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Life cycle assessment of orange peel waste management

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ABSTRACT

The management of orange peel waste constitutes an economic and environmental problem in regions in which there are important citrus processing industries, as is the case of southern Italy. Traditional handling techniques are either not economically attractive (e.g. composting and animal feeding) or discouraged by European policy (landfilling). As an alternative to these technologies, others aimed at recovering energy and resources are currently receiving increasing attention. The consequential life cycle assessment adopted in this work compares the environmental performance of ten orange peel waste management scenarios. These include mono-treatment scenarios (pyrolysis, incineration, and anaerobic mono-digestion) and co-treatment (four anaerobic co-digestion strategies with animal manure and seaweed) ones aimed at energy/resource recovery, which were compared with three traditional non-energy focused handling techniques (landfilling, composting and animal feeding). Overall, the co-digestion scenarios appear to be the best, in terms of global warming and resource depletion mitigation. However, they also suffer from a drawback, that is, a potential eutrophication impact, due to nitrate leaching following on-land digestate use. Orange peel waste use for animal feeding, while appearing interesting from an environmental perspective (for example to reduce meal imports), presents practical challenges as far as the nutritional aspects and costs are concerned, and these eventually hinder its market potential. A preliminary cost flow analysis has concluded that anaerobic digestion strategies are economically preferable to the other alternatives.

1. Introduction

In the European Union, orange production is concentrated in the Mediterranean area, with more than 6 million tonnes gathered each year in Spain, Italy, Greece and Portugal (USDA, 2013). About 30% of this production occurs in Italy, with a corresponding generation of a voluminous waste stream (about 0.6 million tonnes of orange waste) (Ferrari et al., 2016). Orange waste constitutes approximately 50–60% *w/w* (wet weight) of the processed fruit (Wilkins et al., 2007), and it is 60–65% *w/w* composed of peels, 30–35% *w/w* of internal tissue and the remaining share of seeds (Crawshaw, 2003).

Currently, traditional solutions for orange peel waste (OPW) management (landfilling, composting, pectin extraction, animal feeding) are not economically attractive, since they present many drawbacks (Yoo et al., 2011). For example, as far as animal feeding is concerned, the high energy demand for the dehydration process, its bitterness and its low nutritional value currently discourage the use of citrus waste as an animal feed. Composting is economically costly, and the compost produced is often not of interest on the local market. The landfilling of organic waste is discouraged and should be minimized according to the requirements of the EU landfilling directive (EC, 1999). On the other hand, citrus waste may be valorised through energy-focused treatments aiming at optimizing the recovery of energy and resources from this food-industry residual biomass, as suggested in the European resource and bio-economy strategies (de Besi and McCormick, 2015; de Man and Friege, 2016). These energy-focused treatments encompass both biological and thermochemical technologies. If biological processes are of concern, two alternatives are then applicable: extraction and removal of D-limonene from the OPW prior to the subsequent anaerobic mono-digestion process (Negro et al., 2016a) or, alternatively, an anaerobic co-digestion treatment in order to dilute the concentration of D-limonene. Forgács et al. (2012) proved that D-limonene has an inhibitory effect on anaerobic digestion: at concentrations of 400 $\mu L\,L^{-1}$, D-limonene affects mesophilic anaerobic digestion, while the thermophilic process shows inhibition in the range between 450 and 900 $\mu L\,L^{-1}$. When thermochemical processes are of concern, the high moisture content of OPW often discourages their implementation (Ruiz and Flotats, 2016). In this context, a pre-hydration step is needed, prior to the thermochemical processes, as indicated in previous studies (Miranda et al., 2009; Siles et al., 2016; Volpe et al., 2015) that

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investigated the use of OPW as a feedstock for combustion and pyrolysis processes. While a number of studies have focused on the conversion of OPW to biofuels through experimental tests (e.g., El-Shimi et al., 1992; Forster-Carneiro et al., 2013; Negro et al., 2016b), to the best of the Authors' knowledge only one study has so far addressed citrus waste management from an environmental perspective (Pourbafrani et al., 2013). However, in that study, the authors only considered two biorefinery scenarios that were aimed at the production of bioethanol, biogas and D-limonene. Thermal treatments, co-digestion strategies and traditional disposal techniques were not evaluated. Furthermore, no cost analysis was included.

In an attempt to provide deeper insight into OPW management, the aim of the present study has been to quantify the environmental impacts and economic costs that arise from different OPW management strategies and, on the basis of the results, to provide local authorities and decision-makers with recommendations for the optimal management of this biomass waste. To this aim, we applied a consequential life cycle assessment methodology to assess the environmental impacts of ten OPW management scenarios, using southern Italy as a case study. The investigated scenarios included: mono-treatments (incineration, pyrolysis and anaerobic mono-digestion), co-treatments (four different anaerobic co-digestion scenarios with animal manure and seaweed) and traditional handling scenarios (landfilling, composting and animal feeding), which were here used as a reference for comparison purposes. Additionally, a cost flow analysis was performed to estimate the preliminary costs associated with the ten investigated scenarios.

