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Application of life cycle assessment to high-soil conditioner production from biowaste

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Abstract

The recent large-scale urbanization and industrialization resulted in an impressive growth of solid waste generation worldwide. Organic fraction generally constitutes a large fraction of municipal solid waste and its peculiar chemical properties open to various valorization strategies. On this purpose, life cycle assessment is applied to an innovative industrial system that processes 18 kt/y of agricultural and livestock waste into a high-quality soil conditioner. The high-quality soil conditioner production system consists of a series of processes, including anaerobic digestion and vermicomposting, allowing the generation of a peat-like material with high carbon content, porosity, and water-holding capacity. The presence of a photovoltaic plant and a cogeneration plant, fed with the biogas produced in the anaerobic digestion, makes the system entirely self-sufficient from the national grid and generating a surplus of electricity of 1177MWh/y. The high-quality soil conditioner showed better environmental performances in 15 out of 18 impact categories when compared to alternative scenarios. In particular, the high-quality soil conditioner and the related biowaste management resulted in a carbon saving of around 397 kg CO_2 eq/ton compared with a scenario involving the employment of peat in place of the high-quality soil conditioner and a traditional biowaste management, and 165 kg CO_2 eq/ton compared with a scenario where cogeneration is replaced by biomethane upgrading. This study demonstrates the possibility of using organic waste as an environmentally sustainable and renewable source for energy and carbon to soil conditioning.

KEYWORDS: *Biowaste valorization, Life cycle thinking, Agricultural waste, Circular economy, Vermicomposting*

1. Introduction

The large-scale urbanization, industrialization, and changing lifestyle of the city dwellers have resulted in several urgent environmental and socio-economic challenges including a virtuos and sustainable management of solid waste (Das et al., 2020), which is expected to reach 3.40 billion tons per year worldwide, or about +41% respect to the current situation (Singh et al., 2022). The biowaste fraction is estimated to account for more than 34% of the total solid waste generated in the EU-28 (Boccarossa et al., 2021) and to range from 53% to 64% in low to middle income nations (Ardolino et al., 2021). Furthermore, the uncontrolled degradation of the organic fraction is estimated to contribute for about 5% of global greenhouse gas (GHG) emissions (UNEP, 2022), with only 37% of the total organic waste annually generated currently undergoing resource recovery treatments (Ardolino and Arena, 2019). However, the potential future increase of biowaste may play a relevant role in the transition from a linear to a circular economy (CE) (Palazzo et al., 2023). If subjected to proper valorization, biowaste may be a key feedstock to reduce the dependency on non-renewable resources in anthropogenic systems (Rodríguez et al., 2019), due to its notable content of potential nutrients such as nitrogen (Amlinger et al., 2003), phosphorous (Mejia Duque Torres et al., 2023; Tonini et al., 2019), and carbon (Oviedo-Ocaña et al., 2023).

A safe and eco-oriented transformation of solid waste organic fraction into beneficial products is hence one of the main aims of resource recovery and recycling principles (Yadav and Garg, 2011). Some of the most promising management technologies are based on physical-chemical conversion approaches such as composting, vermicomposting (VC), and anaerobic digestion (AD), for the production of bio/organic fertilizers, nutrient sources for microbes, animal feed, biogas, and many others (Kiyasudeen et al., 2020). In the EU-28, in particular, the biogas contributes to more than 35% of the bioenergy generated from biomass sources (Rasapoor et al., 2020), and its production from AD plants increased from 93 to 187 TWh between 2008 and 2016 (Cesaro, 2021), with expectations to double it by 2030 (Kampman et al., 2016). In addition, the unprecedented European energy crisis due to the Russo-Ukrainian conflict further stressed the need to convert energy systems towards decarbonization strategies (Frilingou et al., 2023). Regarding the employed raw materials, to date the agricultural sector largely relies on peat to produce fertilizers and soil conditioners, with exploitation of peatlands being responsible for about 5% of the total annual GHG emission (Paoli et al., 2022; Virginia Gewin, 2020). For this reason, the European Commission has set a target for 30% reduction of the dependency on non-renewable resources in the fertilizer composition (Chojnacka et al., 2020). In this view, AD and VC are widely considered as two of the most preferred strategies to convert biowaste into valuable fertilizing products (Das et al., 2020). The main products of AD and VC comprise biogas and a peat-like material usable as soil conditioner (Kiyasudeen et al., 2020). AD is often applied under anaerobic conditions to process livestock manures, sludge derived by waste water treatments, and solid ligno-cellulosic waste into biogas (Achinas et al., 2020), an energy carrier with a key role for the ecological transition (Varling et al., 2023). On the other hand, VC consists of an aerobic and bio-oxidative process that involves the employment of earthworms to promote the mineralization of biomass and result in a valuable carbon-rich material, usually named "vermicompost" (Santos et al., 2022). The application of vermicompost on land is beneficial to soil properties such as physical texture, porosity, water-holding capacity, seed germination induction, high concentrations of humic and fulvic acids to a greater extent respect to traditional compost (Das et al., 2020). Further advantages of vermicompost relate to its capacity of reducing soil-borne plant pathogens and removing water-soluble metals (He et al., 2016). However, despite VC presents several advantages with respect to traditional management alternatives (e.g., simple traditional composting or dumping), the process and survival rate of earthworms in VC are particularly sensitive to certain operating conditions such as the carbon-nitrogen ratio of the feedstock (Huang et al., 2016), the presence of microplastics (Zhong et al., 2021), the operating temperature (Balachandar et al., 2021), earthworm species (Zziwa et al., 2021) and geometry and type of the reactor (Enebe and Erasmus, 2023). Regarding the latter parameter, VC reactors usually fall within two main categories: batch process/scale and continuous process/scale systems, with a general preference for continuous configurations (Enebe and Erasmus, 2023). Moreover, the VC process can be also negatively influenced by the presence of recalcitrant materials in the feedstock such as plastics used in agriculture or by inhibiting substances like salt, e.g. NaCl (Seesamut et al., 2022).

Although AD and VC have been widely investigated in the relevant literature (Bellitürk et al., 2023; Das et al., 2020; Ferraz Ramos et al., 2022; Goswami et al., 2013; Hanc et al., 2020; Kiyasudeen et al., 2020; Lim et al., 2016; Ruan et al., 2023; Yadav and Garg, 2011), also with the inclusion of assessment of their environmental implications in some cases (Deng et al., 2022; Komakech et al., 2016; Vicentin et al., 2021; Yasmin et al., 2022), the combination of AD and VC to co-production of biogas and a high-quality soil conditioner (HQ-SC) has not been explored yet, ultimately hindering a comprehensive evaluation of the potential waste management options, the related impacts, and achievable benefits from biowaste valorization and the CE. The latter point, in particular, aligns to the new CE action plan for the EU, which claims for a reliable environmental evaluation of products over their whole life cycle, from planning and design stages through end-of-life (EoL) management and final disposal. Life cycle approach should be always applied when an innovation is under study, since it enables comparison of alternative scenarios including potential direct and indirect impacts related to the whole product/process value chain (Pasciucco et al., 2022). To this aim, in this study we applied life cycle assessment (LCA) (ISO, 2006a, 2006b) to estimate the environmental performance of an operating industrial plant comprising a combination of AD and VC to agricultural and livestock waste (ALW) for the co-production of biogas and HQ-SC.

