours (Kowalski et al., 2011). The most relevant item in their analysis is the cost of purchased material (including animal blood), suggesting that this side flow might have quite a high relative price, in which case this valorisation route would be profitable. For the anaerobic digestion of bio-waste, possible proxies can be found in Carlini et al. (2017) and Chinese et al. (2014). Investment cost and labour requirements are quite similar and linked to the size of the operation, therefore the cost of treating biowaste in AD plants will likely depend on this parameter. The profitability of this scenario is quite variable depending on the entity of public subsidies and the average electricity price in each country. Finally, no specific data on the production of blood meal or wastewater treatment was found. Published data on the cost of production of pectin from apple pomace specifically is furthermore lacking, while figures from other studies are too old to represent a reliable proxy (e.g. Graham and Shepherd,1953). Similarly, in the case of feed production, no costing data was retrieved. In the case of BSG, no economic data was found detailing any of the included scenarios. Further research could explore the costs and economics of these valorisation scenarios in order to verify their viability.

4.2. Data and scenario uncertainties

This study highlights effective/problematic valorisation options and gives insights into the effects of certain choices. It rests on generic data based on the most relevant processes with regards to GHG emissions, specifically transport and energy. Therefore, it does not replace a carbon footprint analysis for specific decision-making at company level. In this case, a LCA with full data inventory is recommended. Although specific data uncertainties underlie this streamlined LCA, it shows relevant parameters deserving a closer look. This is its advantage and it could be used in a very early phase of planning to understand the overall context and to prevent a costly full inventory LCA.

The potential and actual quantities used in different valorisation, recycling, and disposal options in Europe are not identifiable for most of the side-flows. A more accurate picture would require broader access to information, which is mostly restricted by companies exercising their rights to withhold commercially sensitive information from interested parties. Furthermore, the identification of comparable products is challenging, especially if there are no functionally similar products or if the more likely comparable products also derive from food chain side-flows. In this study, a range of indicative comparison products are shown which represent possible substitutes. The kind of product which would in reality be substituted on the market will depend on many factors (e.g. availability of infrastructure, transport costs, susceptibility for microbial spoilage, more supply than demand) and therefore depends on the stakeholder's context. For this reason, several scenarios are discussed in this study. Large-scale interventions which might be necessary for large-scale changes in food systems and which also influence the market of substituted products are only reasonably possible to analyse in a consequential approach (Weidema, 2003).

Recovery and recycling options are only under limited consideration in this study. Composting is another major player for the recycling of considered food side-flows but as the focus of this study was rather on the valorisation than on recycling, only one option was chosen to exemplify recycling, and as the considered side-flows have a high moisture content, the selected option was AD. However, the use of food side-flows as feedstock for compost production will play a major role in the future in improving soil quality (increasing organic matter content) for sustainable and secure food production in the EU.

The manual calculation of the biogas yield in the recovery option AD is subject to certain assumptions. Furthermore, it is assumed that 100% of all organic substances are decomposed, which is not true in practice (FNR, 2006). However, as the ruminant digestion process is similar to the digestion in biogas plants, specific parameters of animal feed can be considered to quantify the theoretical biogas yield. The calculated theoretical biogas yield should not be used for operational or economic decisions. However, it can be used to estimate tendencies and to compare different input materials (FNR, 2006), which is the intention of this study.

Furthermore, this study only incorporates up-stream emissions of the primary production of the main products (farming, cultivation) and not their processing (slaughtering, cutting). The importance of these life-cycle stages is low compared to primary production (see Notarnicola et al. (2017), however it is recommended to determine their relevance in future investigations.

4.3. Key challenges of measuring food waste valorisation

The measuring of circularity in the food sector is a challenge in itself due to the complexity of renewable materials and possible options which contrast with the material circularity indicator for stock flows (Ellen MacArthur Foundation, 2015). In order to a transition to a more circular economy and bio-economy it will be essential to monitor the success of recycling or the further use of co-products. Results are often subject to context specific conditions; therefore, generalising statements are not possible. In this study, the substitution approach used in connection with most likely scenarios of superseded products proved to be an appropriate measure for management options for residues of the food industry. This approach served as a good option for screening the environmental benefits of the further use and recycling of food side-flows within the food industry. The results from this study can to some extent fill the gap between qualitative models (e.g. food use hierarchy) and quantitative models (GHG, costs), which could be very supportive in fulfilling the pledge to achieve the climate change targets of the Paris Agreement. Additionally, the difference in the assessment of study objects defined as either co-product (market value above zero) or as waste (zero market value) is clear due to the omission or allocation of up-stream emissions. This is very applicable as in practice the market situation could change, and co-products could become waste or vice versa. The interwoven influence of the market situation on the results is shown in examples and environmental thresholds (minimum relative price where GHG emissions are on the same level as alternative products) given based on economic allocation. If the GHG factor of the main product is relatively high (in the case of animal containing products), then just a small amount of allocated up-stream emissions can heavily influence the results. If on the other hand the GHG factor of the main product is small (in the case of most vegetal products), then the degree of influence depends on the allocation factor and the emissions generated during processing. The allocation factor is determined by price and mass. The higher the allocation factor, the greater the quantity of up-stream emissions that must be allocated. This is the case when using BSG, where the influence of up-stream emissions plays a major role on the overall GHG performance of certain options. Moreover, if the product processing emissions are small, then the influence of up-stream emissions becomes higher. However, it needs to be kept in mind that the overall environmental impact of the process does not change with allocation - it is just a way to split a given amount of environmental impacts, which is however required to compare different scenarios.

