REPAiR

REsource Management in Peri-urban AReas: Going Beyond Urban Metabolism

D4.8 Sustainability assessment for the pilot case studies – Eco-innovative solutions

Version 1.8

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Acronyms and Abbreviations

AMA	Amsterdam Metropolitan Area
AoP	Area of Protection
CAD	Centralised anaerobic digestion
CCP	Centralised composting
EABC	Effectiveness in Achieving a Behavioural Change
FV	Fruit and vegetables
HCP	Home composting
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
EC	European Commission
EIS	Eco-innovative solution
EU	European Union
FA	Focus Area
FSC	Food Supply Chain
FU	Functional Unit
FW	Food Waste
GDSE	Geo-design Decision Support Environment
MCDA	Multi Criteria Decision Analysis
OW	Organic Waste
PA	Public Acceptance
PULL	Peri-Urban Living Labs
SCG	Spent Coffee Ground

SME	Small-and-Medium-Enterprise
SQ	Status Quo
WMS	Waste Management System
WP	Work Package
ww	wet weight

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Publishable Summary

This deliverable assesses the sustainability of a set of eco-innovative solutions for the management of food waste in the Amsterdam Metropolitan Area (AMA). This is done by applying an *ad hoc* sustainability framework developed in the context of the REPAiR project with which solutions or strategies (i.e. combinations of solutions) can be quantitatively compared to their corresponding *Status Quo* or baseline, here identified as the current-day management of the waste. A number of twenty-seven indicators have been assessed, encompassing five areas of protection namely: human health, ecosystem health, natural resource, prosperity, and human well-being. Striving to thoroughly describe the studied areas, primary data have been collected with respect to waste generation and composition flows, collection schemes and treatment operations in the *Status Quo* alongside literature data to describe the eco-innovative solutions proposed. It should be noted that particular attention has been devoted to obtaining a detailed spatial differentiation of the inventory data in terms of collection schemes, distances (e.g. accessibility to the waste containers) and disamenities due to the presence of local incineration plants in line with the overarching project goal to combine spatial with material and life cycle analysis.

For the case of food waste management in the AMA, our findings suggest that solutions aiming to maintain the food within the supply chain appear by far the most favourable. Within this, redistribution of the food (donations, secondary selling, etc.) appears the preferred option followed by conversion into animal feed and use for production of food (e.g. use of bread as feedstock for beer production). While these applications might be especially suitable for specific food waste material fractions and selected actors, e.g. retailers, primary producers, and food industry, other (more conventional) treatments may be ultimately inevitable when dealing with the lower quality mixed food waste collected from the households and from other actors behaving similarly, e.g. small-and-medium-enterprises (SMEs). When tackling mixed food waste, our results suggest that none of the solutions proposed (home/centralised composting and anaerobic digestion with post-composting) is able to improve the performance of the *Status Quo* in all the Areas of Protection (AoP) considered. Anaerobic digestion with post-composting (i.e. producing compost as end-product through anaerobic plus aerobic steps) appears the preferred solution for mixed food waste in all the AoPs investigated, except for the AoP prosperity (higher collection costs overall). Home and direct centralised composting (i.e. only aerobic treatment without a prior digestion for energy recovery) show mostly more adverse impacts compared to the *Status Quo* (incineration with energy recovery). Such deviation from the waste hierarchy is due to the poor energy recovery of centralised composting but also to the currently low market and agronomic value of the product in the particular context of the Netherlands. On this basis, we recommend composting to be coupled with a prior anaerobic digestion step to ensure overall a maximum recovery of materials and energy.

1. Introduction

Assessing the sustainability of a service, product, or system implies addressing the environmental, economic, and social aspects associated with it. In this respect, Taelman *et al.* (2019), accompanied with Deliverable 4.4 and 4.5, proposed an operational framework for sustainability assessment addressing waste and resource management systems in European cities. This has been developed engaging local stakeholders, especially with respect to the selection of the relevant impact categories to be included. In Deliverable D4.6 we applied this framework to assess the impacts of the *Status Quo* management of the food waste in the AMA and of the *Status Quo* management of construction and demolition waste in the area of Naples. As a follow-up of Deliverable D4.6, this study applies the sustainability framework to assess a number of quantifiable eco-innovative solutions (EIS) in respect to the management of the food waste generated in the AMA (as delivered from WP5, provided by stakeholders in the Peri-Urban Living Labs). The aims are as follows:

- Comparing the sustainability of selected EIS against that of the *Status Quo*, as thoroughly illustrated in Deliverable D4.6.
- Illustrating and discussing hotspots in terms of critical aspects of the life cycle as well as in relation to data limitations and challenges.
- Drawing overall learnings and recommendations in relation to the solutions analysed.

The deliverable comprises the following sections:

- Section 2: Assessment method and description of the selected EIS.
- Section 3: Results and identification of relevant hotspots.
- Section 4: Overall discussion and learnings for the EIS analysed.
- Annexes: Providing additional results insights and data.

2. Method

2.1 Scope and functional unit

We focus on the management of food waste generated in a selected area of the Netherlands, from now onwards referred to as the Focus Area (FA; see Figure 1), purposely divided into six geographic sub-units, named after the predominant waste collector, namely i) AEB, ii) Meerlanden, iii) Middenmeer, iv) Purmerend, v) Indaver, vi) Orgaworld. The functional unit is the annual management of the food waste (or selected food waste fractions) generated in the FA expressed as tonnes of wet weight per year (t a^{-1}), with its composition detailed in annexes. The assessment is performed following the framework developed in D4.4 and D4.5 (Taelman *et al.*, 2019) encompassing five areas of protection with a total of 27 indicators covering twenty-five midpoint impact categories, either environmental, social or economic oriented (Figure 2). The assessment applies a consequential approach (Weidema *et al.*, 2009). For the specific indicators to be used in the assessment the reader is referred to the original publication and associated Supporting Information documentation (Taelman *et al.*, 2019). The assessment was facilitated with the life cycle tool EASETECH (Clavreul *et al.*, 2014). The temporal scope of the analysis is 2020-2030. This particularly affects the assumptions regarding the energy system in place (i.e. mix of fuels displaced through waste-to-energy technologies).

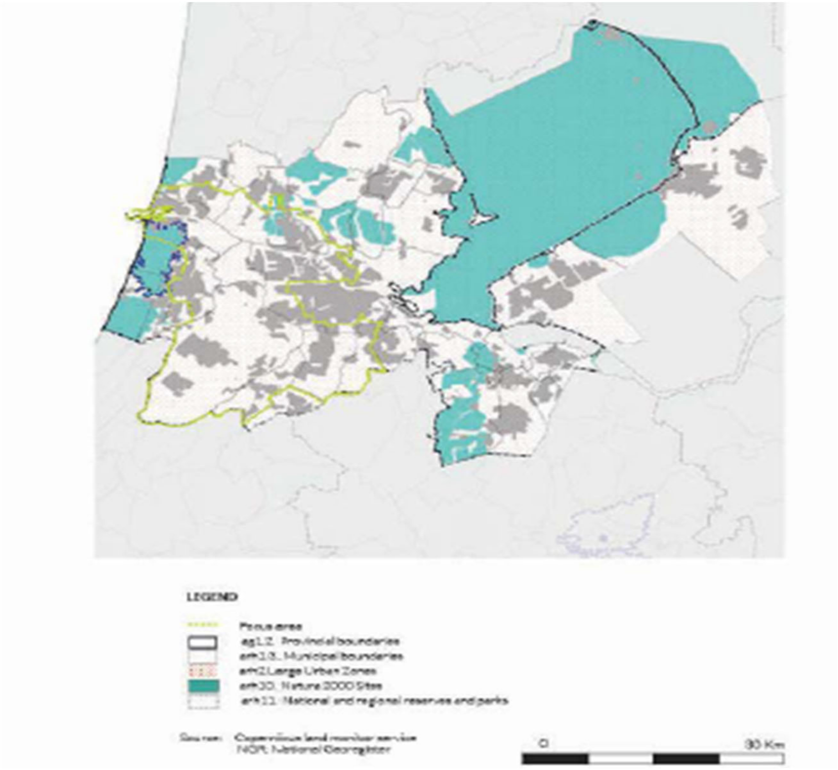

Figure 1. The Focus Area selected for the case of Amsterdam Metropolitan Area (AMA); taken from Deliverable D3.3.

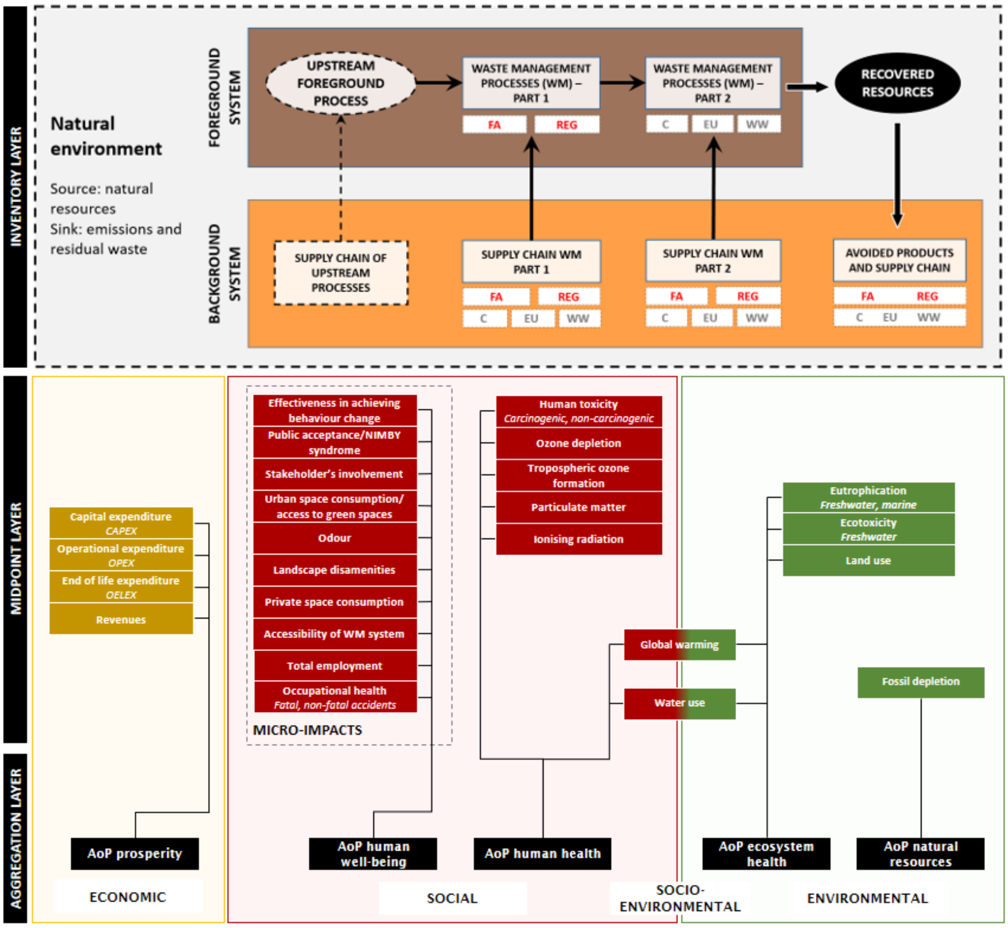

Figure 2. Sustainability framework for waste and resource management (taken from Taelman et al. 2019).