2. Materials and methods

According to the international ISO standards 14040:2006/Amd 1:2020 and 14044:2006/Amd 1:2017+Amd2:2020 (ISO, 2006a, 2006b), LCA is a strategic technique to identify and quantify the potential environmental impacts associated with a product, process or system throughout its life cycle. The common LCA framework (goal and scope definition, life cycle inventory – LCI, life cycle impact assessment – LCIA, and interpretation) applies well-regarded scientific mechanisms and characterization models to relate the LCI results to selected category indicators for a quantitative evaluation of the environmental impacts (LCIA). The interpretation, transversal to the previous three phases, ensures consistency between the aims of the study and its execution to recommendations.

2.1 Case study

The case study is based on a full scale production system (depicted in Figure 1), owned by the PANECO AMBIENTE s.r.l. (Paneco Ambiente S.r.l., 2022). The production system is located in the Piemonte region, northern Italy, serving local farms and breeders for ALW management. Often, the management of ALW may cause both economic and environmental issues at the local level, since the national regulation (Ministero dell'agricoltura e della sovranità alimentare e delle foreste, 2016) sets specific requirements for direct use of ALW on land such as soil quality and conditions, atmospheric temperatures and chemical compositions of the ALW residue. In addition, when the amount of raw ALW to be disposed exceeds the legislation limit (DM 5046 05/02/2016), it is common practice for farmers and breeders to rent neighboring soils and spread the ALW excess. Although complying with the relevant legislation, such ALW management implies, on one side, a worse fixation of carbon in soil (Vidal et al., 2020) and, consequently, higher carbon emissions over time. Moreover, this practice determines additional costs for farmers and breeders, and a growing competition with agriculture and plant cultivation.

As an alternative management strategy, the system implemented by PANECO AMBIENTE s.r.l. combines AD and VC to convert ALW into biogas for energy generation and HQ-SC of greater quality, stability and amendment capacity than raw ALW. Beyond HQ-SC, the installation of an in-situ photovoltaic plant (PV) and a co-generator fed with the biogas outflow, allows the system to be completely independent from external energy sources and to sell the electrical excess to the national grid. A biogas-to-biomethane (Btb) upgrading set up is also evaluated in this case study, as an alternative strategy to cogeneration. Overall, the system under scrutiny provides several advantages since: *i)* it constitutes an alternative to farmers to locally manage their waste with no need to rent supplemental land for spreading raw ALW; *ii)* it reduces the dependency on fossil-based fertilizers (especially peat) to provide nutrients to soil; *iii)* it enables the production of bioenergy from waste. In a broader context, the last point is also mainstreamed by UN sustainable development goals (Dada and Mbohwa, 2018), in goals #7 (affordable and clean energy), #12 (responsible consumption and production) and #13 (climate action). A detailed description of the system is provided in the following sections.

2.2 Goal and scope definition

The aim of the study is to estimate the environmental impacts associated with the conversion of ALW to HQ-SC (named "Baseline scenario" hereafter) and to compare the results with *i)* the replacement of energy cogeneration with biogas to biomethane upgrading (i.e., "Btb scenario"); and *ii)* a scenario modelling the extraction and processing of peat as a non-renewable commercial alternative, together with the AWL management previous to the development of the HQ-SC system (i.e., "Peat+TM scenario"). HQ-SC product is thought as an alternative to traditional peat and to propose an unconventional ALW management practice, able to valorize the carbon content of the residues and avoid the emissions associated to improper managements.

According to an economic breakdown of the company revenues from the valuable outputs, the production of HQ-SC results to be the main product of the system as it represents, at least, about the 65% of the annual revenues (Table ESI 1). Therefore, the functional unit (FU) was set at 1 ton of produced and packed HQ-SC, ready for the market. The study was performed following a *cradle-to-gate* approach, with the system boundaries including infrastructure and machineries, in-bound transportation, the production and supply of auxiliary materials, packaging materials, usage of the energy carriers (i.e., diesel and electricity) involved in the system, the emissions in the atmosphere from the core phase (i.e., production) and the on-site generation of the renewable energy. With the exception of the liquid digestate (LD) outflow (see section 2.1.1), on-site generated waste amounted to less than 1% so that it was excluded from the analysis in reason of cut-off criteria. The *"zero burden"* approach was applied to the raw ALW input, in consistency with previous studies (Arfelli et al., 2023; Ware and Power, 2016).

Lastly, system expansion was carried out to account in the modelling of the Baseline scenario and the Btb scenario for the functions related to the co-products (i.e., HQ-SC and electricity or HQ-SC and biomethane, respectively) and avoid allocation (ISO, 2006b).

2.3Life cycle inventory (LCI)

Data collection and model assumptions for the scenarios investigated are described below. For background information and secondary data, the reference database was ecoinvent 3.8 (Wernet et al., 2016a), while the software SimaPro 9.4 (PRé Consultants, 2022) was employed for modelling and calculations. A detailed description of the scenarios follows.

2.3.1 Baseline scenario

The LCI of the Baseline scenario was compiled with primary data provided by the company, covering the ALW inflow, balances of materials and energy (both purchased and self-produced) involved in the production site. The selected reference year is 2021, being this representative for the contemporary production chain in the case study.

Errore. L'origine riferimento non è stata trovata. depicts the system boundaries and main stages covered by the model, namely: (I) in bound transportation and discharge, (II) AD, (III) solid liquid-separation, (IV) vermicomposting, (V) screening and (VI) packaging. The energy supplied to the system is sourced from either domestic PV, the cogeneration plant and fossil carriers (e.g., diesel). The PV production amounted at 460 MWh_e/y, of which 46% (212 MWh_e/y) is self-consumed, while the remaining amount (248 MWh_e/y) is entirely sold to the national grid. The latter flow was given a credit in the LCA model for avoiding the production of an equivalent amount of electricity generated from the Italian grid mix in 2021 (IEA, 2022a). The energy derived by diesel combustion resulted in 104 MWh_t/y, while the energy produced by the cogeneration plant was not directly measured, but estimated according to the annual biogas production and the low heating value of biogas (2.9 kWh/m^3) indicated in the ecoinvent record used as the reference. A bottom-up approach was then followed to estimate the energy consumption in each process and considering the annual energy input to the system, the nominal power of the machineries, and the cumulative time of employment in the reference year. More details are reported in Table ESI 2.

