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Environmental assessment of three different utilization paths of waste cooking oil from households

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ABSTRACT

Inadequate disposal of waste cooking oil (WCO) through sewage systems causes economic and environmental problems, e.g., hindering sewage treatment at wastewater treatment plants (WWTP). Additionally, it leads to the loss of a valuable resource with high energy content. In this work, the greenhouse gas balances of three different utilization concepts for WCO were investigated. The utilization options assessed were (1) the conversion of WCO to biodiesel, (2) direct combustion in a cogeneration plant and (3) the production of biogas within an agricultural biogas plant. The scope of the study was limited to the treatment of WCO originating from a separate collection system for private households.

The results show that all three options contribute to a reduction of greenhouse gas emissions with esterification of the WCO (scenario 1) being the best environmental option with savings of 3089 kg CO_2eq t^{-1} WCO. The utilization of WCO in a cogeneration plant (scenario 2) results in a similar range of environmental benefits with 2967 kg CO_2eq t^{-1} WCO. When using WCO as a co-substrate in an agricultural biogas plant (scenario 3), an environmental saving of 1459 kg CO_2eq t^{-1} WCO was achieved. Parameter uncertainties were assessed by perturbation analysis and model and scenario uncertainties by scenario analysis. A special focus was put on the substitution potential of the resulting energy outputs concerning primary production of fossil energy carriers. The results confirm that the definition of reference systems in the course of an environmental assessment has a major influence on the overall results.

1. Introduction

The world's energy demand continues to increase due to economic, technological and demographic growth. From a waste-to-energy perspective, waste cooking oil (WCO) is a suitable feedstock for energy generation due to its high heating value. WCO is a domestic waste stream that results from cooking and frying food with vegetable oil. In the European Union, the annual average per inhabitant consumption of vegetable oil for food use was 21.9 kg inh^{-1} a^{-1} between 2010 and 2012 (OECD/FAO, 2013). However, official statistics on the actual level of collection of WCO in Europe vary between 100,000 and 700,000 t a^{-1} (Iglesias et al., 2012) which equals less than 1 kg per inhabitant per year. In Austria, the amount of WCO collected from households was raised from 0.2 kg to 1 kg per inhabitant per year through the implementation of a collection infrastructure (Bioenergy, 2015). In several European countries, collection systems for WCO are established. These collection systems typically involve private as well as public organizations and the establishment of public collection points. If not collected separately, the common waste management practice is to collect the solidified WCO with municipal solid waste or source separated organic waste, or to discharge it into the sewer system (Singhabhandhu and Tezuka, 2010). The inadequate disposal through the sewage system can cause economic and environmental problems as it hinders sewage treatment at wastewater treatment plants (WWTP), reduces sewer diameters, can completely block pipes and cause flooding (Williams et al., 2012; He et al., 2013; Iasmin et al., 2014).

Currently, there exist several options for WCO management in terms of energetic utilization, if WCO is collected separately. High market rates of WCO in the biofuel industry made esterification an attractive utilization option during the last decades. The production and use of biodiesel from WCO and its environmental performance have been profoundly investigated in literature (Knothe and Steidley, 2009; Varanda et al., 2011; Iglesias et al., 2012; Yaakob et al., 2013; Ho et al., 2014). These studies showed

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advantages lie within its renewable character and in the more favourable combustion emission profile than conventional diesel, with lower emissions of carbon monoxide, particulate matter and unburned hydrocarbons. In countries with high feed-in tariffs for renewable energy, the utilization of WCO in a cogeneration plant using a vegetable oil-based combustion motor constitutes an economically feasible utilization path. For this purpose, the WCO needs to be pretreated as the density and viscosity of unmodified vegetable oils can be significantly higher than those of other types of fuel and can cause formation of carbon deposits on injectors (Callegari, 2002; Winfried et al., 2008; Kleinová et al., 2011). Finally, WCO is also used as a co-substrate in an anaerobic digestion process in order to increase the biogas yield (Lansing et al., 2010; Li et al., 2011; Fierro et al., 2014).

So far these utilization pathways have been individually environmentally assessed and also different collection schemes for WCO have been analyzed from an environmental and social point of view (Vinyes et al., 2012). However, a direct comparison of different utilization pathways aiming at the high energy content of WCO has not been performed so far. Therefore, the novelty of this study lies in the direct comparison of the environmental performance of three different utilization systems (in an esterification plant, a cogeneration plant and in an agricultural biogas plant) of WCO from households on the same basis. To ensure comparability, the mass balances for all concepts were modelled for the same quantity and quality of waste, and state-of-the-art technology was assumed for all scenarios investigated. In addition, a sensitivity analysis was conducted to determine the parameters with the highest influence on the final result of the scenario analysis.

The first part of the article presents the methodology applied, the different scenarios assessed, the life cycle inventory (LCI) modelling framework and the chosen method to handle multifunctional processes. The environmental performances of the different concepts concerning greenhouse gas (GHG) emissions are stated in detail in the result and discussion section. Here also the findings of the sensitivity analysis are shown. Finally, the most important outcomes are summarized in the conclusion section.

