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Environmental sustainability of bark valorisation into biofoam and syngas

Sara González-García [a,*], Clement Lacoste [b], Thomas Aicher [c], Gumersindo Feijoo [a], Lucía Lijó [a], Maria Teresa Moreira [a]

[a] Department of Chemical Engineering, School of Engineering, University of Santiago de Compostela, 15782 Santiago de Compostela, Spain
[b] LERMAB, University of Lorraine, Epinal, France
[c] Division Energy Technology, Fraunhofer-Institut für Solare Energiesysteme ISE, 79110 Freiburg, Germany

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ABSTRACT

Conventional foams derived from petroleum are extensively used for insulating uses. Research into alternative sources to petroleum based chemicals is attracting a great deal of attention. Softwood bark and in special, maritime pine bark from European forests is an abundant co-product from forest industries. In this study, the production of formaldehyde-free tannin based biofoams to be used as building insulation materials was environmentally assessed using the Life Cycle Assessment methodology (cradle-to-grave approach) as well as their valorisation into bioenergy (electricity and thermal energy) at end of their life cycle by means of their gasification into tar-free syngas and its further combustion in a CHP unit. The production chain was divided into four subsystems: forest activities (SS1), sawmill (SS2), biofoams production (SS3) and bioenergy production (SS4). Wherever possible, primary data from pilot plants were managed. Since two main co-products are obtained, three different approaches were considered and discussed: total allocation of environmental burdens to the electricity (main product), exergy based allocation and system expansion.

According to the results, SS3 was identified as the environmental *hotspot* regardless the impact category considered for assessment. The large requirements of electricity in the tannin extraction unit as well as the production of chemicals required for the biofoam formulation were the responsible factors of these notable contributions. Special attention should also be paid to the uncontrolled pentane emissions associated to the biofoam formulation, specifically in terms of photochemicals oxidant formation.

Remarkable environmental benefits were obtained in terms of climate change, fossil fuels depletion as well as in some toxicity related impact categories in comparison with the petroleum based foams, mainly based on the use of an abundant renewable source as raw material to produce the foams. Improvement actions should look at the reduction (or even recovery) of chemicals used, the control of diffuse emissions (e.g. pentane from evaporation unit and CHP unit) as well as the installation of a cogeneration unit to produce the electricity requirements to reduce dependence on fossil fuels.

1. Introduction

Nowadays there is growing concern and interest in the use of renewable raw materials as alternative to petroleum based ones, mainly due to the limited availability of fossil fuels, their fluctuating prices as well as the consciousness on the reduction of environmental impacts, specifically greenhouse gases (GHGs) emissions (Feng et al., 2013; Klein et al., 2015). Forest biomass is one of the most important renewable and sustainable sources in Europe, used to produce wooden products and energy (Shabani et al., 2013; González-García et al., 2014a). Within this sector, the intensive biomass production has also concerns related to the ecological consequences derived from the use of fertilisers and fossil fuels (Schulze et al., 2012). Thus, the possibility of upgrading processes from forest biomass to high added value products could derive on interesting profits when compared to their direct conventional combustion (Kemppainen et al., 2012).

* Corresponding author. Tel.: +34 881816806.
E-mail address: sara.gonzalez@usc.es (S. González-García).

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Bark from European forest species represents one major feedstock that is currently burnt in wood processing facilities. Bark is defined as all the tissues external to and surrounding the vascular cambium and represents around 13–21% of the total dry weight (Feng et al., 2013). It can be collected at sawmills, pulp and paper mills (Kemppainen et al., 2012), being an important source of high added chemicals such as tannins. Thus, the valorisation of bark into the production of chemicals (leather dyes, spices, …) and woody materials (panels, adhesives, resins, foams or oils) could be a promising biorefinery perspective in the forest sector (Feng et al., 2013).

Polyurethane and synthetic phenolic foams are commonly used as insulation materials as well as in electronic applications due to their low thermal conductivity and high fire resistance (Tondi et al., 2009a; Tondi and Pizzi, 2009). They are obtained by the combination of polyols, diisocyanates and pentane (polyurethane based foams) or by the reaction of phenol with formaldehyde (synthetic phenolic foams) (Boustead, 2005a). However, the negative environmental impacts associated to their production are mainly due to the use of chemicals and fossil fuels. The demand on alternative production systems based on renewable raw materials has noticeably increased. Therefore, foams based on natural materials could replace industrial petroleum based foams in most applications provided that they present comparable properties (Tondi et al., 2009a).