The total amount of the ALW inflow (i.e., 3 kt/y of agricultural waste and 15 kt/y of livestock waste respectively) was supplied from several local farmers and breeders to the company through diesel-fueled freight lorries, and covering an average distance of 15 km (Stage I, **Errore. L'origine riferimento non è stata trovata.**). AD (Stage II, **Errore. L'origine riferimento non è stata trovata.**) is performed at 40°C for 2 months and enables the production of 17 kt/y of digestate and 1 E+06 m^3/y of biogas (assuming an average productivity of 3500m^3/day in a period of 300 days and 70 m^3 biogas/t of ALW). The biogas is then conveyed into the cogeneration plant, for heat and electricity production. According to Odeh (2017), 1% of the biogenic methane generated during the AD is assumed to be lost in the atmosphere. Part of the heat by the AD is self-consumed for maintaining the required temperature in the digestor (40°C), while the heat excess is dissipated into the atmosphere. The electricity surplus (estimated at 1528 MWh_e/y) is instead sold to the national grid and considered in the model as an avoided product.

In the separation stage (Stage III, **Errore. L'origine riferimento non è stata trovata.**), the solid and liquid fractions of the digestate are separated into two streams. The solid-liquid separation step requires a continuous handling by a mechanical shovel, with a related diesel and electricity consumption estimated, respectively, in 58 MWh_t/y and 20 MWh_e/y. The LD is handed back to the waste suppliers and spreaded on soils, complying with the emission limits for pollutants to air and soil set by the law (European Union, 2019). LD and the properties of local soils may both increase the nutrient enrichment in the soil (Black et al., 2017), but they might be also responsible for eventual emission of pollutants not able to be fixed. Due to a lack of data related to the chemical composition of LD, the related emissions occurring from its Use on Land (UOL) are estimated by assuming the same characterization factors as those applied for UOL of raw ALW, in an extremely conservative approach. More details are available in Table ESI 3.

In contrast, the solid fraction is continuously fed to the VC process (Stage IV, **Errore. L'origine riferimento non è stata trovata.**) where it remains, on average, for 12 months. The worm species employed for VC is *Eusenia fetida*, in reason of their natural ability to mineralize organic waste, relatively short life cycle and reasonable tolerance to a wide range of atmospheric conditions (Dominguez and Edwards, 2011), and the presence of recalcitrant or inhibiting substances in the feedstock (Seesamut et al., 2022). The best process rate occurs at an operating temperature of 20-25°C and 80-85% of moisture content (Singh et al., 2018). The periodic handling of the solid digestate by mechanical shovel is also required (12 MWh/y of diesel). According to the relevant literature, the removal of earthworms from vermicompost can be managed, relatively easily, by means of light, vertical or sideways separation stages (Lin et al., 2021). After separation, the vermicompost is then subjected to screening (Stage V, **Errore. L'origine riferimento non è stata trovata.**) through an electric rotary screen (6 MWh/y). The final product (i.e., HQ-SC) is moved to an adjacent site by a bucket equipped tractor, and then packed in bags with a capacity of 5, 15 or 22 kg HQ-SC for the market. The overall diesel and electricity amount consumed is 11 m^3/y and 837 kWh_t/y, respectively (Stage VI, **Errore. L'origine riferimento non è stata trovata.**).

The LCI related to transportation, cogeneration process, electricity, AD, diesel combustion and supply, and packaging material were retrieved from ecoinvent 3.8 (Wernet et al., 2016b) and complemented with primary data from the company. In Table ESI 4 a list of proxy processes drawn by ecoinvent with further details and assumptions are also reported.

2.3.2 Peat+TM scenario

Peat is the youngest and among the least altered combustible rocks. Compared with similar fossil fuels, it is characterized by the lowest content of fixed carbon and the highest content of volatile constituents (Grumpelt, 2000). Thanks to its properties (i.e., high natural moisture content, high compressibility and water-holding capacity, low specific gravity, low bearing capacity, and mediumto-low permeability), peat is widely used as soil conditioner (Wong Sing, 2008) and, for this reason, in this study was set as a commercial alternative to HQ-SC for comparative purposes. In Peat+TM scenario, the modelling covered peat extraction, processing, supply stages (Wernet et al., 2016b) and collection; and UOL emissions of the ALW. Due to the unavailability of primary data related to the behavior of ALW spreaded to soil, the elemental emissions to soil and atmosphere of the raw feedstock were estimated according to Hamelin et al. (2014) and Tambone et al. (2017). More details about the emissions' modelling are reported in Table ESI 3.

2.3.3 Biogas to Biomethane (Btb)

Biomethane is a renewable substitute of natural gas, and suitable for a variety of uses such as cooking, heating, shipping and transportation (Ardolino and Arena, 2019). In Europe, Btb represents a well-established technology to upgrade biogas from AD (European Biogas Association, 2021) and, for this reason, it was selected as a promising alternative to the Baseline scenario. Therefore, the main difference between the two scenarios is the substitution of the cogeneration unit with a Btb upgrading unit in the Btb scenario. Since the generated biomethane is then pressurized and distributed to the national pipeline network for natural gas, an LCA credit was given the biomethane for avoiding the production of natural gas from fossil sources (**Errore. L'origine riferimento non è stata trovata.**). The assumption of shipping biomethane to the national grid is consistent with national data, which attest that 98% of 1.5 million TJ of natural gas demanded in Italy in 2020 was employed for energy purposes (IEA, 2022b). The inventories of the Btb was compiled according to literature dataset (Ardolino et al., 2021), from which the membrane separation resulted to be the most sustainable solution to perform the upgrading and, for this reason, modelled in the Btb scenario. In this scenario, since the upgrading phase does not allow a direct heat production (i.e., for instance, through cogeneration), the amount of heat fed to AD was estimated at 0.81 MJ/m^3 of produced biogas based on proxy record in the ecoinvent database (Wernet et al., 2016b).

2.4 LCIA

The LCIA phase consists in a quantitative determination of the potential environmental impacts resulting from the system under scrutiny (ISO, 2006a). To this aim, environmental mechanisms and cause-effect characterization models are applied to relate the LCI results to impact category indicators. The ReCiPe 2016 method (Huijbregts et al., 2017) was adopted for the evaluation. The hierarchical perspective was set as the default perspective, with this being preferred choice in previous LCA application to biowaste valorization processes (Brancoli et al., 2020; Chazirakis et al., 2023; Oviedo-Ocaña et al., 2023). In the LCIA phase, the environmental performance of the existing system (i.e., Baseline) were compared with those resulting from Peat+TM and Btb scenarios. In addition, the LCIA allowed the identification of the main contributing processes to the observed impacts, which were further analyzed in sensitivity analysis as following described.

2.5 Sensitivity and uncertainty analysis

The outcomes of the contribution analysis were taken as reference to elaborate the sensitivity analysis, performed to test the robustness of the model created and enable identification and quantification of the influence of the main exogeneous parameters onto the environmental impact of the entire system (Goedkoop M., 2020).

