Environmental assessment of hydrogen production based on *Pinus patula* plantations in Colombia

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**Abstract**

*Pinus Patula* is widely distributed in Colombia and has become a useful timber species for reforestation programs. Forest biomass can be used to produce directly hydrogen through thermochemical technologies (e.g., gasification). The aim of this work is to assess the environmental impact of hydrogen production via gasification using *P. patula* as raw material. The life cycle assessment was carried out considering a cradle-to-gate perspective starting at the seedlings production and finishing at the hydrogen production. Inventory data of the forest system was obtained from a plantation located in Manizales, Colombia and additional data were provided with bibliographic resources. Mass and energy balances for hydrogen were obtained from the software Aspen Plus V8.0. The seedling production and *P. patula* cultivation were identified as hotspots of the hydrogen production. Agrochemicals application and seedbeds materials have the highest contribution to most of the environmental impacts in the seedlings production system. In the *P. patula* cultivation system, the fertilizer application and the collection/transportation of wood generate the highest emissions. The rotation periods of the cutting cycles strongly influence the agrochemicals dosage depending on the wood final purpose. The use of diesel in the collection/transportation of wood has an important share of the total environmental impact.

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1. Introduction

Colombia is considered as a suitable country for forestry; it has approximately 60 million hectares of natural forest with a deforestation rate of 280,000 Ha per year [1]. Colombia has a high potential to develop reforestation programs due to its excellent weather, geographic and topographic conditions for the tree growth, the geostrategic location for foreign trade and the relatively high number of signed free trade agreements [2]. The lack of incentives and clear policies for commercial plantations, in addition to the lack of security and other issues (private property and land use) have affected the development of the reforestation programs in rural areas [3]. *P. patula* is considered one of the most promising reforestation species in Colombia, especially in the Andean region. [4,5]. *P. patula* has a relatively high yield in comparison to the other species used in reforestation programs, ranging between 10 and 35 m$^3$ Ha$^{-1}$ year$^{-1}$ and a short rotation time: 10–25 years [4]. Despite all these advantages, the cultivation of *P. patula* could generate an important environmental impact, mainly due to the pesticides, fungicides, and fertilizers used during the forest practices.

The energy matrix in Colombia has been transformed throughout the last years. Currently, the electricity generation in Colombia is distributed as follows: hydroelectric power plant is the most used technology in the generation of electricity accounting to 69.97%, followed by Gas- and Coal- thermal plants accounting for 9.85% and 8.20%, respectively. Liquid (diesel) and gaseous fuels account for 11.30% of the generated electricity in Colombia. In contrast, the electricity generation from renewable energy sources such as biomass and wind account for 0.57% and 0.11%, respectively [6]. Fig. 1 presents the energy matrix of Colombia and its distribution among the different energy sources. In recent years, the influence of the climate change such as “El Niño” phenomenon and
The increase in the fossil fuels price has promoted the search for alternative and renewable energy sources. Hydrogen is an alternative and renewable energy source that can be used directly or indirectly as fuel with low environmental emissions, especially without CO₂ emissions. Most of the hydrogen is produced from fossil fuels accounting for the 96%; the remaining (4%) is obtained from renewable energy sources (e.g. biomass). Different technologies (e.g. thermochemical, biochemical, electrochemical) for hydrogen production have been widely studied using biomass as energy source. Gasification is a mature technology that directly converts biomass into a gas composed of hydrogen, carbon monoxide, carbon dioxide, among others using a gasifying agent (e.g. air, steam, oxygen, CO₂ or mixtures of these). The life-cycle assessment (LCA) is a methodology suitable to establish those systems or “hotspots” that generate the highest impact in the natural environment, human health, and resources associated with a product or service. In this way, the LCA has become a very important tool in the industry as decision criteria [7]. LCA considers the entire life cycle of a product, from raw material production or extraction, manufacturing and use to the final waste treatment or disposal [8]. However, the system can be delimited based on the purpose (goal and scope) of the environmental assessment. Through this overview, the distribution of the potential environmental burdens between life cycle stages or individual processes can be identified and possibly avoided [8]. The inventory data involved in an LCA should be specified and detailed, mainly about the source, i.e. database, field information, questionnaires, literature reports, etc.

