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Evaluation of different end-of-life management alternatives for used natural cork stoppers through life cycle assessment

Martha Demertzi, Ana Cláudia Dias *, Arlindo Matos, Luís Manuel Arroja

Center of Environmental and Marine Studies (CESAM), Department of Environment and Planning, University of Aveiro, 3810-193 Aveiro, Portugal

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ABSTRACT

An important aspect of sustainable development is the implementation of effective and sustainable waste management strategies. The present study focuses on a Life Cycle Assessment (LCA) approach to different waste management strategies for natural cork stoppers, namely incineration at a municipal solid waste incinerator, landfilling in a sanitary landfill, and recycling. In the literature, there are no LCA studies analyzing in detail the end-of-life stage of natural cork stoppers as well as other cork products. In addition, cork is usually treated as wood at the end-of-life stage. Thus, the outcome of this study can provide an important insight into this matter.

The results showed that different management alternatives, namely incineration and recycling, could be chosen depending on the impact category considered. The former alternative presented the best environmental results in the impact categories of climate change, ozone depletion and acidification, while the latter for photochemical ozone formation and mineral and fossil resource depletion. The landfilling alternative did not present the best environmental performance in any of the impact categories. However, when the biogenic carbon dioxide emission was assessed for the climate change category, the landfilling alternative was found to be the most effective since most of the biogenic carbon would be permanently stored in the cork products and not emitted into the atmosphere.

A sensitivity analysis was performed and the results showed that there are various parameters that can significantly influence the results (e.g., carbon content in cork and decay rate of cork in the landfill). Thus, LCA studies should include a detailed description concerning their assumptions when the end-of-life stage is included in the boundaries since they can influence the results, and furthermore, to facilitate the comparison of different end-of-life scenarios. The present study and the obtained results could be useful for the decision-making process concerning public solid waste policies and industrial strategies.

1. Introduction

Cork is the bark of the cork oak (*Quercus suber* L.), a long-lived tree (~170 years) located in different Mediterranean countries and northern regions of Africa. Most cork oak forests are found in Portugal and Spain (34% and 27% of the total cork oak area, respectively) resulting in a considerable cork industry of great economic importance (APCOR, 2014).

Cork is used for the production of various products in a wide range of sectors due to its versatility. However, the main sector of cork use is the wine industry due to the need for cork stoppers to seal wine bottles. In Portugal, cork stoppers represent 70% of the total exports of the sector (in value), with natural cork stoppers having the leading role with 42% (APCOR, 2014). Due to the relevance of the natural cork stopper production to the economy of the country, an increasing interest in the evaluation of its environmental impacts is observed. This evaluation can be done through Life Cycle Assessment (LCA), a useful tool for the environmental assessment of a product throughout its life cycle according to specific guidelines recommended by the International Organization for Standardization (ISO), such as ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b). According to the aforementioned standards, four phases are included in a LCA study, namely goal and scope definition (determining the depth and direction that the study will have), inventory analysis (the unit processes of the system are analyzed for the identification and quantification of energy, water, materials use and environmental releases), impact assessment (evaluation of potential human health and environmental impacts of the environmental resources and releases identified during the previous stage) and interpretation (the results of the inventory analysis and the impact assessment are evaluated

* Corresponding author.
E-mail addresses: marthademertzi@ua.pt (M. Demertzi), acdias@ua.pt (A.C. Dias), amatos@ua.pt (A. Matos), arroja@ua.pt (L.M. Arroja).

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and validated before making and reporting conclusions, with a clear understanding of the assumptions used to generate the results).

A few examples of LCA studies focusing on natural cork stoppers can be found in the literature, both in Portugal (e.g., Demertzi et al., 2015a; PwC/Ecobilan, 2008) and abroad (e.g., Rives et al., 2011). However, none of these studies performed an in depth analysis of the end-of-life stage. More specifically, Demertzi et al. (2015a) excluded the end-of-life stage due to lack of information, while Rives et al. (2011) and PwC/Ecobilan (2008) only considered one option for the final disposal of the natural cork stoppers, namely landfilling. Furthermore, in these studies, cork was assumed to have the same emissions as wood. This assumption may increase uncertainty since cork and wood have different components (e.g., suberin and lignin) and different chemical compositions (e.g., carbon and oxygen) (Pereira, 2013; Jianju et al., 2004). Cork mainly consists of four chemical components – carbon (55%), oxygen (35%), hydrogen (8%) and nitrogen (2%) (Pereira, 2007, 2013). Furthermore, it should be noted that the existing studies regarding LCA of waste management systems do not tackle cork since they consider other waste fractions (Laurent et al., 2014; Turconi et al., 2011; Cherubini et al., 2009).