Uncertainty evaluation was performed at midpoint level. In general, as discussed above, the LCA model for the system under scrutiny was entered with primary data provided by the company owner of the system. As such, data of the Baseline scenario can be considered very reliable and fulfilling the highest scores for data quality criteria commonly applied in LCA such as, for instance, geographical, temporal, and technological representativeness. The same considerations were assumed also for the Btb scenario, with the exception of the Btb unit, for which literature data (Ardolino et al., 2021) were taken as reference for uncertainty assigned by means of the pedigree matrix (Weidema and Wesnæs, 1996). Higher uncertainty scores were attributed to the UOL of ALW and LD emissions. More details on pedigree matrix and Monte Carlo results are reported in Table ESI 5 and Table ESI 6a, 6b, 6c.

3. Results

3.1 LCIA

The LCIA comparison between Baseline, Btb and Peat+TM scenarios, using ReCiPe 2016, concerning the Global Warming Potential (GWP) and Particulate Matter Formation Potential (PMFP) categories are displayed in **Errore. L'origine riferimento non è stata trovata.**. GWP and PMFP have been selected for graphic visualization, since they allow a comparison between cogeneration and biomethane upgrading processes. Moreover, these categories have been identified, under the hierarchical perspective, as those having the greatest influence on the single score results in ReCiPe 2016 (Arfelli et al., 2022) and other LCIA methods (Bulle et al., 2019). From the outcomes, it resulted that the highest impacts are related to the UOL of the LD (for Baseline and Btb scenarios) and raw ALW (for Peat+TM scenario). More specifically, the UOL of raw ALW was estimated at 883.7 kg CO_2 eq/FU, while the UOL of dumped LD amounted to 625.5 kg CO_2 eq/FU. Compared to total impact for GWP, the UOL of LD contributes for 87% and 75% in the Baseline and Btb scenarios respectively, while the UOL of AWL achieves 98.5% in the Peat+TM scenario. However, as early discussed, the model created for UOL of LD assumed the same characterization factors as those for UOL of AWL due to lack of information. This assumption is dictated by a conservative approach that very likely overestimates the release of emissions from UOL of LD, and ultimately it boils down the difference between UOL of LD and AWL to the higher amount of AWL to be disposed of inventoried in the in Peat+TM scenario. Therefore, to enable a highly detailed process contribution between the investigated waste management alternatives, in Figure 3 only the net emission to GWP (Figure 3a) and PMF (Figure 3b) is displayed for Peat+TM, with the impact of UOL of LD being subtracted to all the scenarios. Normalized results related to all the investigated categories are reported in the Figure ESI 7. Particularly, the Baseline scenario results to be the less impacting one for 14 out of the 18 categories. In contrast, the Btb scenario and Peat+TM scenario, respectively, rank as the most harmfull pathways for 11/18 and 7/18 categories.

Considering the GWP category (**Errore. L'origine riferimento non è stata trovata.**a), the Baseline scenario demonstrated to be the best solution, showing a GWP of -125.4 kg CO_2 eq/FU, followed by Btb scenario (39.2 kg of CO_2 eq/FU) and Peat+TM scenario (271.5 kg CO_2 eq/FU). A similar trend is also showed for PMFP (**Errore. L'origine riferimento non è stata trovata.**b), where the HQ-SC produced in the Baseline scenario still ranks as the best alternative (-96.0 g PM 2.5 eq /FU), followed by Btb (50.9 g PM 2.5 eq /FU) and Peat+TM (771.3 g PM 2.5 eq /FU). The main contribution to the overall environmental preference for the Baseline scenario results from the credit given to i) renewable electricity production delivered by PV, and ii) the cogeneration plant for avoiding the generation of an equivalent amount of electricity from the national grid. The influence of the electricity mix on the environmental impacts is discussed in 3.3.

Then, a Monte Carlo simulation with 10,000 runs was carried out to determine how the intrinsic variability of the parameters and the quality of the data used in the modelling may affect the outcomes. The uncertainty analysis confirmed the overall findings, attributing a net preference to the Baseline scenario for both GWP and PMFP.

3.3 Contribution analysis

The contribution analysis related to Baseline and BtB scenarios is depicted in **Errore. L'origine riferimento non è stata trovata.**, again by excluding the emissions occurring after the UOL f the LD. In the case of GWP, AD represents the main contributing stage to the impact quantified for the Baseline (about 54% of the total impact) and Btb (46%) scenarios. In the Baseline scenario, AD step is followed by transportation (17%), diesel combustion and supply (13%), the packing phase (12%) and the cogeneration stage (5%). In the case of Btb scenario, the biomethane upgrading stage ranks as the second main impacting process (35%), followed by transport (7%), diesel (6%) and packing phase (5%).

In contrast, PMFP showed a different trend, since for this category the main impacting processes resulted to be the diesel supply and its consumption in the Baseline scenario, while in Btb the main burdens still occur in AD. Concerning the whole spectrum of impact categories, AD resulted the main impacting process only for 3 of the 18 categories (i.e., GWP; Land Occupation Potential, LOP and Fossil Resources Scarcity, FFP) in the Baseline scenario and for 10/18 in the Btb (namely, GWP; Ozone Depletion Potential, ODP, Ionizing Radiation Potential, IRP; PMFP; Terrestrial Acidification Potential, TAP; Freshwater Ecotoxicity Potential, FETP; Marine Ecotoxicity Potential, METP; Human Carcinogenic Toxicity Potential, HTPc; LOP, and Mineral Resources Scarcity, SOP). Regarding the remaining contributing processes for the Baseline scenario, diesel ranked as the main contributor to Ozone Formation Potential-Human Health (HOFP), PMFP, Ozone Formation Potential-Ecosystem (EOFP), TAP, and Human non-Carcinogenic Toxicity Potential (HTPnc), while transportation for Terrestrial Ecotoxicity Potential (TETP) and METP. In the Btb scenario, biomethane upgrading is the main contributor to Freshwater Eutrophication Potential (FEP), Marine Eutrophication Potential (MEP), FFP, and Water Consumption Potential (WCP), with transportation mainly for TETP. In case of Peat+TM, instead, the impacts are attributed for about 76% of the total to extraction operations, with the rest being attributed to transportation. The complete contribution analysis referred to all the 18 environmental categories examined is reported in Table ESI 8.

3.4 Sensitivity analysis

For sensitivity analysis, the effects of two main parameters were investigated, which include: *i)* the distance covered by local supplier of ALW from the farm to the plant, and ii) the percentage of fossil electricity in the national mix. Accordingly, in sensitivity scenario *i)*, the kilometers of ALW local suppliers was re-calculated ($GWP_{\mathrm{system}} = 0$) to determine the minimum average distance at which the system can be considered carbon neutral (i.e., $GWP_{\mathrm{system}} = 0$), see section 3.4.1). In the sensitivity scenario *ii)*, the upper bound market share of fossil electricity in the national mix (≅49%) was reassessed to determine the break-event point for fossil percentage that makes the system suitable for the neutrality (3.4.2). Also in this case the emissions associated to raw ALW and LD UOL were excluded.

