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Research article

Comparative life cycle assessment of alternative strategies for energy recovery from used cooking oil

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ABSTRACT:

The separate collection of Used Cooking Oil (UCO) is gaining popularity through several countries in Europe. An appropriate management of UCO waste stream leads to substantial benefits. In this study, we analyse two different possibilities of UCO energy reuse: the direct feed to a reciprocating internal combustion engine (ICE) for cogeneration purpose, and the processing to generate biodiesel. Concerning biodiesel production, we analyse four among conventional and innovative technologies, characterised by different type and amount of used chemicals, heat and electricity consumptions and yields. We perform a systematic evaluation of environmental benefits and drawbacks by applying life cycle assessment (LCA) analysis to compare the alternatives.

For the impact assessment, two methods are selected: the Global Warming Potential (GWP) and Cumulative Exergy Consumption (CExC). Results related only to the processing phases (i.e. not including yet the avoided effects) show that the recovery of UCO in cogeneration plant has in general lower values in terms of environmental impacts than its employment in biodiesel production.

When products and co-products substitution are included, the savings obtained by the substitution of conventional diesel production, in the biodiesel cases, are significantly higher than the avoided effects for electricity and heat in the cogeneration case. In particular, by using the UCO in the biodiesel production processes, the savings vary from 41.6 to 54.6 GJ_{ex} per tUCO, and from 2270 to 2860 kg CO_{2eq} per tUCO for CExC and GWP, respectively. A particular focus is put on sensitivity and uncertainty analyses. Overall, high uncertainty of final results for process impacts is observed, especially for the supercritical methanol process. Low uncertainty values are evaluated for the avoided effects. Including the uncertain character of the impacts, cogeneration scenario and NaOH catalysed process of biodiesel production result to be the most suitable solutions from the process impacts and avoided effects perspective.

1. Introduction

The global demand for vegetable oils and fats for edible purposes has grown consistently over the past decade. It is estimated that the worldwide consumption of vegetable oils and fats will increase by 25% and reach 178 Mt in 2025 (FAO and OECD, 2016). According to the statistics presented by Food and Agriculture Organization of the United Nations (FAO) (Food and Agriculture Organization of the United Nations (FAO), 2013), in 2013, about 11.1 Mt of vegetable oils with an average of 15 kg per capita per year was consumed in Europe for edible purposes. The average oil consumption per capita in the Mediterranean area is significantly higher than in the rest of Europe. In particular, Spain, Italy and Greece are the greatest oil consumers, with the average of 28.3 kg, 27.6 kg and 26.6 kg per capita per year, respectively. A significant rate of those oils, about 20%, is disposed of after the cooking process. The properties of the Used Cooking Oil (UCO) are different with respect to the fresh one because of the physical and chemical changes (mainly due to oxidative and hydrolytic reactions) that take place during frying (Cvengroš and Cvengrošová, 2004). The products of oxidation and decomposition make the UCO unsuitable for culinary use and extremely harmful to the environment. Thus, the increased production of UCO is creating severe disposal problems. In most of the cases, UCO is drained as a waste, causing water treatment problems such as reduction of sewer diameters or even

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Abbreviations:

UCO	used cooking oil
FAME	fatty methyl esters
FFA	free fatty acids
LCA	life cycle assessment
CHP	combined heat and power
ICE	internal combustion engine
CExC	cumulative exergy consumption
GWP	global warming potential
GHG	greenhouse gases
CV	coefficient of variation
CTV	contribution to variation

blockages in the wastewater plant infrastructure (Wallace et al., 2017).

It is well known that an appropriate management of UCO waste stream leads to substantial environmental and economic benefits. Due to its high methane potential, UCO can be used as a co-substrate in anaerobic co-digestion with sludge (Alqaralleh et al., 2016) or with biodegradable wastes, such as the organic fraction of municipal solid wastes (Martín-González et al., 2011), to improve the process efficiency. It is also reported that addition of UCO increases cement strength and improves the cement grinding process (Li et al., 2016). Alternatively, UCO can be used as a raw material for biodiesel production, which is obtained as a result of chemical processes of trans-esterification and oil separation (Phan and Phan, 2008; Felizardo et al., 2006; Kawentar and Budiman, 2013).

Being of renewable origin, the effective re-use of UCO as an energy source represents an opportunity to reduce dependency on fossil fuels, reduce carbon emissions (thus contributing to meet challenging international targets) and support local economies.