2.2 Eco-innovative solutions assessed

In Deliverable D3.5, n=9 main EIS have been proposed for the case of AMA. These were the following ones:

1. From bread to beer
2. BIO-BEAN: from waste coffee ground to biofuel
3. Food Waste Insect Protein Tanks
4. Peel Pioneer
5. Fruit Leather
6. Food Rescue Platform
7. Smart Biorefinery
8. Decentralised food waste collection
9. Re-Compost Land. Short supply chain of organic waste

EIS #9, namely "Re-Compost Land. Short supply chain of organic waste", can be further split into three technical solutions, i.e. home composting, centralised composting and anaerobic digestion followed by post-composting. This adds up to a total of n=11 EIS. After careful evaluation of these 11 solutions by WP3 and WP4 scientific staff, we selected a list EIS that could be assessed from a sustainability point of view (see section 2.2.1-to-2.2.3). The exclusion of a few EIS is motivated by either lack of data (this was the case of "Peel Pioneer", "Smart Biorefinery", and "Fruit Leather") or because they are implicitly already part of other solutions (this was the case for "Decentralised food waste collection"). We here assess the selected EIS individually and compare them with their counterpart or *Status Quo* (i.e. current-day feedstock management). The solutions are differentiated between those that prevalently apply to the mixed food waste as a whole and those that focus on selected material fractions of the whole food waste (e.g. bread). The assessment is performed using as a baseline the *Status Quo* for households and SMEs as these actors represent the vast majority of the waste generators in the FA and those for which immediate actions for improvement appear necessary, building upon the results of D4.6.

2.2.1 EIS tackling the whole mixed food waste generated

EI-I	**Home & Centralised Composting (FW-HCP)**
Description	Involves separate collection of the food waste and aerobic home composting of the separately collected food waste for all households having private gardens; involves centralised aerobic composting of the separately collected food waste from the remaining households not having private garden
FSC sector affected	Households and SMEs
Material affected	Food waste, all (amount generated: 153,320 t/year)
FU	Management of the FW generated annually

EI-II	**Centralised Composting (FW-CCP)**
Description	Involves separate collection of the food waste and direct centralised aerobic composting of the separately collected food waste (aerobic treatment only)
FSC sector affected	Households and SMEs
Material affected	Food waste, all (amount generated: 153,320 t/year)
FU	Management of the FW generated annually

EI-III	**Centralised Anaerobic digestion with Post-Composting (FW-CAD)**
Description	Involves separate collection of the food waste and involves anaerobic digestion followed by a post-composting of the separately collected food waste
FSC sector affected	Households and SMEs

Material affected	Food waste, all (amount generated: 153,320 t/year)
FU	Management of the FW generated annually

2.2.2 EIS tackling selected food waste fractions

EI-IV	**Spent Coffee Ground to biofuels (SCG-pellet)**
Description	Involves separate collection of the SCG. The collected SCG is then pelletized in a dedicated plant and transformed into pellets for use as heating fuel.
FSC sector affected	Food industry, Wholesale & Retail, Food Service
Material affected	SCG (amount generated: 23,800 t/year; see shares in D4.6)
FU	Management of the SCG generated annually

EI-V	**Bread to beer (BR-beer)**
Description	Involves the separate collection of bread from retailers, food service sector, and processing industry. The bread collected is then processed and used as feedstock for beer production in place of barley grains.
FSC sector affected	Food industry, Wholesale & Retail, Food Service
Material affected	Bread (amount generated: 23,800 t/year; see shares in D4.6)
FU	Management of the bread generated annually

EI-VI	**Bread to animal feed (BR-feed)**
Description	Involves the separate collection of selected former foodstuff, which conditions are assumed to be in line with the relevant EU legislation for redistribution, from retailers, food service and food processing industry. The collected material is converted into dry animal feed substituting for conventional energy-feed.
FSC sector affected	Food industry, Wholesale & Retail, Food Service
Material affected	Bread (amount generated: 18,000 t/year; see shares in D4.6)
FU	Management of the bread generated annually

EI-VII	**Bread redistribution (food rescue platform) (BR-redistr)**
Description	Involves the separate collection of selected former foodstuff, which conditions are assumed to be in line with the relevant EU legislation for redistribution, from retailers, food service and food processing industry. The collected material is redistributed substituting for corresponding food production.
FSC sector affected	Food industry, Wholesale & Retail, Food Service
Material affected	Bread (amount generated: 18,000 t/year; see shares in D4.6)
FU	Management of the bread generated annually

EI-VIII	**Fruit & vegetables to animal feed (FV-feed)**
Description	Involves the separate collection of selected former foodstuff, which conditions are assumed to be in line with the relevant EU legislation for redistribution, from retailers, food service and food processing industry. The collected material is converted into dry animal feed substituting for conventional energy-feed.
FSC sector affected	Food industry, Wholesale & Retail, Food Service
Material affected	Fruit & vegetables (amount generated: 63,400 t/year; see shares in D4.6)
FU	Management of the fruit and vegetables generated annually

EI-IX	**Fruit & vegetables redistribution (food rescue platform) (FV-redistr)**
Description	Involves the separate collection of selected former foodstuff, which conditions are assumed to be in line with the relevant EU legislation for redistribution, from retailers, food service and food processing industry. The collected material is redistributed substituting for corresponding food production.
FSC sector affected	Food industry, Wholesale & Retail, Food Service
Material affected	Fruit & vegetables (amount generated: 63,400 t/year; see shares in D4.6)
FU	Management of the fruit and vegetables generated annually

For all the above listed EIS, an overarching solution applies simultaneously (EI-0), i.e. an improved waste collection for food waste. This is the basis for capturing the food waste stream and applies any subsequent treatments.

2.2.3 EIS tackling the collection system

EI-0	**New food waste collection system**
Description	Involves a spatially new collection system in the area to increase capture rate of food waste up to 65% of FW generated. (1) A new separate food waste collection system is proposed in the AEB wasteshed. In the centre of Amsterdam, a new food waste collection system, using floating containers, is proposed for households that do not have access to a garden and for SMEs. Food waste is collected by boat or truck from these points. Outside the centre of Amsterdam, accessibility to the food waste collection system is increased by decreasing the number of households per container and collection point to the level of current residual waste collection. This results in an increase in the number and density of waste containers. (2) Door-to-door collection is implemented in high-density areas in all the other wastesheds. Areas with more than 5,000 inhabitants per square km, which is a high density in the Netherlands, have door-to-door collection for both households with and without access to a garden. This means that every apartment building, row house, semi-detached house and single-family house have one container where all households and SMEs in the building will dispose their food waste. In these areas, SMEs and households without access to a garden have one collection point per building, whereas households with access to a garden have one collection point every four households. (3) In the remaining wastesheds (other than AEB) where population density is lower than 5,000 inhabitants per square km, accessibility to food waste collection system is increased by decreasing the number of households per container and collection point to the level of residual waste collection.
FSC sector affected	Households and SMEs
Material affected	Food waste, all (amount generated: 153,320 t/year)
FU	Collection of the food waste generated annually

2.3 System boundary

For all scenarios assessed, the system boundary includes all the activities involved in the life cycle of the generated waste: collection, treatment, transportation of waste, treatment residues and/or products to end-use or further disposal (e.g. ashes, digestate, compost, etc.), and eventual final disposal (e.g. landfilling when applicable). Activities (e.g. effort and time spent by households) and goods (e.g. garbage bins and bags) associated with in-house source segregation of the waste have been disregarded. Following common practice in LCA of waste systems, the products and services generated alongside the treatment of the waste (i.e. the FU) were credited by assuming substitution of corresponding market products or services, expanding the system boundary to account for these displacements. These products/services were identified in the market marginal products/services for the area under assessment, i.e. those that are capable to respond to changes in demand (Weidema *et al.*, 2009). On this basis, electricity provision was assumed as the future Dutch marginal mix (Ecoinvent centre, 2019); likewise, a marginal heat mix was elaborated on the basis of a recent study for the Netherland and EU14 (European Commission, 2018) (56% natural gas and 46% heat pumps). With respect to production of gaseous fuel, such as upgraded biogas (natural gas-quality, injected into the gas grid), we assumed a 1-to-1 energy-basis substitution of natural gas extraction, (long-distance) distribution, and combustion on the basis of the energy content. With respect to NPK mineral fertilisers, we relied on the choices justified in previous studies (Tonini *et al.*, 2016), assuming urea-N, diammonium phosphate, and potassium chloride as marginal mineral fertilisers. The actual nutrient substitution was quantified following the commonly applied maintenance principle as illustrated in Vadenbo *et al.* (2018) and as applied in a number of recent LCAs (e.g. De Vries *et al.*, 2012; Hamelin *et al.*, 2014; Styles *et al.*, 2018). Details on the calculation methods can be found elsewhere (e.g. Tonini *et al.*, 2020). When energy-feed was produced from the waste, barley was assumed as the marginal energy-feed product for the local market conforming with the suggestion of Weidema (2003). The market substitution was based on the respective digestible energy content following a common approach (Albizzati *et al.*, 2019), with digestible energy of barley equalling 12.8 MJ kg^{-1} TS (Moeller *et al.*, 2000) and that of the waste entering the feed producing factory derived upon mass balances that consider loss during collection and pre-treatment. The substitution of barley in beer production was assumed one-to-one as the content of carbohydrates and starch is similar. Use of aged bottom ash as road sub-base was assumed to substitute for natural gravel extraction and production, on a one-to-one mass basis.