3.4.1 Influence of local suppliers

Regarding the Baseline scenario, the in-bound transportation phase of ALW, calculated assuming an average distance of 15 km between its source and the plant, resulted to contribute for about 17% of the direct GHG emissions. To estimate the theoretical minimum distance that could enable the achievement of carbon neutrality, we first computed the total potential contribution to GWP resulting from system as function of the relative terms for cogenerator (GWP_{cogen}), PV (GWP_{PV}), packaging (GWP_{pack}), AD (GWP_{AD}) and diesel (GWP_{diesel}), but excluding the transportation term (GWP_{T}), as described in ESI 9, Eq. 1.

Second, the difference between the GWP of the Baseline scenario in a carbon neutral state (i.e., $GWP_{system} = 0$, or $\mathrm{GWP}_{\mathrm{system,GWP=0}}$) and $GWP_{system(ex,T)}$ calculated from Eq. 1 (ESI 9) (and resulting in 109.9 kg CO_2 eq/t) was used to estimate the theoretical break even distance for transportation. This was made by disaggregating GWP_T by the main explanatory variables. Third, knowing the value of $GWP_{\mathrm{system}(ex,T)}$ (calculated with Second, the difference between the GWP of the Baseline scenario in a carbon neutral state (i.e., $GWP_{system} = 0$, or $\mathrm{GWP}_{\mathrm{system,GWP=0}}$) and $GWP_{system(ex,T)}$ calculated from Eq. 1 (ESI 9) (and resulting in 109.9 kg CO_2 eq/t) was used to estimate the theoretical break even distance for transportation. This was made by disaggregating GWP_T by the main explanatory variables.) and fixing GWP_{system} equal to 0 ($\mathrm{GWP}_{system,GWP=0}$) to fulfill the carbon neutrality as the target condition, the theoretical break-even has resulted in about 211 km (ESI 9, Eq. 2).

3.4.2 Influence of fossil electricity in the national mix

To establish the limit fossil percentage in the national mix, Eq. 3 (ESI 10) was applied. The national grid mix is constituted for 49% by fossil sources (i.e., 40% natural gas, 6% coal, and 3% oil) and for 51% by renewable sources including biofuels (5%), hydroelectric (16%), wind (7%), solar (8%), waste (2%), nuclear (12%) and geothermal (2%) (IEA, 2022a). However, the fossil fraction is responsible for about the 94% of the total GHG emissions of the Italian mix. Accordingly,

GWP_{credit} is calculated by summing the GWP from renewables (GWP_{ren}) and that from fossil sources (GWP_{fossil}). Then, the single contributions of each fossil source was evaluated by multiplying the amount of electricity produced from the specific source in the national mix (El), by the GWP of each energy carrier used (e.g., natural gas GWP, $GWP_{NG,kwh} = 468\ g\ CO_2\ eq/kWh$) of a specific source (ESI 10, Eq. 4). Scaling the percentages of the three fossil sources composing the non-renewable fraction of the mix onto 1, it resulted that 1 kWh from fossil sources (kWh_{fossil}) derives for 84% from natural gas electricity, for 10% from coal and for 6% from oil. From which, an average impact of 1 kWh_{fossil} can be estimated by the Eq. 5, where $El(\%)$ represents the percentage of the carrier contribution from a source (e.g., $El_{NG}(\%) = 0.84$).

The same calculation was followed for the average GWP from renewable sources ($GWP_{ren,kwh}$), obtaining a value of 0.039 kg CO_2 eq/kWh. For the Baseline scenario, Eq. 6 (ESI 10) is accordingly defined. Setting GWP_{system} = 0, the electricity fraction deriving from fossil resources in a condition of carbon neutrality ($El_{fossil,GWP=0}$) can be calculated according to Eq. 7 (ESI 10).

The estimated amount of $El_{fossil,GWP=0}$ allows the calculation of the complementary amount of electricity deriving from renewables in the mix ($El_{ren,GWP=0}$) with Eq. 8 (ESI 10).

In this way, it is possible to state that the system is considered sustainable ($GWP_{system}=0$) until the fossil fraction of the national electricity mix is higher than the 17%.

4. Discussion

In the case study, the results confirmed that a properly management of AD+VD for biowaste treatment would represent a promising and environmentally preferable alternative to the traditional management of ALW. Transforming the ALW from waste to resource as achieved in the examined system, indeed, showed that direct and indirect GHGs and particulate matter emissions of the Baseline scenario, although the emissions occurring from UOL of LD make an exception as they are not avoidable at today conditions, are offset by the avoided energy production. This allows the output of a product (HQ-SC) with net-avoided impacts for GWP, ODP, IRP, HOFP, PMFP, EOFP, TAP, FEP, MEP, FETP, METP, HTPc, LOP, SOP, FFP and WCP categories. The notable impacts associated to the UOL of ALW and LD imply the need of focusing on both policies and research that can valorize the LD fraction, preventing the release of potentially impacting emissions into the atmosphere. Future studies should be also aimed at investigating the chemical composition of LD in order to estimate waste-specific characterization factors for emissions. Concerning the Btb scenario, it demonstrated to be competitive, although less environmentally preferable than the Baseline (with the only exception of FFP category). The main reason is that, notwithstanding the avoided production of natural gas achievable by biomethane recovery, which mitigates the impacts associated to biofuel upgrading, the conversion of biogas into methane requires supplemental heat inputs that worsens the overall environmental performance of this scenario. Despite not being the most preferable pathway among those investigated here, Btb might benefit from higher economic feasibility, as the selling price of electricity to grid is around 0.2 €/kWh, which is quite lower than that of biomethane to grid (estimated to be 13.5 €/kWh + tradable certificates based on the quota obligation for fossil fuel traders contribution or *Certificati di Immissione in Consumo*) (MISE, 2018). The economic advantage may be also enforced by the incentives introduced in some European countries including Italy (Pasciucco et al., 2023). For both the Baseline and Btb scenarios, the credit associated to the renewable energy produced by PV allowed a net impact reduction for all the 18 examined categories. In particular, in the Baseline scenario, the PV plant conveys 88 kWh/FU to the system and 103 kWh/FU distributed to the national grid. If the PV was not installed in the system (the diagram of the configuration which excludes the presence of the PV is depicted in Figure ESI 11), the credit associated to electrical energy recovery would have been replaced by that attributed to the cogeneration plant, ultimately reducing the avoided impacts from PV and those from cogeneration to 548.6 kWh/FU. These results confirm that the main advantage associated to the credit of electricity is attributed to the cogeneration plant, which allows an overall net-negative impact of the system (Figure ESI 12).