Recent research works prove that tannin based foams are materials more resistant to fire than phenolic and polyurethane foams (Celzard et al., 2011). Moreover, they have excellent performance especially as insulation materials (Tondi et al., 2008; Lacoste et al., 2014a) for interior and exterior wooden doors (Tondi and Pizzi, 2009; Tondi et al., 2009b). Up to 98% of their composition is based on renewable materials such as bark extracts (tannins), which are vegetal products commonly obtained by water extraction from woody bark (Navarrete et al., 2010; Lacoste et al., 2013b), and furfuryl alcohol, obtained as co-product in sugar hydrolysis of agricultural crops (Zhao et al., 2010; Basso et al., 2013).

There are several tannins commercially available; the most relevant ones are obtained from mimosa (*Acacia mearnsii*) and quebracho (*Schinopsis lorentzii* and *Schinopsis balansae*) (Tondi and Pizzi, 2009; Lacoste et al., 2014a). In recent years, special attention has being paid on pine (*Pinus radiata* and *Pinus pinaster*) as raw material for tannin extraction. Pine, a forest species abundant in Europe and extensively cultivated to produce timber (González-García et al., 2014b, 2014c), presents high potential for bark extraction (Navarrete et al., 2010). However, condensed pine tannins are highly reactive and present fast curing time (if compared with those from quebracho or mimosa). Thus, specific research on pine tannin based foams has been required for a better understanding of their formulation kinetics. Nowadays, conifer species have been recognised to give economical yields of condensed tannins (Tondi et al., 2009b; Lacoste et al., 2013a, 2013b, 2014a).

As a consequence of the interest in more environmental-friendly materials, different alternatives have been presented in the formulation of tannin based foams (Lacoste et al., 2014a). The phenolic nature of tannins is known to react with all types of aldehyde under acid or alkaline conditions (Lacoste et al., 2013a). From the initial formulations of tannins based on formaldehyde (Tondi et al., 2008), alternatives have been developed, either with another aldehyde (e.g. glyoxal) or even in the absence of aldehyde and solvent (Basso et al., 2013).

In this study, the production of formaldehyde-free pine tannin foams was evaluated from an environmental cradle-to-grave perspective, considering this production process as a potential alternative not only for conventional phenolic foams but also for previous tannin foams combinations based on the use of formaldehyde. The production process is based on the use of glyoxal, a non-toxic and non-volatile hardener, which substitutes formaldehyde (Lacoste et al., 2014a, 2014b). Additionally, the gasification of tannin based foams at the end of their life was proposed to obtain thermal energy and fuel gas or synthesis gas (syngas) (González-García et al., 2012). Hydrogen releases usable energy in the form of electricity and heat when it reacts with oxygen in a fuel cell (Fraunhofer ISE, 2014).

Life Cycle Assessment (LCA) was used to evaluate the environmental sustainability of pine tannin foam because it can quantify the environmental impacts of all the related processes or activities involved throughout its life cycle (ISO 14040, 2006; Hou et al., 2015). Other LCA studies were related with green strategies in the sector such as the substitution of phenol-formaldehyde resins by two-component bio-adhesives formulated with a wood-based phenolic material (lignosulfonate) and a phenol-oxidising enzyme (laccase) (González-García et al., 2011).

The present study could be considered as an interesting and potential research innovation not only in the woody but also in the construction and bioenergy sectors due to the development of a bio-based material, which can be converted into bioenergy at the end of its lifetime integrating both green strategies and biorefinery concepts. Moreover, one additional advantage of this type of insulating foam is that the market is large and mostly untapped.

2. Materials and methods

Life Cycle Assessment (LCA) is a procedure for assessing the potential environmental impacts and resources consumption associated with a production system as well as for identifying opportunities to achieve environmental advantages (ISO 14040, 2006; Finnveden et al., 2009). LCA methodology was selected to perform the environmental analysis according to the principles described in ISO standards (ISO 14040, 2006) from an attributional perspective.

2.1. Goal and scope definition

The main goal of this research study was to evaluate the environmental performance derived from the production of pine tannin based foams to be used as building insulation materials. The assessment was performed from a cradle-to-grave approach. Accordingly, the analysis considered all the activities or processes involved from the production of the raw materials up to the final conversion of the biofoams into bioenergy (heat and electricity) at the end of their life cycle.

Another objective included the identification of the most critical stages (environmental *hotspots*) throughout the life cycle with the aim of promoting actions to achieve further environmental burdens reductions. Finally, the environmental profile was compared with the one of conventional polyurethane based foams in order to demonstrate the environmental sustainability associated with the tannin based foams. The functional unit considered for assessment was 285 kWh, which is the potential electricity produced per day in the gasification plant.

2.2. Description of the system under study

The pine tannin based system was analysed from the production of raw materials (resources) up to the biofoam conversion in a gasification process for the final production of bioenergy (heat and electricity) in a CHP unit. Biofoam use related activities as well as the transport activities up to the bioenergy plant were excluded since they are not available at commercial scale and their consideration should increase the uncertainty of environmental results.