Overall, it should be noted that the system boundaries and related choices (e.g. regarding the conventional products substituted in the market by secondary waste-derived products) are the same as for Deliverable D4.6 except for the choice of the electricity mix of the Netherlands. Indeed, while in D4.6 the 2015 Dutch electricity mix (mainly based on natural gas) was used, in this analysis the future (2015-2030) Dutch mix is instead applied (mainly based on wind, biomass, and other renewables; retrieved from Ecoinvent centre, 2019 and based on the data published by European Commission 2016). The choice was taken after an internal discussion between REPAiR team members and stakeholders from AMA involved in the Amsterdam circular economy and future waste strategy. Such assumption is justified as the Netherlands has recently strongly committed to decrease consumption of natural gas fuel and invest in low-carbon energy technologies. On this basis, we believe that this choice is thus more in line with the future expected energy mix of the region.

2.4 Inventory data

Inventory data were collected for the proposed EIS. This involved collecting data on the waste collection system and technologies (i.e. input-output data for material, resource and energy consumptions as well as associated costs). Background data for modelling of energy, electricity, material, fuels and resource provisioning was taken from the ecoinvent database 3.5 (Ecoinvent centre, 2019), consequential system, in line with what done for the *Status Quo* assessment in Deliverable 4.6. A summary of the inventory data used in the assessment is provided herein. For all technologies and processes, unit-costs are calculated following the methodology for economics of waste as illustrated in Martinez-Sanchez, et al. (2015). OPEX are calculated on the basis of the energy, resources, and chemicals used in the processing, consistently with the life cycle inventory used. CAPEX are quantified based on information from the literature and OELEX are quantified similarly to the *Status Quo* (see D4.6) relying on the approach suggested by (Homes and Communities Agencies, 2015). REVENUES are quantified knowing the market price of the products generated within each scenario. Market prices are taken as for the year 2015, which was used as reference. An overview of the inventory data applied can be found in Table 1.

Table 1. Overview of the inventory data used in modelling the EIS.

EIS	**Source for inventory data**
EI-0	Builds on the datasets provided in (Tonini *et al.*, 2020) See Supplementary Tables (distributed to project partners).
EI-I HCP	Builds on the datasets provided in (Tonini *et al.*, 2020) See Supplementary Tables (distributed to project partners).
EI-II CCP	Builds on the datasets provided in (Tonini *et al.*, 2020) See Supplementary Tables (distributed to project partners).
EI-III CAD	Builds on the datasets provided in (Tonini *et al.*, 2020) See Supplementary Tables (distributed to project partners).
EI-IV SCG-pellet	See Annex III – Table A1.
EI-V BR-beer	Modelled assuming that bread substitutes for barley that would otherwise be used in the beer production process; the additional energy consumption for pretreatment of the feedstock (0.67 kWh/kg ww) is calculated based on the data reported in Almeida *et al.* (2018). Due to lack of data, CAPEX and OELEX data are assumed to be similar as for feed factories (see Table A2).
EI-VI BR-feed	See Annex III – Table A2.
EI-VII BR-redistr.	Redistribution is modelled conform the redistribution scenario designed in Albizzati et al. (2019). We assume that the displaced food is exactly the same as the food redistributed, i.e. bread,

	assuming that the selling price (i.e. revenues) is 30% of the original market price for the good (i.e. drop of 70% in market value to account for secondary distribution). Loss in the redistribution chain is assumed 80% (i.e. 20% is sent to incineration) based on the scenario analyses illustrated in Albizzati *et al.* (2019) – Supplementary Information.
EI-VIII FV-feed	See Annex III – Table A2.
EI-IX FV-redistr	As EI-VII.

3. Results for the eco-innovative solutions (EIS)

We present the results on two layers, with increasing level of detail:

- The first layer is the overarching synthesis obtained after aggregation (applying the MCDA (D4.5); Table 2-to-5) and provides a synthetic overview of the performance of each EIS as compared to the corresponding *Status Quo*. This is directed to decision- and policy-makers that search for a final aggregated synthesis of the information.
- The second layer shows the detailed breakdown of the midpoint impact contributions for each EIS and for the corresponding *Status Quo* and it is directed to specialists in the field of life cycle analyses that search for additional insights on the results. The breakdown of the impact is displayed in Annex I for the EIS tackling mixed food waste and Annex II for the EIS tackling selected waste material fractions (Figure A1-to-A10).

Here we provide an overview of the abbreviations used per EIS considered and of the respective *Status Quo* scenarios assessed:

- FW-SQ: *Status Quo* for mixed food waste
- FW-HCP: home composting for mixed food waste (EI-I)
- FW-CCP: centralised composting for mixed food waste (EI-II)
- FW-CAD: centralised anaerobic digestion followed by post-composting for mixed food waste (EI-III)
- SCG-SQ: *Status Quo* for spent coffee ground (as for mixed food waste)
- SCG-pellet: conversion of spent coffee ground to pellets (EI-IV)
- BR-SQ: *Status Quo* for bread (as for mixed food waste)
- BR-beer: conversion of bread to beer (EI-V)
- BR-feed: bread conversion to feed (EI-VI)
- BR-redistr: redistribution of bread (EI-VII)
- FV-SQ: *Status Quo* for fruit and vegetables (as for mixed food waste)
- FV-feed: fruit and vegetables conversion to feed (EI-VIII)
- FV-redistr: redistribution of fruit and vegetables (EI-IX)

3.1 EIS tackling mixed food waste

3.1.1 Synthesis of the results applying MCDA

All the EIS performed worse than the *Status Quo* in the AoP prosperity. The scenario based on anaerobic digestion and post-composting (*CAD*) achieved an equal or better performance of the *Status Quo* on all the AoPs except for Prosperity. The remaining EIS based on home or (direct) centralised composting (i.e. without combination with prior AD) performed always worse than the *Status Quo* except for the AoP human well-being (Table 2).

Table 2. Ranking of the EIS after applying MCDA. Green colour indicates a better performance than the *Status Quo*, a yellow colour a comparable and the red colour a worse one.

EIS	Ecosystem health	Human health	Human well-being	Natural resource	Prosperity
FW-SQ	1	2	3	2	1
FW-HCP	4	3	1	3	2
FW-CCP	2	3	2	4	3
FW-CAD	1	1	3	1	3

3.1.2 Hotspots and critical aspects identified through contribution analysis

The poor performance of the home and (direct) centralised composting solutions (HCP and CCP) is mostly due to the impacts associated with composting operations and use-on-land and to the poor energy substitution effects. This can be observed, for instance, in the AoP human health (Figure A1) for the impact categories Global Warming, Ozone Depletion, and Human Toxicity (both cancer and non-cancer) or in the AoP and ecosystem health (Figure A2) for the impact categories Marine and Freshwater Eutrophication and Ecotoxicity. Particularly, nutrient leaching from compost and metals return on agricultural soil drive the impacts on these categories. The same pattern is observed for the AoP natural resource (Figure A4) and prosperity (Figure A3), where the performance of the EIS based on home and centralised composting is worse than that of the *Status Quo* owing to the lower energy recovery and substitution effects. On the other hand, CAPEX and OPEX increase following increased collection efforts required to capture the food waste stream as compared to a simpler mixed collection system in the *Status Quo* (Figure A4). In the AoP human well-being (Figure A5) most social indicators show a better performance, e.g. Accessibility, Public Acceptance, stakeholder Involvement, Disamenities (due to decrease in waste incinerated), and Effectiveness in Achieving a Behaviour Change (higher efficiency of food waste separate collection). However, this is not the case for Odour Footprint and Urban Space Consumption. Total Employment is expected to increase because of the increased collection efforts required. The number of accidents followed the trend observed for Total Employment.

Compared to the EIS based on home and (direct) centralised composting, the overall improved sustainability of the EIS based on anaerobic digestion and post-composting is principally due to the increased energy recovery and substitution effects. This can be notably observed in the AoP human health (Figure A1) for the impact category Global Warming and, likewise, in the AoP natural resource (Figure A3). The increased energy recovery also incurs higher revenues compared to the *Status Quo* and to the remaining EIS (Figure A4). In the AoP human well-being this solution incurs higher urban space consumption, employment, and accidents relative to the alternatives analysed (Figure A5).

3.2 EIS tackling selected fractions of the food waste

3.2.1 Synthesis of the results applying MCDA

All the EIS performed better or at least comparable to the corresponding *Status Quo*. For the management of the spent coffee ground fraction (SCG), the EIS based on pellet production and subsequent use for energy performed better on all AoPs except for prosperity where the performance was comparable to the *Status Quo* (Table 3). For the management of the bread waste fraction, all EIS performed better than the *Status Quo* on all AoPs except again for prosperity because the options to produce beer and feed showed bad performances (Table 4). For the management of the vegetable and fruit waste fraction, both the option of producing animal feed and redistributing achieved better performances than the *Status Quo* across all the AoPs (Table 5).

Table 3. Ranking of the EIS after applying MCDA. Green colour indicates a better performance than the *Status Quo*, a yellow colour an equal and the red colour a worse one.

EIS	Ecosystem health	Human health	Human well-being	Natural resource	Prosperity
SCG-SQ	2	2	2	2	1
SCG-pellet	1	1	1	1	1

Table 4. Ranking of the EIS after applying MCDA. Green colour indicates a better performance than the *Status Quo*, a yellow colour an equal and the red colour a worse one.