This outcome highlights the essential role of renewable electricity generation and consumption to achieve an overall environmental sustainability of the Baseline system. Clearly, the higher the market share of fossil sources in the national mix, the greater is the credit for avoiding fossil GHG emissions. The sensitivity analysis quantified in about 211 km the average distance limit for ALW suppliers at the current operating conditions (e.g., truck types, fuel types, etc.), emphasizing the role of local ALW suppliers in the overall sustainability of the system. On one hand, this finding highlights the importance of a local ALW supply network to approach a carbon negative or, at least, a carbon neutral system. On the other hand, it implies a potential for expanding the existing ALW supply network as the current average distance covered by local farmers and breeders amounts to "only" 15 km. The analyzed system could be also implemented in areas where similar amounts of ALW must be properly managed at EoL. The sensitivity analysis has also highlighted an apparent conundrum: the overall system's GWP performance tend to improve with increase of the share of the fossil fraction used in the national mix. About 50% of the electricity consumed in Italy are fossil-based, which corresponds to about 94% of the total carbon intensity (IEA, 2022a). According to the EU regulation 1999/2018 (EU, 2018), the percentage of renewable sources within the European electricity mixes will gradually increase with a consequent reduction of the theoretical benefits related to the avoided production from the grid. In the specific case, the GWP of the Baseline scenario demonstrated to be equal to 0 at a reduction of the fossil percentage in the mix from 50% to 17%. However, an overaching LCA method could reveal an increasing beneficial trend in terms of avoided extraction of metal resources such as critical materials used in the ecological transition (e.g., wind, electric vehicles, etc.). In addition, further technological developments could be considered to achieve a systemic and overarching improvement all over the supply chain, as exemplified by reduced carbon-intensity building blocks synthetized using renewable energy sources for reducing the potential burdens of chemical products (Cucciniello et al., 2023). In particular, the advantages associated to the coupling of AD and VC technologies might be further improved by working on operating conditions such as temperature, moisture, pH control, and the reactor type employed in the two phases. Further improvements in this direction could enhance the quality of the outgoing product, making it even more competitive in the market, but they could also reduce the generation of byproducts (i.e., LD) or to increase biogas production, positively impacting the energy balance.

About the HQ-SC produced, the expected benefits align to the principles of CE, including waste and pollution minimization, reduction of disposed biowaste; achievement of material circularity in product and material cycles; preservation and regeneration of natural ecosystems through soil amendment. In addition, the total independency of the system from external energy suppliers is a furher advantage, especially now, in Europe, because of the dramatic crisis of the energy sector (Frilingou et al., 2023), in part due to the still-standing (at the time of writing) Russian-Ukraine (Nerlinger and Utz, 2022), but also to the European policies against nuclear energy (Nam et al., 2021). Moreover, the biogas produced through the Baseline scenario is not in competition with food crops, making its generation and utilization more socially and ethically preferable than the first-generation of biofuels (Patterson et al., 2011), peat extraction and utilization, or raw ALW landfarming. One drawback might be the limitation to which biofuels (among which biogas) will be subjected from 2035. However, while a ban will be enforced for road vehicles (European Parliament, 2022), no restrictions related to residential or industrial markets are instead expected.

5. Conclusions

In this study, the sustainability of a local system producing high quality soil conditioner and biogas from biowaste have been analyzed by means of LCA. This quantitative assessment framework enabled the evaluation of the environmental impacts associated to different configurations implemented in this system. From the outcomes, some clear patterns can be summarized as follows. First, the potential emissions resulting from the UOL of unprocessed biowaste, as well as liquid digestate, can be significant in absolute terms and be also responsible for the largest contributon to the overall environmental performance of organic waste management practices and, as such, the development of techniques and technologies aiming at preventiving and reducing those emissions is highly recommended. Second, the Baseline configuration (cogeneration plant plus the photovoltaic system) is the less impacting solution among those investigated, while the upgrading of biogas to biomethane demonstrated to be competitive, but less environmentally preferable than the Baseline scenario. Third, the credit and thus the advantages of the system on the combustion-related categories are dependent on the primary electricity sources used in the national grid mix. Lastly, the agricultural and livestock suppliers must be located into neighborhood areas and possibly within a radious of approximately 200 km to achieve ideal carbon neutrality. The results provide more in-depth understanding of the implications associated to the vermicomposting and anaerobic digestion management of biowaste. More broadly, LCA confirmed to be a fundamental metholdogy for system-thinking approaches, which may ultimately support decision-makers and local communities for planning near- and long-term strategies aimed at mitigating anthropogenic burdens on the ecosystem.

Table of acronyms

AD	Anaerobic digestion	LCA	Life cycle assessment
ALW	Agricultural and livestock waste	LCI	Life cycle inventory
BtB	Biogas to Biomethane	LCIA	Life cycle impact assessment
CE	Circular economy	LD	Liquid digestate
EOFP	Ozone formation potential (ecosystem)	LOP	Land use occupation
EoL	End of life	MEP	Marine eutrophication potential
FEP	Freshwater eutrophication potential	METP	Marine ecotoxicity potential
FETP	Freshwater ecotoxicity potential	ODP	Ozone depletion potential
FFP	Fossil resources scarcity	Peat + TM	Peat + Traditional Management
FU	Functional unit	PV	Photovoltaic plant
GHG	Green house gasses	SOP	Mineral resources scarcity
GWP	Global warming Potential	TAP	Terrestrail acidification potential
HOFP	Ozone formation potential (human health)	TETP	Terrestrial ecotoxicity potential
HQ-SC	High quality soil conditioner	UOL	Use On Land
HTPc	Human carcinogenic toxicity potential	VC	Vermicomposting
HTPnc	Human non carcinogenic toxicity potential	WCP	Water consumption potential
IRP	Ionizing radiation potential		