A consequential approach is recommended to deepen the research strongly focussing on the market behaviour of superseded products and changes regarding the upcoming energy transition. It is recommended to model consequential impacts on the basis of actual quantities on the market and currently used management options which are however hardly identifiable due to a lack of data. Certainly, the relevance of superseded products is a crucial point which needs to be regarded in the measuring of circularity of renewable flows.

Next to the study, a tool called FORKLIFT (Davis et al., 2019) is proposed which was developed within the EU H2020 funded project REFRESH. It is a learning tool and provides a good understanding in the dynamics of selected parameters usually controlled by the generator or the user of the side-flow. It was developed to help stakeholders gain a general understanding and to highlight the environmental impacts and life cycle costs for selected valorisation routes of a given side-flow and serves as a good supplement to this study.

4.4. Key challenges of food waste valorisation

Food waste prevention has highest priority in the waste management hierarchy. Yet, if prevention is not possible, as is the case regarding unavoidable food side-flows, conversion or valorisation should be planned. Industrial symbiosis which aims to use waste from one sector as an input for other sectors will probably gain importance in upcoming years due to an emphasis on circular economy solutions. However, it does not always lead to GHG savings. The valorisation process often comes together with energy intensive technology to process food side-flows into valuable compounds. Compared to alternative products, in some cases it does not result in GHG savings (GHG emissions are higher than for the substituted products). If the process can be improved by switching from fossil fuel-based energy sources into renewable energy sources, then GHG savings can be observed in all scenarios compared to alternative products. Thus, the challenge is to build up a circular system based on primarily renewable energy sources. Nevertheless, even if market volumes for such high-value food ingredients are growing, the actual amount of redirected food side-flows is still limited. To achieve large volumes of food waste reduction, the animal feed option is essential as well. The conversion into animal feed results in all cases in GHG savings, as energy intensive products can be replaced, e.g. hay, soybean meal, fish meal. For food side-flows there are also limited distances coverable, and especially for further processing of biomass into food ingredients or animal feed, careful handling is necessary. Another pre-treatment step such as drying and pelletizing can increase the ability to store and distribute, but this also requires additional energy input which may increase GHG emissions.

The anaerobic digestion of food side-flows is associated with significant GHG emissions, but alternative products (heat and energy) also display a high GHG factor. In comparison with a ‘green’ electricity mix, like the Norwegian mix, the emissions for digesting food side-flows are higher. However, in comparison with other more fossil based energy mixes it is in most cases lower and therefore GHG savings can be generated by the digestion of food side-flows. In countries where the electricity mix is mostly based on fossil fuel, anaerobic digestion may become a better solution than valorisation. In countries, where the electricity mix is already largely based on renewables, another industrial symbiosis may be more appropriate. In any case the disposal of valuable food side-flows must phase out soon. Although, GHG emissions of the disposal are lower compared to emissions from anaerobic digestion and valorisation, there are no alternative products to compare with, and therefore no associated GHG savings. In the sense of a circular and sustainable economy, such disposal options are no alternative. Infrastructure and logistics are though required to redirect food side-flows to options further up the waste hierarchy, which can be supported by market-based instruments (e.g. taxes or incentives) or focused policies (e.g. national targets, federal waste management plans).

5. Conclusions

The study highlights environmental hotspots for different management options of the specific food side-flows animal blood, apple pomace, and BSG. Such side-flows have a relevant market in the EU and represent valuable resources for a circular economy. The simple disposal of food side-flows, e.g. by land spreading, is therefore no alternative. According to EU Regulation 2008/98/EC, the option with the “best overall environmental outcome” (European Commission, 2008) should be used for the management of such side-flows from the food industry. The best option depends however on many factors, which hinders the identification of options that are per se better or worse. The study indicates that possible superseded products but also used energy sources in processing are the most dominant parameters in determining GHG savings in the management of food side-flows. Food is a valuable material which is suitable to use in closed systems (industrial symbiosis, in which the goal is to use wastes from one sector as an input for other sectors), but not on the cost of energy intensive processing to reach this circular system as the example of apple pomace for pectin production has shown. The situation is different, if an enhanced utilization of renewable energy can be provided for this processing step. The primary focus is however on the substituted product. If a product can be replaced on the market, whose manufacturing is energy intensive and largely based on fossil energy sources, considerable GHG savings can be achieved (e.g. 500 kg CO_2e/t animal blood used as food ingredient). The use of food side-flows as animal feed is another important step to mitigate Global Warming as the production of conventional feed can be reduced and so the GHG emissions (in case of replacing soybeans with BSG, GHG savings of 390 kgCO_2e/t BSG can be achieved). Next the exploitation of existing potentials is essential, meaning that for example all valuable outputs of anaerobic digestion should be used: the electricity generated, the waste heat as well as the digestate which presents a valuable source for fertilizing. The use of such outputs can outweigh the high emission generation during the digestion. It supports the goal of the energy transition, where the use of fossil fuels shall be phased out soon to mitigate Global Warming. This further contributes to the development of more environmentally sustainable handling of different food side-flows in the future and keeps its valuable resources in a circular system.

CRediT authorship contribution statement

S. Scherhaufer: Methodology, Resources, Writing - original draft, Visualization. **J. Davis:** Methodology, Resources, Data curation, Validation, Writing - review & editing. **P. Metcalfe:** Methodology, Investigation, Resources. **S. Gollnow:** Methodology, Resources, Writing - review & editing. **F. Colin:** Methodology, Resources, Writing - review & editing. **F. De Menna:** Methodology, Resources, Writing - review & editing. **M. Vittuari:** Conceptualization, Writing - review & editing. **K. Östergren:** Conceptualization, Methodology, Writing - review & editing, Supervision.

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

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