EIS	Ecosystem health	Human health	Human well-being	Natural resource	Prosperity
BR-SQ	3	3	4	4	2
BR-beer	2	2	1	3	4
BR-feed	3	3	3	2	3
BR-redistr	1	1	1	1	1

Table 5. Ranking of the EIS after applying MCDA. Green colour indicates a better performance than the *Status Quo*, a yellow colour an equal and the red colour a worse one.

EIS	Ecosystem health	Human health	Human well-being	Natural resource	Prosperity
FV-SQ	2	2	3	3	3
FV-feed	2	2	2	2	1
FV-redistr	1	1	1	1	1

3.2.2 Hotspots and critical aspects identified through contribution analysis

For the waste material fraction SCG, the sustainability performance across all AoPs is better than that of the *Status Quo* except for prosperity where it is comparable. The magnitude of the environmental and socio-economic savings is however in the same order of magnitude as that of the *Status Quo* (Figure A6-to-A10). The main benefits are related to energy recovery and related substitution effects.

For the waste material fractions, bread and fruit and vegetables, the performance across all AoPs is driven by the savings associated with material substitution (purple stack; Figure A6-to-A10). These are directly related to the substitution of barley grains in the food waste-to-feed solutions (where barley grains are assumed as conventional animal feed; see method section) and of food production in the food waste redistribution solutions. The pattern of savings is similar in all categories belonging to the AoPs human health and ecosystem health (Figure A6 and A7, respectively). This is not the case, however, for the material fraction bread in the AoP prosperity (Figure A9) where BR-feed and BR-beer solutions achieve worse performances compared to the *Status Quo* mainly because of lower revenues. Yet, the difference here may also be a result of the assumptions taken in terms of market price for the feed produced (assumed as barley grains).

While for many of the social indicators (accessibility, effectiveness in achieving behaviour change, public acceptance, etc.), the trend is similar to what already observed earlier for the mixed waste, the savings obtained in Odour Footprint reflect the reduced N-fertilisers use during feed and food production because of the decreased crop-supply needed (substitution effect). The savings in the category Disamenities reflect the reduced amount of waste incinerated. Increased impacts in Private space Consumption are a consequence of the increased efforts in separate door-to-door collection. This also incurs increase in Total Employment and related accidents in Occupational Health (Figure A10).

4. Discussion

4.1 Learnings and recommendations

Our analysis indicates that producing high-value outputs such as feed and food from the collected food waste appear by far as the most favourable options, whenever this is possible and applicable. These findings are in line with food waste hierarchy proposed in the literature (Papargyropoulou *et al.*, 2014) and with the most recent scientific studies documenting the increased environmental and socio-economic benefits of these solutions (Albizzati *et al.*, 2019; Eriksson *et al.*, 2016; Eriksson and Spanngberg, 2017). While maintaining the food within the supply chain appears the favourable option, the implementation of these pathways may be challenging because of the existing regulations about safety and hygiene. Focusing on specific actors such as primary producers, food industry, retailers, and selected food service appear critical in order to minimize risks and comply with the main EU food safety regulations. If such high-value pathways cannot be implemented, our findings indicate that a combination of anaerobic digestion and post-composting should be supported. This combination allows recovering energy from the waste while preserving nutrients and organic matter value in the end-product (compost obtained from digestate). The C-content of the compost is typically similar (or only slightly lower) to that of a normal compost obtained under aerobic conditions but with the key-advantage of recovering energy during the AD process instead of solely consuming energy during the composting process to oxidise the organic matter, i.e. making a maximum energetic recovery out of the oxidised carbon.

Conversely, the implementation of treatments such as home and/or centralised composting (aerobic only, without digestion) appear environmentally and socio-economically less preferable relative to the *Status Quo* (mostly incineration with energy recovery). Such deviation from the waste hierarchy is due to two main reasons: first, direct centralised composting is an energy-intensive technology where energy is used to oxidise the carbon contained in the waste to CO_2 in order to stabilise the organic material, as opposite to the combined “anaerobic digestion followed by post-composting” treatment. The latter uses the carbon in the waste to generate energy in the form of methane, thus providing benefits to the treatment with additional environmental and economic savings. Second, the low value of the product; in the Netherlands farmers are often paid to apply compost and digestate on land and the market price for these is typically in the range -5 to +2 € per tonne indicating an extremely low market value (Tonini *et al.* 2020; Tonini *et al.* 2019; Huygens *et al.*, 2019). This is directly related to the high concentration of N and P nutrient in the agricultural soils following the well-known "high-animal-and-people-density" situation of the region (Huygens *et al.*, 2019). For domestic compost (home composting) the market substitution effects is considered to be low as citizens typically use this product for landscaping or backfilling purposes and only to a minor extent to actually substitute NPK fertilisers or peat (see Andersen, et al., 2010).

Bearing the above considerations in mind, our recommendation for the case of Amsterdam Metropolitan Area is to develop EIS on technologies and processes that may potentially increase the market value of food waste. Suggestions can be found in recent market and technical analyses by Alexa *et al.*, (2019), Parisi *et al.* (2019) and Tonini *et al.* (2019). These include, among the others, high-value N and P fertilisers, animal feed, biomaterials (e.g. bioplastics) and biochemicals. Next to these, a combination of anaerobic digestion and composting is recommended in order to maximise the environmental and economic benefits. Direct centralised composting (without anaerobic digestion) and home composting appear to be instead suboptimal solutions.

4.2 Limitations and perspectives

The main limitations of this analysis are:

- Data choices: the data and assumptions taken regarding the substitution of conventional market materials (e.g. barley for bread-to-beer, bread-to-feed and fruit and vegetable to feed), both in respect to the actual physical substitution ratio and the prices. In this analysis we have assumed a displacement of barley as feed with a market price around 110 € per tonne of grains. This figure may be different if alternative crops are considered as displaced feed and/or depending on the price fluctuations of the feed market. Further limitations concern the capital costs and labour assumed for the factories in the beer-to-bread (BR-beer) and feeding scenarios (BR-feed and FV-feed) due to limitations in the data availability.
- Suitability of selected impact categories: selected impact categories originally identified as relevant to be included in the framework by the REPAiR stakeholders may be difficult to quantify or not always relevant. This is the case of "Stakeholder Involvement" for which it is difficult to quantify an impact per each eco-innovative solution or strategy analysed (in other words, per scenario assessed). The same applies to the category "Landscape Disamenities" essentially because it is unknown whether the proposed treatment process may incur loss of real estate's value in its surroundings. In this analysis, we have assumed that only incineration actually incurs loss of real estate's value in its surroundings based on public perception/fear. Additionally, the impact categories "Accessibility to Waste Management System (Accessibility to WMS), Effectiveness in Achieving a Behaviour Change (EABC), Public Acceptance (PA) may not be relevant as they are directly related to the success of the separate collection system (food waste capture rate) and not much on the final treatment/valorisation of the collected waste.
- Use of these findings: It should be born in mind that the findings of this analysis are very specific to the case of Amsterdam Metropolitan Area and should not be used to draw general conclusions on other EU geographic regions. The main reason for this is that site-specific data have been used in this analysis, notably agricultural soil P-saturation conditions and high incineration efficiency. In other contexts, the reference treatment for food waste may be different (e.g. landfilling or less efficient incineration plants)

and the market for compost/digestate may vary in terms of demand, prices and environmental benefits derived from substituting mineral fertilisers and conventional amending materials (e.g. peat). This could dramatically change the ranking between the assessed food waste management options and the related conclusions and recommendations to authorities and policy-makers.

As a suggestion to the REPAiR partners, based on the experience from this analysis, we strongly recommend to focus the data collection on the EIS as these incur significant time and efforts. Indeed, while for conventional technologies such as incineration, composting and anaerobic digestion data are typically available, it is instead not the case for innovative pathways such as redistribution, animal feed production, etc. This does not only apply to technologies but also to collection systems and associated expenses/labour that may be one of the key solutions in areas with low capture rate (e.g. also for the case of AMA; see Tonini *et al*, 2020).

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Annexes

Annex I - Contribution analysis – EIS for mixed food waste

The following scenarios are assessed:

- *Status Quo* (FW-SQ)
- Home & Centralised Composting (FW-HCP)
- Centralised Composting (FW-CCP)
- Centralised anaerobic digestion + post-composting (FW-CAD)