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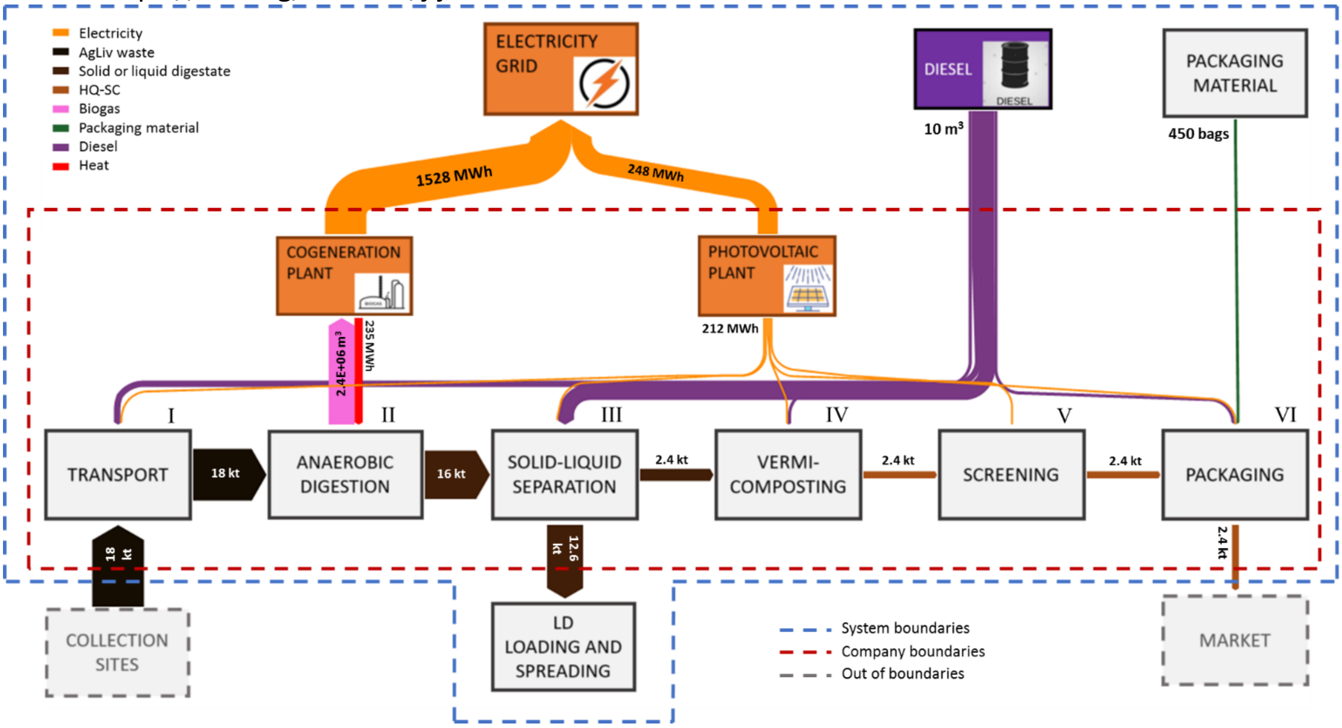
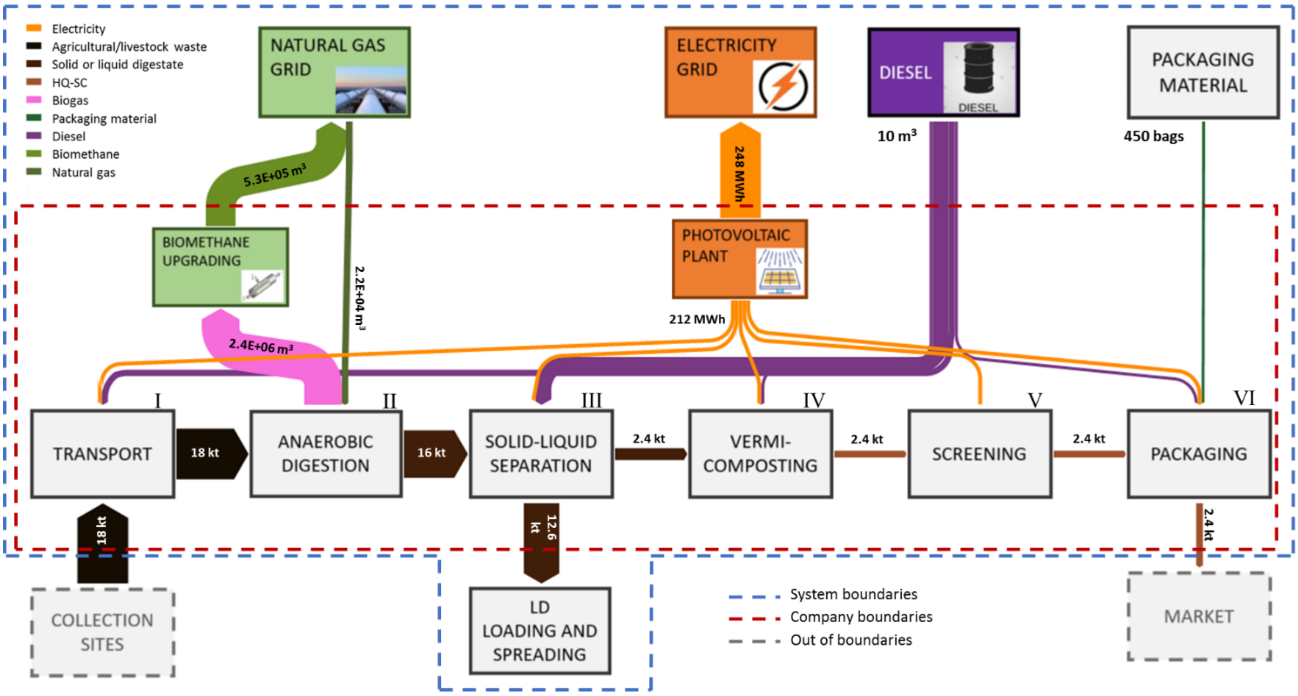


Figure 1: Diagram of the system with annual flows (Baseline scenario). System boundaries represented by red dashed line and company boundaries by blue dashed line.



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752 *Figure 2: Diagram of the system with annual flows (biogas to biomethane scenario). System boundaries represented by red dashed*
753 *line and company boundaries by blue dashed line.*