Nowadays, in Italy as well as in other European countries, biodiesel is mainly manufactured from rapeseed oil (Banerjee and Chakraborty, 2009). However, due to the heavy consumption of oils for edible purpose and to the lower raw material cost, UCO is a promising substitute. It is estimated that biodiesel produced from UCO could replace around 1.5% of the EU27 diesel consumption, helping the Member States to reach the 2020 targets (Recoil Project, 2016).

Furthermore, the UCO as regenerated fuel, through physical treatment (mainly consisting of preheating, sieving, decantation, extraction and filtration), may also be used as a fuel in combined heat and power (CHP) production (Winfried et al., 2008). Cogeneration, especially if applied locally, leads to additional advantageous effects due to the decreasing of energy transformation and distribution losses.

The choice among the possible options for UCO re-use should be based on the systematic evaluation of environmental benefits and drawbacks: this can be accomplished by applying life cycle assessment (LCA). Environmental assessment of UCO valorization, especially involving LCA, was already implemented in several studies.

The majority of the studies focus on the comparison of the biodiesel production from UCO and virgin oils (Escobar et al., 2014; Iglesias et al., 2012; Kiwjaroun et al., 2009; Varanda et al., 2011; Font de Mora et al., 2015). The result show, in general, that the environmental impacts can be reduced when UCO is employed as a raw material for biodiesel production. On the other hand, the results of the comparative studies for biodiesel production from UCO lead to ambiguous conclusions. For instance, Kiwjaroun et al. (2009), analysing the biodiesel synthesis by alkali conventional and supercritical methods, conclude that the supercritical process generates significantly higher environmental impacts related to human health, ecosystem quality and resources consumption, than the conventional one. On the contrary, Morais et al. (2010), comparing the conventional alkali-catalysed process, the acid-catalysed process, and the supercritical one, indicate the supercritical process as the most environmentally favourable alternative. As another example, Ortner et al. (2016) evaluate the life cycle greenhouse gas emissions (GHG) due to three different pathways of UCO re-use, including heat and electricity production directly in cogeneration unit and in biogas plant after anaerobic digestion process, and also biodiesel production in alkali KOH catalysed process. Their results show that all the three analysed alternatives lead to a saving of GHG emissions. However, benefits due to biodiesel production and cogeneration resulted more than two times higher with respect to the anaerobic digestion scenario.

The above-mentioned comparative studies strongly focus on classical environmental indicators. However, such analysis should also be performed from a natural resources depletion point of view. To address this aim and to evaluate the different quality of energy carriers, the exergetic analysis in the whole production chain, with the concept of cumulative exergy consumption analysis (CExC) proposed by Szargut (Szargut, 2005; Szargut et al., 2002) and Bosch (Bosch et al., 2007) can be applied. Exergy (Szargut, 2005) is defined as the maximum ability of an energy carrier to perform work in a reference to the standard environment or the minimum theoretical work required to obtain the substance with given parameters and composition. Such a concept was used in several studies concerning the analysis of technologies of biodiesel production from UCO (Font de Mora et al., 2015; Talens et al., 2007, 2008; Peiró et al., 2008).

In this paper, the comparative assessment of the environmental impacts and the primary resource consumptions, by means of life cycle GHG emissions and cumulative exergy consumption of different pathways of UCO utilisation is presented. Five alternative pathways of UCO re-use are defined and compared under consequential approach. Scenario 1, considers the use of the previously regenerated UCO as a fuel in a cogeneration plant. In Scenarios 2–5, different options of biodiesel production from UCO focusing on conventional and future technologies are evaluated. The results are supported by the sensitivity and uncertainty analyses.

The analysis is reported and described according to the LCA phases (ISO 14040-44, 2009) (ISO, 2006a; ISO, 2006b): the goal and scope definition, as well as the inventory analysis, are reported in the materials and methods section, while impact assessment, interpretation, sensitivity and uncertainty analyses, are presented in the results section.

2. Materials and methods

2.1. Goal and scope definition

The purpose of the present LCA study is to analyse and compare the environmental impacts and resource consumption of different pathways of energy recovery from UCO.

In Scenario 1 (S1-CHP), we analyse the use of UCO for CHP production in a cogeneration plant. In the further variants, we consider four different methods of transesterification of UCO to yield biofuel. The process alternatives for biodiesel production include the alkali- catalysed process employing sodium hydroxide (SC2-NaOH) and potassium hydroxide (SC3-KOH) as a catalyst, the acid catalysed process (SC4-ACID) and in the non-catalytic supercritical methanol process (SC5-SC).

The mass balances for all the scenarios are modelled assuming

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