Area of Protection: Human health

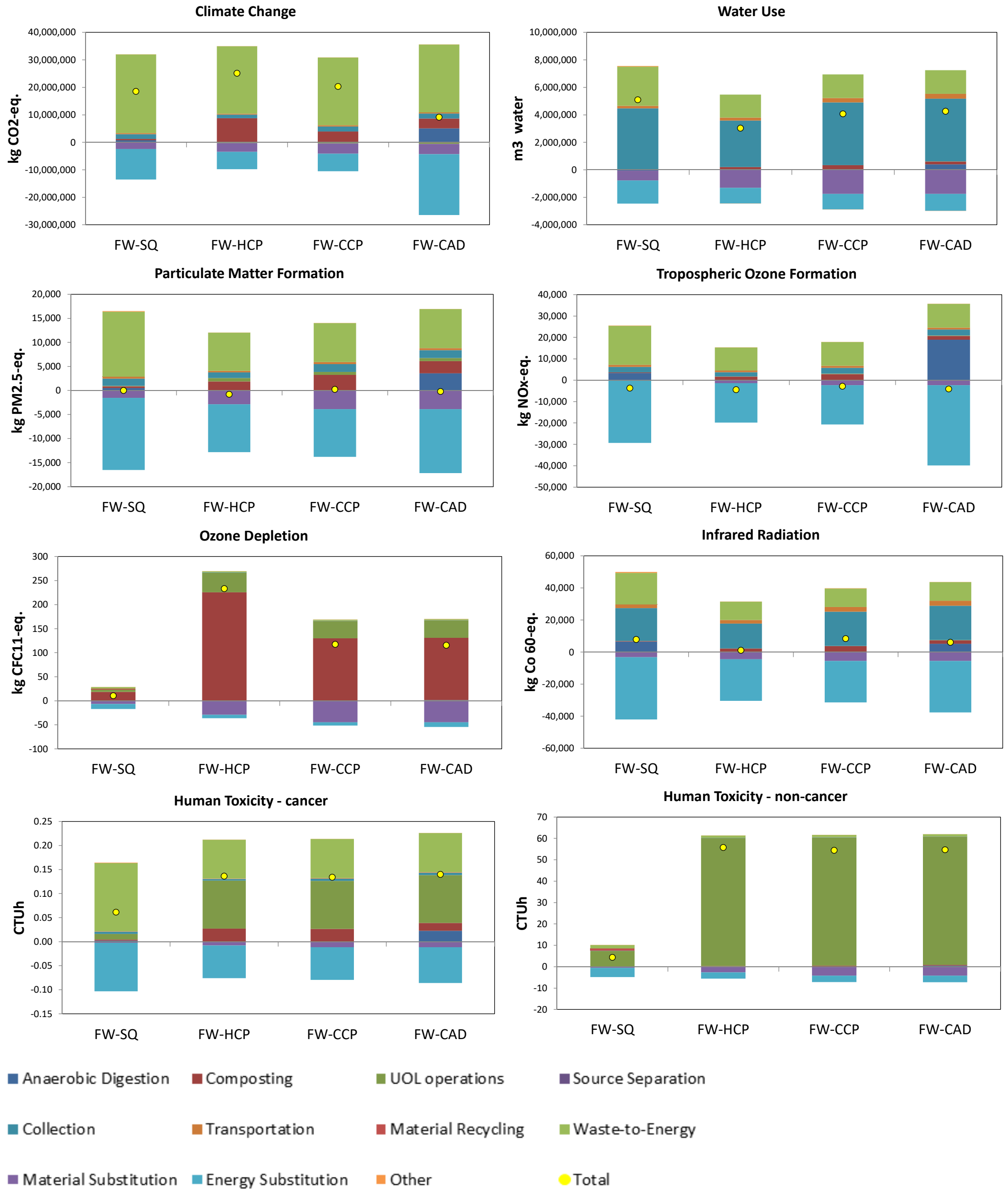

Figure A1. Breakdown of the impact for the categories falling under the AoP human health. With respect to the legends: “Anaerobic Digestion” represents all processes involved at the digestion plant including eventual pre- and post-treatment of the waste/digestate; ”Collection” represents all operations of waste collection; “Composting” represents all processes involved at the composting plant including eventual pre- and post-treatment of the waste/compost; “Waste-to-Energy” represents all processes transforming the waste via thermal processing (this broad category thus includes incineration, bioenergy production, cement kiln, and co-combustion of waste in existing power plants); “Material recycling” represents all processes involved in sorting and reprocessing waste into new raw materials; “Material Substitution” represents savings from

substitution of market materials and products (e.g. fertilisers); "Energy Substitution" represents savings from substitution of market electricity, heat, and other fuels; "Source Separation" represents all processes associated with separating waste at the place of generation; "UOL operations" represent all processes involved in application of organic fertilisers on-land (operations and emissions, e.g. leaching).

Area of Protection: Ecosystem health

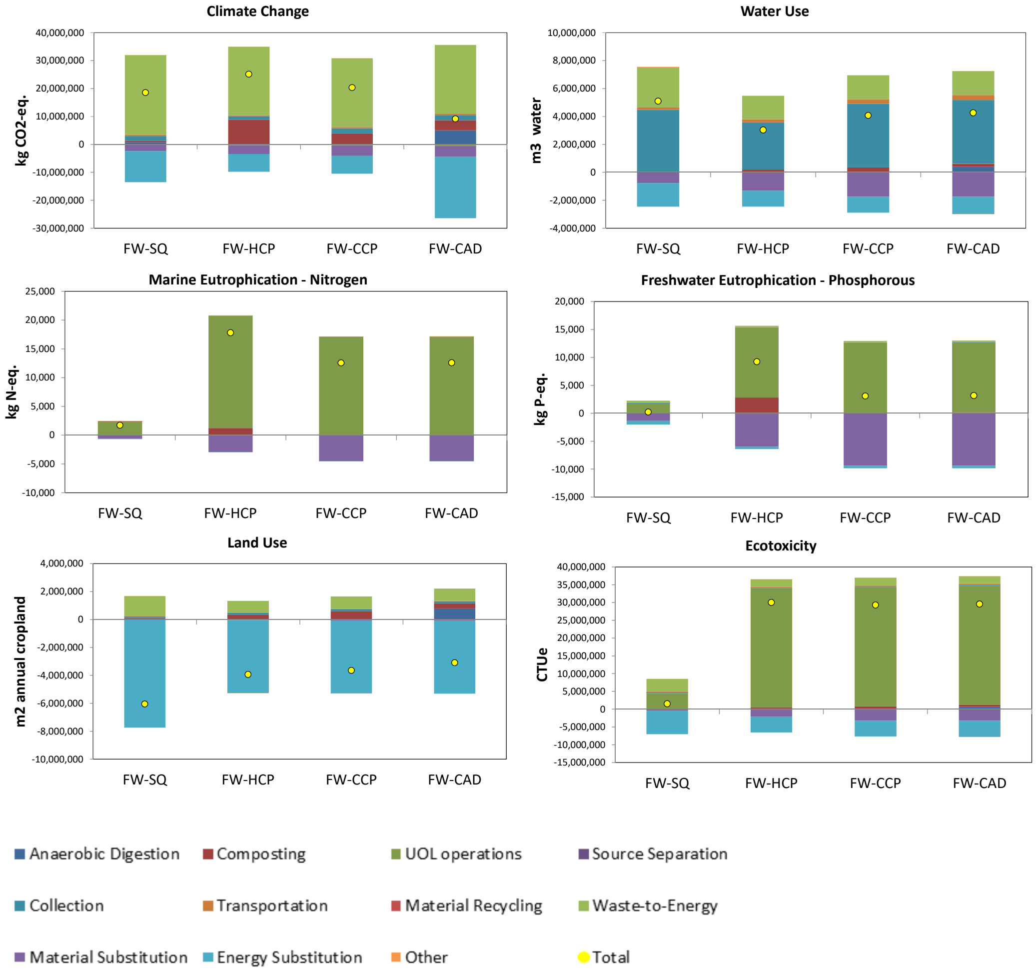

Figure A2. Breakdown of the impact for the categories falling under the AoP ecosystem health. With respect to the legends: "Anaerobic Digestion" represents all processes involved at the digestion plant including eventual pre- and post-treatment of the waste/digestate; "Collection" represents all operations of waste collection; "Composting" represents all processes involved at the composting plant including eventual pre- and post-treatment of the waste/compost; "Waste-to-Energy" represents all processes transforming the waste via thermal processing (this broad category thus includes incineration, bioenergy production, cement kiln, and co-combustion of waste in existing power plants); "Material recycling" represents all processes involved in sorting and reprocessing waste into new raw materials; "Material Substitution" represents savings from substitution of market materials and products (e.g. fertilisers); "Energy Substitution" represents savings from substitution of market electricity, heat, and other fuels; "Source Separation" represents all processes associated with separating waste at the place of generation; "UOL operations" represent all processes involved in application of organic fertilisers on-land (operations and emissions, e.g. leaching).

Area of Protection: Natural resources

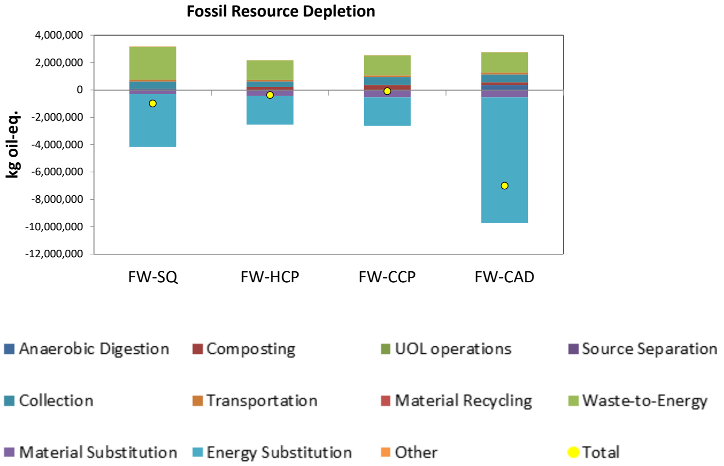

Figure A3. Breakdown of the impact for the categories falling under the AoP natural resources. With respect to the legends: “Anaerobic Digestion” represents all processes involved at the digestion plant including eventual pre- and post-treatment of the waste/digestate; ”Collection” represents all operations of waste collection; “Composting” represents all processes involved at the composting plant including eventual pre- and post-treatment of the waste/compost; “Waste-to-Energy” represents all processes transforming the waste via thermal processing (this broad category thus includes incineration, bioenergy production, cement kiln, and co-combustion of waste in existing power plants); “Material recycling” represents all processes involved in sorting and reprocessing waste into new raw materials; “Material Substitution” represents savings from substitution of market materials and products (e.g. fertilisers); “Energy Substitution” represents savings from substitution of market electricity, heat, and other fuels; “Source Separation” represents all processes associated with separating waste at the place of generation; “UOL operations” represent all processes involved in application of organic fertilisers on-land (operations and emissions, e.g. leaching).