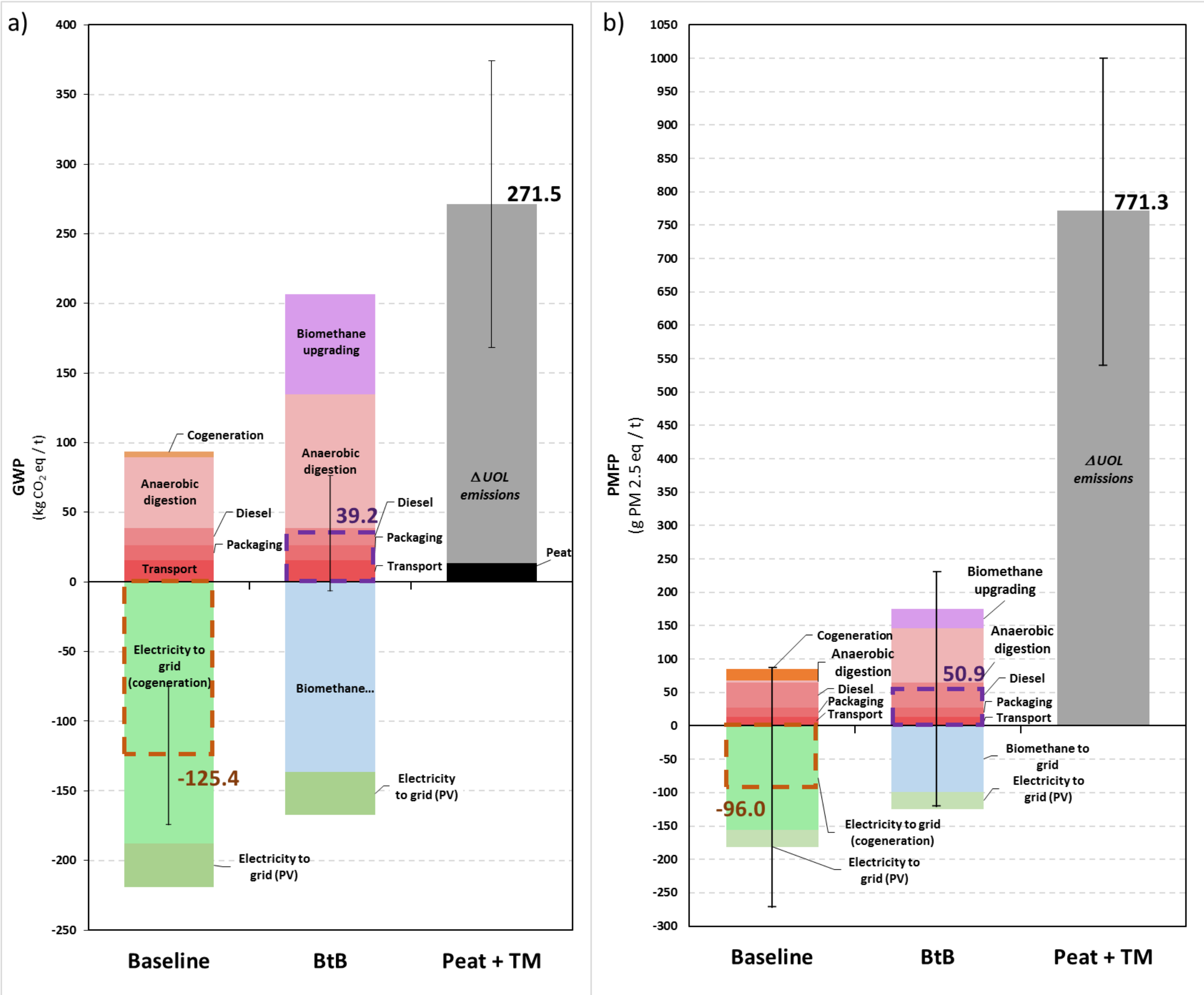

Figure 3: Comparison between HQ_SC (high quality soil conditioner) produced via Baseline, BtB (biogas to biomethane) and Peat+TM (peat + traditional management) scenarios for the GWP (global warming potential) (a) and PMFP (particulate matter formation potential) (b) categories (net values represented by dashed lines).

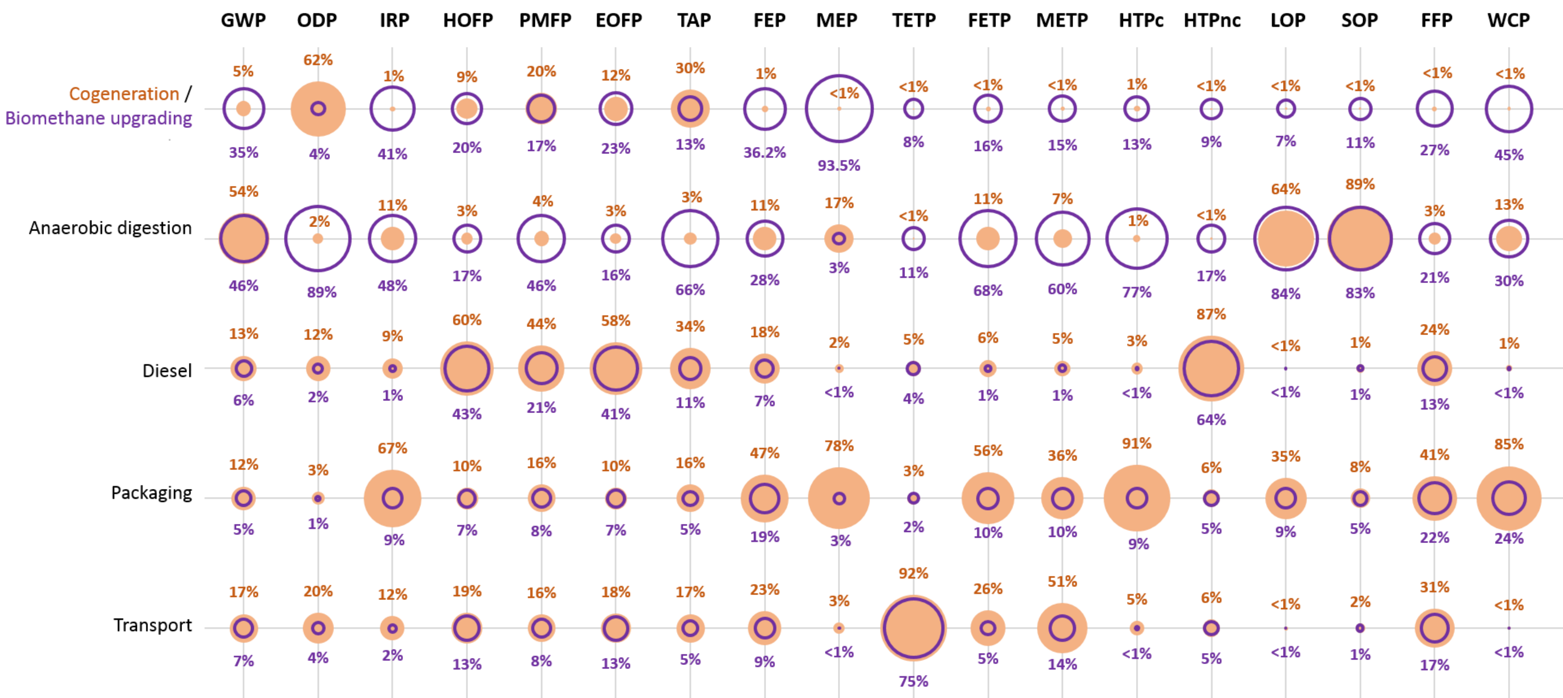

Figure 4: Impact contribution for Baseline (orange) and Btb (biogas to biomethane, purple) scenarios. GWP: Global warming; ODP, Stratospheric ozone depletion; IRP, Ionizing radiation; HOFP, Ozone formation, Human health; PMFP, Fine particulate matter formation; EOFP, Ozone formation Terrestrial ecosystems; TAP, Terrestrial acidification; FEP, Freshwater eutrophic.; MEP, Marine eutrophic.; TETP, Terrestrial ecotoxicity; FETP, Freshwater ecotoxicity; METP, Marine ecotoxicity; HTPc, Human carcinogenic toxicity; HTPnc, Human non-carcinogenic toxicity; LOP, Land use; SOP, Mineral resource scarcity; FFP, Fossil resource scarcity; WCP, Water consumption