2. Materials and methods

2.1. Goal and scope

The goal of this study is to present the current utilization pathways for WCO from households which are economically feasible from an ecological perspective. The results can be used by decision makers as a first environmental evaluation of potential management pathways, when introducing a separate collection system for WCO. However, it is the author's opinion that a profound decision-making process requires a case-specific economic and ecological assessment, where, e.g., local feed-in tariffs and energy supply and heat utilization infrastructure are taken into account. Beside the limitation of the study to one impact category, the results shall serve the research community as an input for the ongoing discussion in the field of waste to energy and the topic of energy crediting within an ecological assessment.

The functional unit used is the management of 1 t [fresh matter (FM)] waste cooking oil in terms of collection, treatment and utilization. For this study, it was assumed that the WCO originates from a separate collection system for private households with an annual collection amount of 680 t [FM]. The WCO consists of plant oils used for frying, drippings and oil from food preserved in oil. Other liquids, chemicals, animal oil, butter, mayonnaise or dressings occurring in households as well as WCO from gastronomy are not considered in this study. Although the virgin oils and the waste oil have different chemical and physical characteristics, the differences are not extensive from a GHG perspective. Usually heating and filtration are sufficient processing steps to remove particulate matter and to obtain a raw material that can be used in an esterification plant or a cogeneration plant (Varanda et al., 2011).

Biochemical characteristics are based on average values from our own investigations and are in a comparable range with data in the literature (Callegari, 2002). The dry matter (DM) content of the WCO is 95% of FM and 39% of FM for the impurities such as remnants from frying. The loss on ignition (LOI) was defined with 87% DM for waste cooking oil and 77% DM for the impurities.

The authors followed the recommendations of the international reference life cycle data system (ILCD) handbook (European Commission, 2010) concerning the identification of context situation and the LCI modelling framework. It is our understanding that this study has a comparative character which can serve as a first basis for decisions concerning the waste management system for WCO. Large-scale consequences on background systems can be expected in case of a nationwide introduction of a separate collection scheme as the energetic utilization of WCO creates renewable alternatives for fossil fuels and energy carriers and thereby potentially leads to changes in energy-markets. Therefore, a consequential modelling approach with the system expansion method for multi-output processes was considered as adequate. Hence, marginal technologies were chosen for reference processes and the energy consumptions.

2.2. System boundaries and scenario description

The system boundaries chosen in the study are from the point of delivery by the citizens at public collection points to the final utilization of the outputs of the utilization plants. The process steps assessed include collection, processing of the WCO, transport of the WCO to further utilization facilities (esterification plant, cogeneration plant, agricultural biogas plant) and the energetic utilization of the products. Positive and negative environmental impacts were taken into account in the balance as credits and debits. The investigation includes system exchanges with energy systems, biodiesel industry and the waste and wastewater industry. For instance, the screen overflow (e.g., >10 mm and 25 μm) from the screening of the waste cooking oil during the processing step is assumed to be used as a co-substrate in an anaerobic reactor of a WWTP generating biogas and superseding fossil energy. Therefore, the resulting energy output is credited in the study.

Align with common waste-management-oriented LCA methodologies a zero burden assumption was defined for the study (Laurent et al., 2014). Meaning the WCO is not associated with any environmental impacts when it enters the system. For example, usually biodiesel from oil crops produce considerable shares of indirect GHG emissions in the life cycle stage of the cultivation of the feedstock crops (i.e., production of the fertilizers and pesticides, soils emissions of N_2O, the consumption and emissions of the tractors, etc.) (Nanaki and Koroneos, 2012; Iriarte and Villalobos, 2013). When applying the zero burden approach, these emissions are not assigned to the WCO.

Another key assumption of this study is that GHG emissions contributing to the anthropogenic global warming effect were considered, meaning emissions resulting from the degradation and combustion of renewable resources were classified as neutral (Christensen et al., 2009; Boldrin et al., 2010; Hermann et al., 2011). The overall debits (positive) and credits (negative) of GHG emissions are expressed in kilograms CO_2eq for 1 t of WCO processed. In accordance with the guidelines of the International Panel on Climate Change (Forster et al., 2007), the following conversion factors were applied: $CO_{2\text{-fossil}} = 1\ \text{kg}\ CO_2\text{eq}\ \text{kg}^{-1}\ CO_{2\text{-fossil}}$, $CO_{2\text{-renewable}} = 0\ \text{kg}\ CO_2\text{eq}\ \text{kg}^{-1}\ CO_{2\text{-renewable}}$, $CH_4 = 25\ \text{kg}\ CO_2\text{eq}\ \text{kg}^{-1}\ CH_4$ and $N_2O = 298\ CO_2\text{eq}\ \text{kg}^{-1}\ N_2O$.