Area of Protection: Prosperity

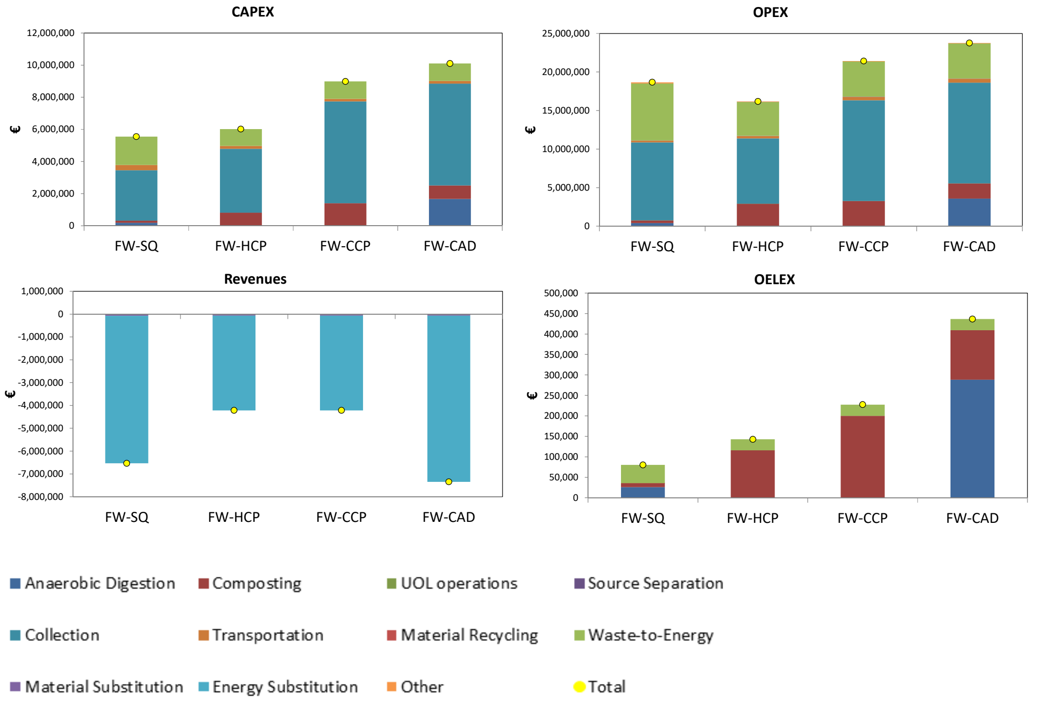

Figure A4. Breakdown of the impact for the categories falling under the AoP prosperity. With respect to the legends: "Anaerobic Digestion" represents all processes involved at the digestion plant including eventual pre- and post-treatment of the waste/digestate; "Collection" represents all operations of waste collection; "Composting" represents all processes involved at the composting plant including eventual pre- and post-treatment of the waste/compost; "Waste-to-Energy" represents all processes transforming the waste via thermal processing (this broad category thus includes incineration, bioenergy production, cement kiln, and co-combustion of waste in existing power plants); "Material recycling" represents all processes involved in sorting and reprocessing waste into new raw materials; "Material Substitution" represents savings from substitution of market materials and products (e.g. fertilisers); "Energy Substitution" represents savings from substitution of market electricity, heat, and other fuels; "Source Separation" represents all processes associated with separating waste at the place of generation; "UOL operations" represent all processes involved in application of organic fertilisers on-land (operations and emissions, e.g. leaching).

Area of Protection: Human well-being

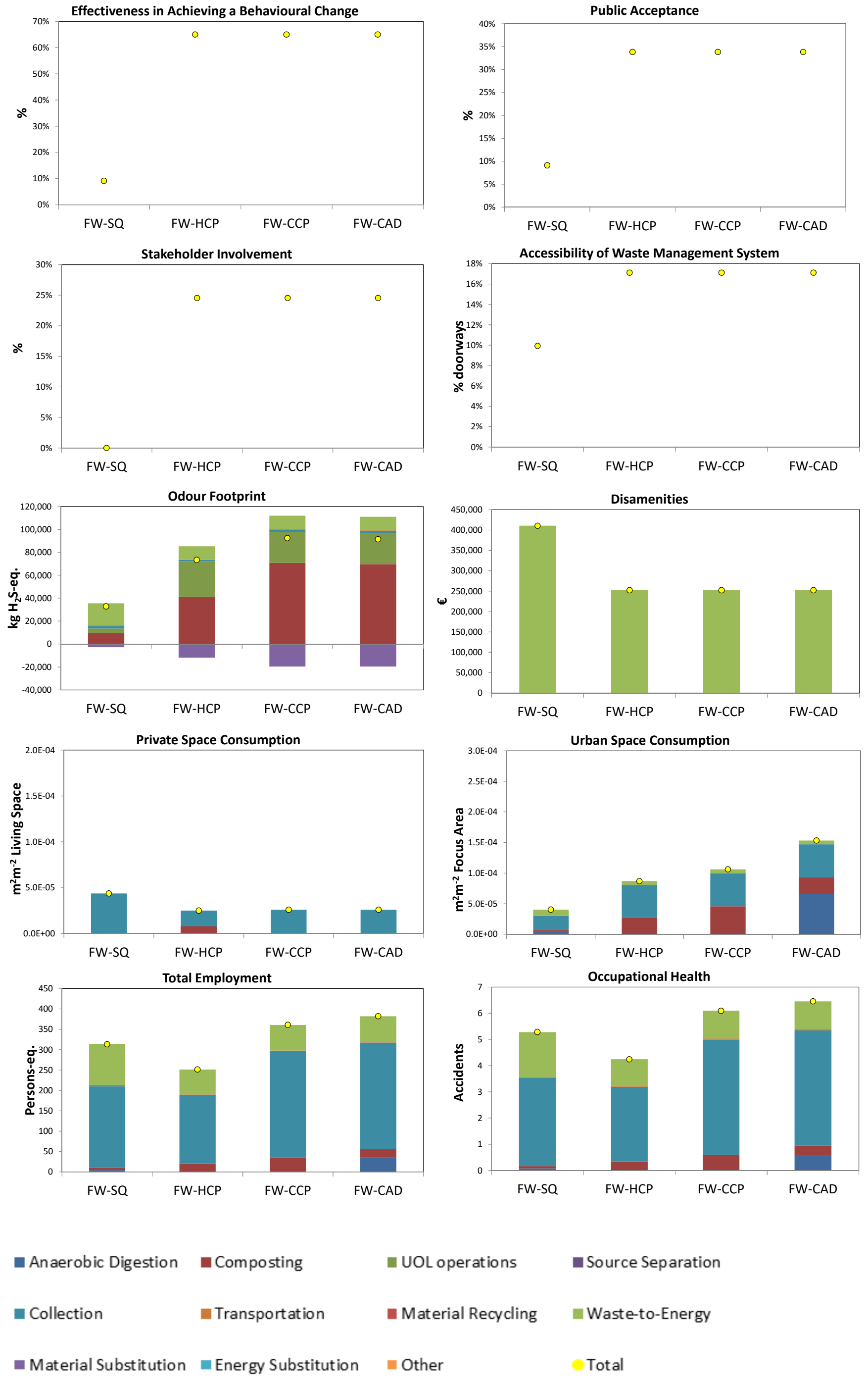

Figure A5. Breakdown of the impact for the categories falling under the AoP human well-being. The breakdown of the impact contributions is shown when relevant. With respect to the legends: “Anaerobic Digestion” represents all processes involved at the digestion plant including eventual pre- and post-treatment of the waste/digestate; ”Collection” represents all operations of waste collection; “Composting” represents all processes involved at the composting plant including eventual pre- and post-treatment of the waste/compost; “Waste-to-Energy” represents all processes transforming the waste via thermal processing (this broad category thus includes incineration, bioenergy production, cement kiln, and co-combustion of waste in existing power plants); “Material recycling” represents all processes involved in sorting and reprocessing waste into new raw materials; “Material Substitution” represents savings from substitution of market materials and products (e.g. fertilisers); “Energy Substitution” represents savings from substitution of market electricity, heat, and other fuels; “Source Separation” represents all processes associated with separating waste at the place of generation; “UOL operations” represent all processes involved in application of organic fertilisers on-land (operations and emissions, e.g. leaching).

Annex II - Contribution analysis – EIS for selected waste fractions

The following scenarios are assessed:

- Spent Coffee Ground to biofuels (SCG-pellet)
- Bread to beer (BR-beer)
- Bread to animal Feed (BR-feed)
- Bread redistribution (food rescue platform) (BR-redistr)
- Fruit & vegetables to animal feed (FV-feed)
- Fruit & vegetables redistribution (food rescue platform) (FV-redistr)