2. Methodology

2.1. Scope and functional unit

The environmental impacts of the OPW management scenarios were quantified using a consequential life cycle assessment (LCA). Consequential LCA is a useful tool to assess the environmental performance of alternative scenarios and to identify critical environmental consequences associated with management strategies (Finnveden et al., 2009; Weidema et al., 2009). In this case study, the changes that could be induced on the energy and feed markets through the management of OPW (e.g. due to the production of electricity, bio-methane, or animal feeds) were expected to be "small enough" (infinitesimal) not to change the overall market trends, in this way justifying the application of a consequential approach (Ekvall et al., 2016). For example, if the whole amount of OPW (0.6 Mt per year, i.e. 0.14 Mt dry matter) was used as an animal feed, this would still represent less than 1.5% of the overall energy-feed demand for Italy (more than 10 Mt dry matter from corn and wheat; USDA, 2013). The LCA was performed according to the principles outlined in the ISO standards (ISO 14040-44, 2006), using system expansion to handle multi-functional processes as this technology fulfils the waste management service but also recovers energy, resources and products. The functional unit of the assessment was the management of 1 t of OPW (wet weight). Conforming with typical waste management LCAs, we used a "zero burden" approach, i.e. the activities related to the generation of the OPW were not taken into account, as they were the same for all of the investigated waste management scenarios. A middle-term temporal scope (2015–2030) was considered for the choice of waste treatment technologies (efficiencies and emissions) and background information (e.g. displaced technologies and products, transport distances, legislative context), while the south of Italy was focused on as the geographic scope of the analysis.

The environmental impact categories considered in this assessment were selected according to the recommendations for relevant categories to be addressed in biomass/bioenergy LCA from Broeren et al. (2017). On this basis, we addressed: global warming, acidification, marine nitrogen-eutrophication, toxicity to humans, toxicity to ecosystems and abiotic resource depletion (the latter mainly concerns fossil fuel depletion). Other categories were disregarded as they were not considered relevant for this study. For example, ozone depletion was not considered, as this is mainly associated with the release of CFCs (not a relevant issue in this context), photochemical ozone formation, as this is mainly related to urban smog (not a relevant issue in this context), and metal depletion as metal use/recovery is not an issue in the studied system. The corresponding characterization methods were based on the recommendations of Hauschild et al. (2013): global warming (GW) was quantified according to IPCC 2007 (Forster et al., 2007), acidification (AC) was calculated as the accumulated exceedance, that is, according to Seppälä et al. (2006), marine nitrogen-eutrophication (EP(N)) was quantified in line with the EUTREND method (ReCiPe, 2008), toxicity to humans in relation to carcinogenic substances (HTc) and ecotoxicity to freshwater (ET) were evaluated according to the ECOtox model (Rosenbaum et al., 2008), and abiotic depletion of fossil resources (AD fossil) was quantified according to CML 2002 (Guinée et al., 2002). The environmental impacts were quantified for a 100-year time horizon. Furthermore, the environmental impacts due to capital goods were not included in this assessment because of a lack of data. The assessment was conducted with the EASETECH LCA-model, which was specifically developed for the modelling of waste and energy technologies (Clavreul et al., 2014).

2.2. Orange peel waste (OPW) management scenarios

Three biomass substrates were considered in this assessment: OPW, animal manure and seaweed. The latter two are needed as co-substrates for co-digestion strategies in order to dilute the concentration of toxicants and prevent process inhibition. The related chemical composition is reported in Table S1 (Supporting Information). Ten OPW management scenarios were assessed: three were mono-treatments, four were co-treatments (with the use of the co-substrates) and three traditional non-energy focused techniques. Overall, ten OPW management scenarios were assessed (Fig. 1): (i) pyrolysis with tar upgrading for biofuel production (PYR), (ii) incineration with electricity production (INC), (iii) extraction of D-limonene and anaerobic mono-digestion with biogas combustion in a stationary engine for electricity production (EXT + AD), (iv) anaerobic co-digestion of OPW and manure with biogas combustion in a stationary engine for electricity production (CD1), (v) anaerobic co-digestion of OPW and manure with biogas upgrading to biomethane for use in vehicles (CD1 + UP), (vi) anaerobic co-digestion of OPW, manure and seaweed with biogas combustion in a stationary engine for electricity production (CD2), (vii) anaerobic co-digestion of OPW, manure and seaweed with biogas upgrading to biomethane for use in vehicles (CD2 + UP), (viii) conventional landfilling with flaring (LANDF), (ix) direct composting with bio-filter (COMP) and (x) animal feeding (FEED).

2.3. System boundaries

In line with the normal practice in consequential LCA, the energy carriers and products generated along with the management of the OPW were assumed to substitute the corresponding energy carriers/products produced through conventional market technologies, i.e. the system boundary was expanded to account for the benefits of avoiding the production and supply of these products. These conventional market technologies/products, in consequential LCA, should be identified as "marginal technologies/products", i.e. those that are able to react to changes in demand (Weidema et al., 2009; Weidema, 2003). As far as the Italian market is concerned, these were identified as: a natural gas power plant for electricity generation (Turconi et al., 2011) and gasoline (with the related supply and production) as transport fuel. The N, P and K nutrients applied on-field with the digestate (residual organic substrate after anaerobic digestion) and compost were assumed to substitute calcium ammonium nitrate, diammonium phosphate and potassium chloride, respectively, on the basis of the NPK content of the digestate (and compost), in agreement with the common practices in