At the end-of-life stage, natural cork stoppers are, at the moment, considered municipal solid waste (MSW), and as such they are traditionally sent for incineration and/or landfilling (OECD, 2010). However, apart from these traditional final disposal options and in line with the Directive 2008/98/EC that sets a waste management hierarchy (European Commission, 2008), there is a recent alternative concerning the selective collection and recycling of used natural cork stoppers. In fact, there are various running campaigns worldwide (e.g., "Greencork" in Portugal, "ReCORK" in USA and "Cork Recycling Program" in Australia), aimed at the collection and recycling of used natural cork stoppers. Even though the recycled cork stoppers cannot be used for the production of new cork stoppers (due to low quality), they can be harnessed for their reentrance to the manufacturing of cork granules and agglomerated cork products such as coverings, cork fabrics and decorative products (Amorim, 2014). However, there are rising doubts about the environmental benefits of the recycling procedure since it requires the transportation of the natural cork stoppers to the transformation industry (Garcia, 2011).

The aim of this study is to evaluate and compare three waste management alternatives for the final disposal of used natural cork stoppers, namely, incineration at a MSW incinerator, landfilling and recycling. Several scenarios are included in each management alternative and LCA is applied in order to identify the most environmentally efficient alternative and scenario for the end-of-life of natural cork stoppers.

2. Methodology

2.1. Goal definition

The goal of this study is to evaluate the different environmental impacts of different management alternatives in order to be used in the future decision-making process of the natural cork stoppers' end-of-life destinations. Thus, it is considered that fits in Situation A (micro-level decision support) as suggested by the ILCD Handbook (European Commission, 2010). In LCA there are two modeling principles that can be applied, namely the attributional and the consequential approaches (European Commission, 2010). The attributional approach was considered to be more appropriate for the present study, based on the objective established and thus, attributional LCA will be used.

2.2. Functional unit and multi-functionality

The functional unit (FU) provides a reference to which the inputs and outputs are related. The FU used in all of the alternative scenarios evaluated in this study is the disposal/valorization of one ton of used natural cork stoppers. When comparing the different systems, the attributional modeling principle was chosen for this comparative LCA, and the system expansion by substitution approach was considered for solving multi-functionality (Situation A). In the case of system expansion, the multi-functional processes lead to the inclusion of further products into the functional unit. Thus, the initially-defined product system is expanded into a whole system model, including different functions (Werner, 2006). The alternatives and associated scenarios under study are as follows:

A. Incineration at a MSW incinerator:
   - Scenario 1: with electricity generation (substituting electricity generation from the Portuguese electricity mix).
   - Scenario 2: with electricity generation (substituting electricity generation from natural gas).
   - Scenario 3: with electricity generation (substituting electricity generation from hard coal).
   - Scenario 4: with combined heat and power generation (CHP) (substituting cogeneration of energy from natural gas).

B. Landfilling in a sanitary landfill:
   - Scenario 5: without landfill gas recovery.
   - Scenario 6: with landfill gas recovery for flaring.
   - Scenario 7: with landfill gas recovery for electricity generation (substituting electricity generation from the Portuguese electricity mix).
   - Scenario 8: with landfill gas recovery for electricity generation (substituting electricity generation from natural gas).
   - Scenario 9: with landfill gas recovery for electricity generation (substituting electricity generation from hard coal).

C. Recycling:
   - Scenario 10: for the production of agglomerated cork used for agglomerated cork products. In this scenario, the production of cork slab used as covering material in construction is considered, avoiding the use of raw cork (namely, 'falca' that is the cork from the branches of the cork oak tree).
   - Scenario 11: for the production of cork slab (as in Scenario 8) but in this scenario avoiding the use of industrial cork waste resulting from the production of natural cork stoppers (e.g., punched planks). Currently, those residues are exclusively used for the production of cork agglomerates. Thus, in practice, recycled cork stoppers cannot substitute for the industrial residues. However, this scenario will quantitatively show if it is actually more efficient or not to use the industrial waste or the recycled stoppers.

Even though not all of the above-mentioned technologies are currently applied in Portugal, they were all considered in order to be evaluated for future consideration for the final disposal of natural cork stoppers. This could be useful for decision-making concerning public solid waste policies and industrial strategies.

2.3. Boundaries of the system

In the present study, in all of the alternatives, a consumer-to-grave approach was applied. This approach included the transport of the used natural cork stoppers from the consumer to their final