Area of Protection: human health

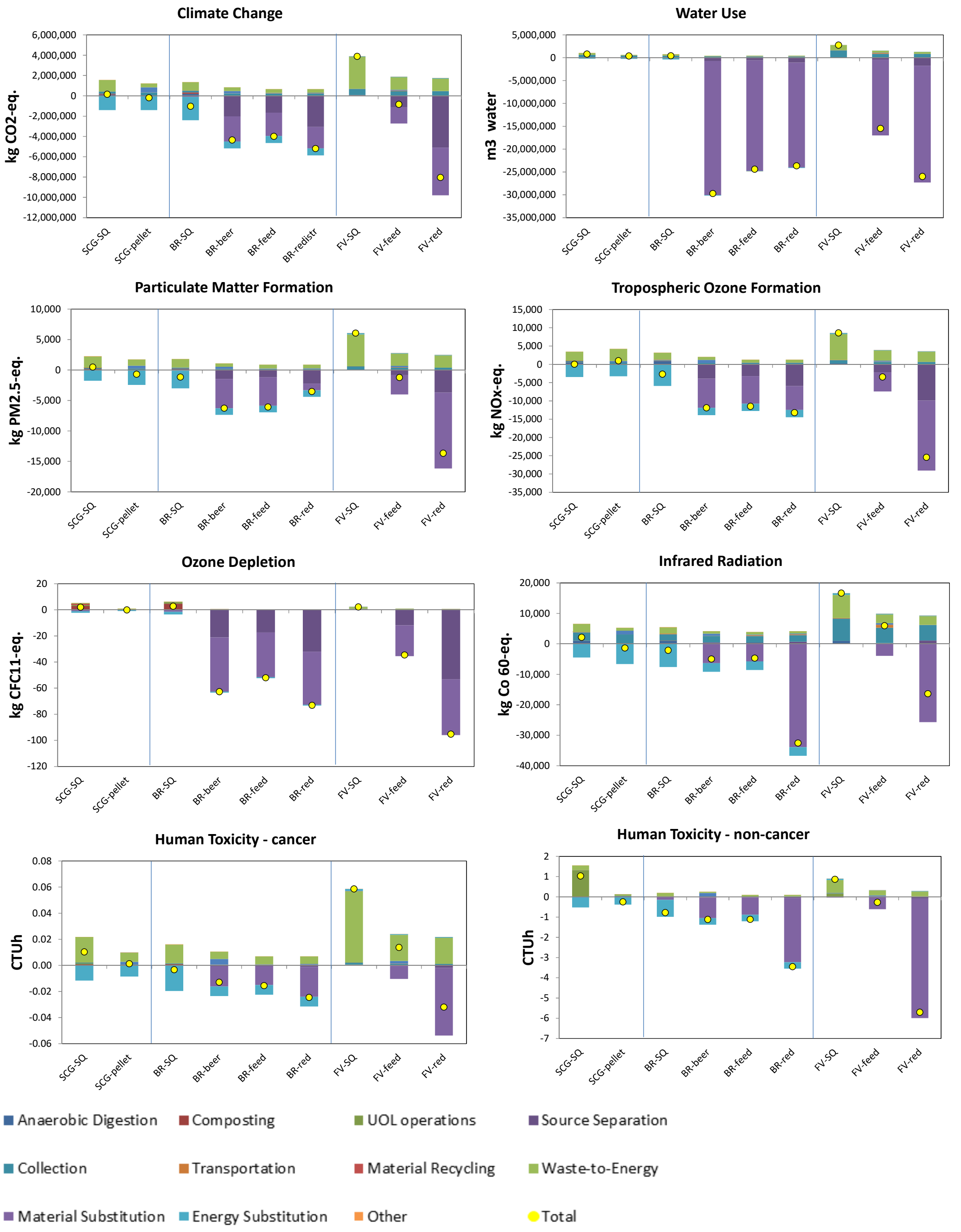

Figure A6. Breakdown of the impact for the categories falling under the AoP human health. With respect to the legends: "Anaerobic Digestion" represents all processes involved at the digestion plant including eventual pre- and post-treatment of the waste/digestate; "Collection" represents all operations of waste collection; "Composting" represents all processes involved at the composting plant including eventual pre- and post-treatment of the waste/compost; "Waste-to-Energy" represents all processes transforming the waste via thermal processing (this broad category thus includes incineration, bioenergy production, cement kiln, and co-combustion of waste in existing power plants); "Material recycling" represents all processes involved in sorting and reprocessing waste into new raw materials; "Material Substitution" represents savings from substitution of market materials and products (e.g. fertilisers); "Energy Substitution" represents savings from substitution of market electricity, heat, and other fuels; "Source Separation" represents all processes associated with separating waste at the place of generation; "UOL operations" represent all processes involved in application of organic fertilisers on-land (operations and emissions, e.g. leaching).

Area of Protection: Ecosystem health

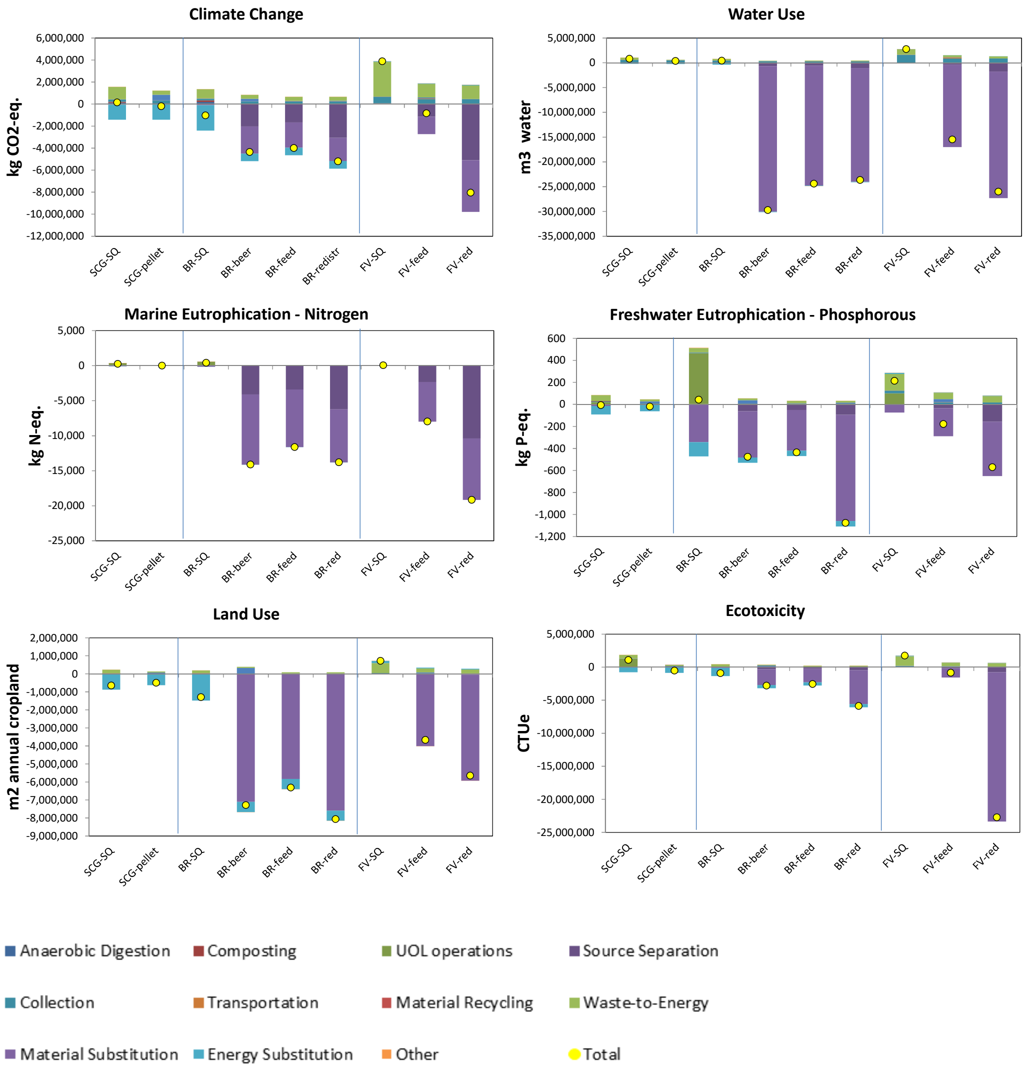

Figure A7. Breakdown of the impact for the categories falling under the AoP ecosystem health. With respect to the legends: "Anaerobic Digestion" represents all processes involved at the digestion plant including eventual pre- and post-treatment of the waste/digestate; "Collection" represents all operations of waste collection; "Composting" represents all processes involved at the composting plant including eventual pre- and post-treatment of the waste/compost; "Waste-to-Energy" represents all processes transforming the waste via thermal processing (this broad category thus includes incineration, bioenergy production, cement kiln, and co-combustion of waste in existing power plants); "Material recycling" represents all processes involved in sorting and reprocessing waste into new raw materials; "Material Substitution" represents savings from substitution of market materials and products (e.g. fertilisers); "Energy Substitution" represents savings from substitution of market electricity, heat, and other fuels; "Source Separation" represents all processes associated with separating waste at the place of generation; "UOL operations" represent all processes involved in application of organic fertilisers on-land (operations and emissions, e.g. leaching).

Area of Protection: Natural resources

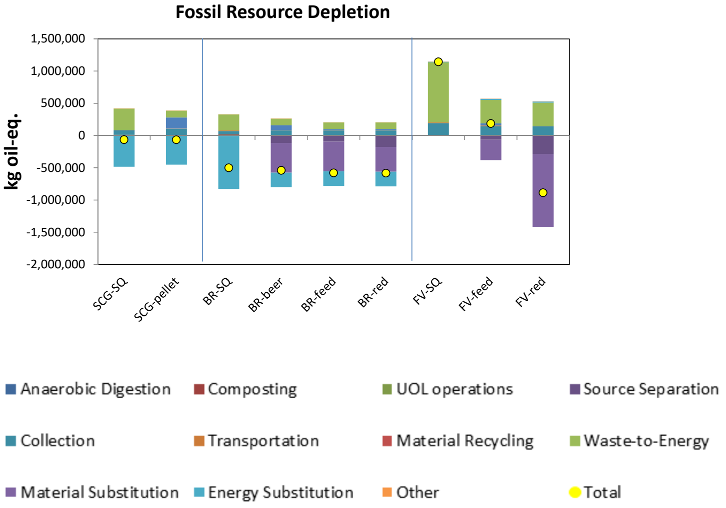

Figure A8. Breakdown of the impact for the categories falling under the AoP natural resources. With respect to the legends: "Anaerobic Digestion" represents all processes involved at the digestion plant including eventual pre- and post-treatment of the waste/digestate; "Collection" represents all operations of waste collection; "Composting" represents all processes involved at the composting plant including eventual pre- and post-treatment of the waste/compost; "Waste-to-Energy" represents all processes transforming the waste via thermal processing (this broad category thus includes incineration, bioenergy production, cement kiln, and co-combustion of waste in existing power plants); "Material recycling" represents all processes involved in sorting and reprocessing waste into new raw materials; "Material Substitution" represents savings from substitution of market materials and products (e.g. fertilisers); "Energy Substitution" represents savings from substitution of market electricity, heat, and other fuels; "Source Separation" represents all processes associated with separating waste at the place of generation; "UOL operations" represent all processes involved in application of organic fertilisers on-land (operations and emissions, e.g. leaching).

Area of Protection: Prosperity

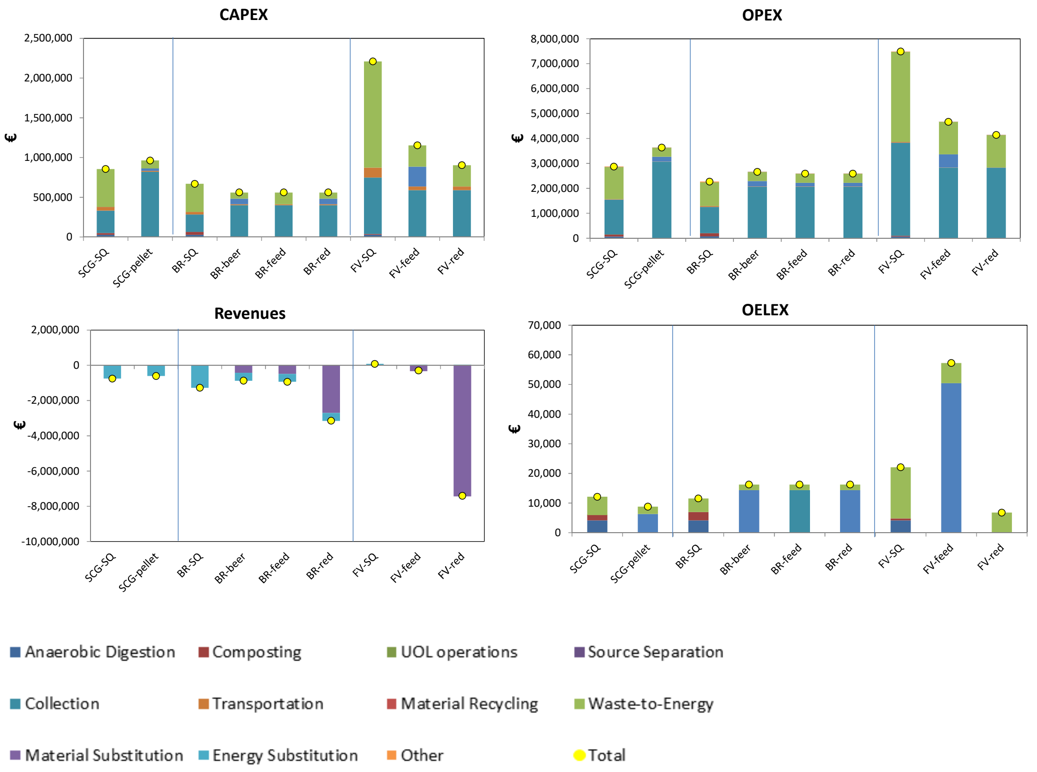

Figure A9. Breakdown of the impact for the categories falling under the AoP prosperity. With respect to the legends: "Anaerobic Digestion" represents all processes involved at the digestion plant including eventual pre- and post-treatment of the waste/digestate; "Collection" represents all operations of waste collection; "Composting" represents all processes involved at the composting plant including eventual pre- and post-treatment of the waste/compost; "Waste-to-Energy" represents all processes transforming the waste via thermal processing (this broad category thus includes incineration, bioenergy production, cement kiln, and co-combustion of waste in existing power plants); "Material recycling" represents all processes involved in sorting and reprocessing waste into new raw materials; "Material Substitution" represents savings from substitution of market materials and products (e.g. fertilisers); "Energy Substitution" represents savings from substitution of market electricity, heat, and other fuels; "Source Separation" represents all processes associated with separating waste at the place of generation; "UOL operations" represent all processes involved in application of organic fertilisers on-land (operations and emissions, e.g. leaching).

Area of Protection: Human well-being

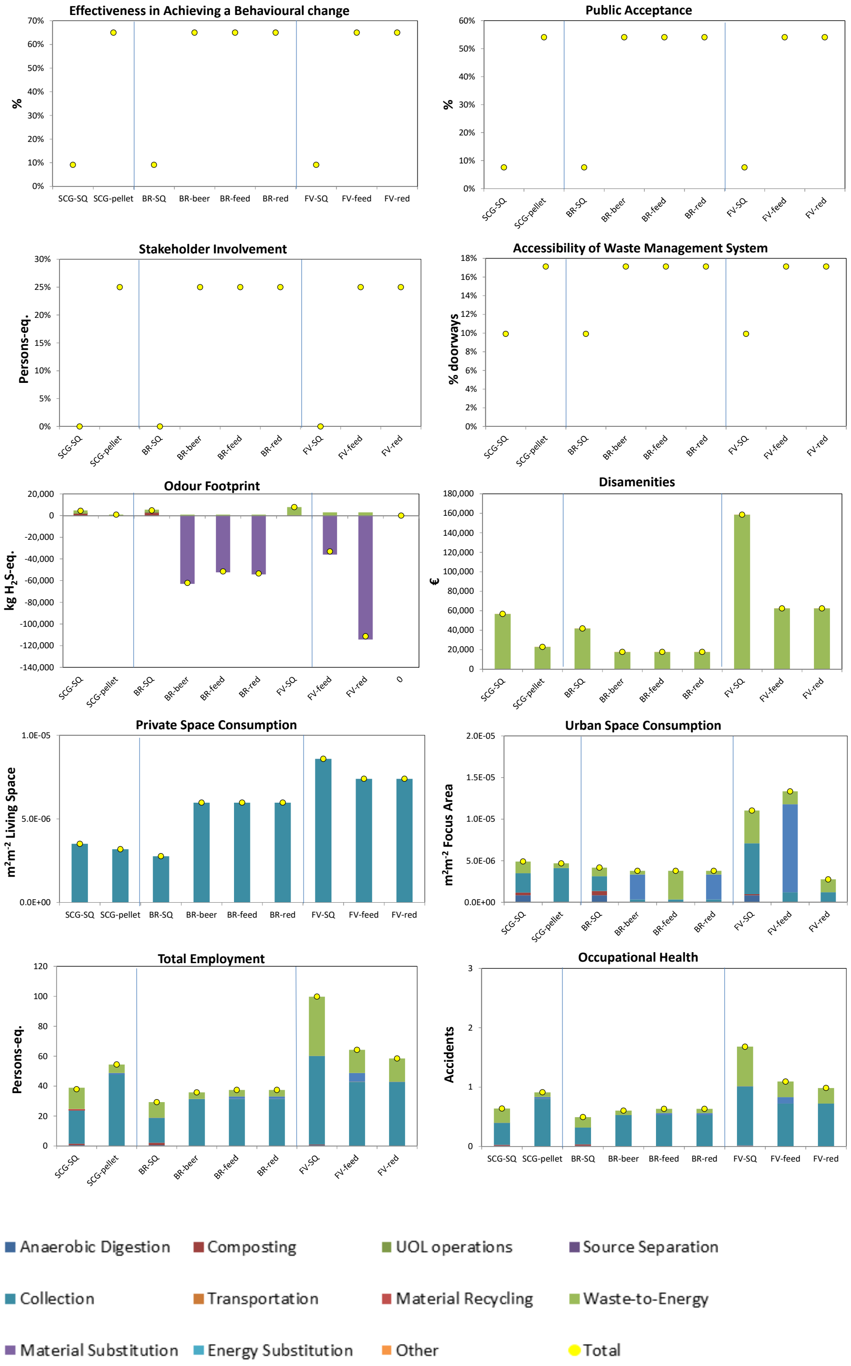

Figure A10. Breakdown of the impact for the categories falling under the AoP human well-being. The breakdown of the impact contributions is shown when relevant. With respect to the legends: "Anaerobic Digestion" represents all processes involved at the digestion plant including eventual pre- and post-treatment of the waste/digestate; "Collection" represents all operations of waste collection; "Composting" represents all processes involved at the composting plant including eventual pre- and post-treatment of the waste/compost; "Waste-to-Energy" represents all processes transforming the waste via thermal processing (this broad category thus includes incineration, bioenergy production, cement kiln, and co-combustion of waste in existing power plants); "Material recycling" represents all processes involved in sorting and reprocessing waste into new raw materials; "Material Substitution" represents savings from substitution of market materials and products (e.g. fertilisers); "Energy Substitution" represents savings from substitution of market electricity, heat, and other fuels; "Source Separation" represents all processes associated with separating waste at the place of generation; "UOL operations" represent all processes involved in application of organic fertilisers on-land (operations and emissions, e.g. leaching).

Annex III – Additional data

Table A1. Pelletization process from biomass/waste, based on literature.

Parameter	Unit	Pelletization process	Source
Annual usage rate	t/year	50,000	wood pellet factory production - RER
Life time plant	year	20	wood pellet factory production - RER
Land occupation	m2	20,000	https://en.wikipedia.org/wiki/Bio-bean
CAPEX			
Initial investment	€/facility	3,977,211	Proxy with Wood pellet plants (Value from 2006, reported to 2015 with inflation)
OPEX			
Annual Maintenance	% Capex	6.0	Proxy with Wood pellet plants (6-12%)
Annual Insurance	% Capex	1.5	As AD
Labor	man*h/t	0.850	25 persons (info online)
Water	kg/kg TS	3.1e-03	Wood pellet production RER
Electricity	kWh/kg TS	0.096	Wood pellet production RER
Heat	MJ/kg TS	3.45	Wood pellet production RER
Lubricant oil	kg/kg TS	8.4e-05	Wood pellet production RER
Packaging	kg/kg TS	0.0023	Wood pellet production RER
Starch (maize)	kg/kg TS	0.01	Wood pellet production RER

Table A2. Dry-feed production process based on literature.

Parameter	Unit	Dry-feed process	Source
Annual usage rate	t/year	36,500	(Salemdeeb *et al.*, 2017)
Life time plant	year	20	Eunomia 2002, Table11,p.52 - 20y
Land occupation	m2	50,000	Assumed as for wood pellet plant
CAPEX			
Initial investment	€/facility	8,313,138	(Salemdeeb *et al.*, 2017)
OPEX			
Annual Maintenance	% Capex	3.0	Assumed as for waste facilities
Annual Insurance	% Capex	1.5	Assumed as for waste facilities
Labour	man*h/t	0.6	
Feed	kg/t	-	(De Menna *et al.*, 2019) (Kitani, 2018)
Water	kg/t	2.5	(De Menna *et al.*, 2019) (Kitani, 2018)
Electricity	kWh/t	24.0	(De Menna *et al.*, 2019) (Kitani, 2018)
Heat	kWh/t	110.5	(De Menna *et al.*, 2019) (Kitani, 2018)
Diesel	l/t	-	(De Menna *et al.*, 2019) (Kitani, 2018)
NaOH	kg/t	1.2	(De Menna *et al.*, 2019) (Kitani, 2018)
H2SO4	kg/t	1.2	(De Menna *et al.*, 2019) (Kitani, 2018)