Different authors have evaluated the environmental impacts of forestry biomass production based on the LCA methodology. Gonzalez-Garcia et al., [9] evaluated the environmental impacts of the production of Maritime Pine biomass in France under different management scenarios (an intensive scenario and an extensive one). The logging stage and, especially, the final cutting process were the main environmental key factors in the production of Maritime Pine. The selection of the suitable management scenario can contribute not only to different impact categories (e.g. climate change and acidification potential) but also in the biomass yield. May et al., [10] developed a cradle-to-gate inventory for softwood plantations and hardwood native forests across Australia including the forest establishment, management, harvesting and transportation of logs and chips. Key inputs for wood from softwood plantations and hardwood forests are the use of land, water, and fuel. Wood transportation, harvesting, and chipping are the largest contributors to the use of energy (diesel) in both softwood plantations and hardwood forests. Dias et al., [11] evaluated the environmental impacts associated with the production of Eucalyptus globulus Labill. and Pinus pinaster Ait. in Portugal using three different management scenarios. The logging stage and the fertilizers application have the highest contribution to the environmental impact of both Eucalyptus and Pine production. For the same management scenario, the production of Eucalyptus wood generates higher emissions than Maritime Pinewood. In South America, there are not many literature reports of the life cycle assessment of forest biomass. Morales et al., [12] evaluated the potential environmental impacts of the Chilean short rotation Eucalyptus globulus for bioenergy production considering the LCA methodology. The harvesting phase (fertilization and forwarding) was the main contributor to almost all the environmental impact categories. Arteaga-Pérez et al., [13] analyzed the environmental impact associated to the co-firing of coal and forest biomass (Pinus Radiata and Eucalyptus globulus) for electricity generation in Chile. The environmental impact of the electricity generation using these forest biomass is highly influenced by the harvesting and logistic chain.

As mentioned before, several studies have evaluated the environmental impacts of the forest biomass procurement process. However, few studies have integrated the production of bioenergy with the forest biomass cultivation [12,14,15]. Iribarren et al., [15] performed the life cycle assessment of the hydrogen production using Poplar wood as raw material following a cradle-to-gate approach, starting at the feedstock plantation and finishing at the purification facility. Raw material cultivation, harvesting and pretreatment, and syngas cleaning were identified as the subsystems with the largest contributions to the environmental impacts.

The main objective of this study is to perform the life cycle assessment of the hydrogen production via air gasification using P. patula as raw material, following a cradle-to-gate approach, starting at the seedlings production, to the P. patula production (site establishment, harvesting, collection and transportation) and finishing at the hydrogen production process (raw material pretreatment, processing, and purification and conditioning). In order to identify the main processes contributing to the environmental impacts.

2. Materials and methods

Life-cycle assessment (LCA) is a methodological tool used to measure the environmental impact of a product or service throughout its life cycle (from the raw material production until the process end of life) [16]. The methodology is based on the compilation and analysis of the inputs and outputs of the system in order to assess the potential environmental impacts, aiming to determine different strategies to reduce these impacts [17].

2.1. Goal and scope definition

The objective of this study is to identify the main environmental aspects and impacts related to the production of P. patula and hydrogen (via gasification), in order to detect the hotspots in each stage of the life cycle. There are not structured forest management practices in Colombia due to the lack of government policies and control. Therefore, forest inventory data was gathered together from seed nurseries, farmers, and sawmills located in Manizales, Colombia. The LCA was carried out from a cradle-to-gate perspective, starting at the production of the raw material (i.e. seedlings production, P. patula harvesting, transportation from the collection center to the processing plant, among others) and finishing at the hydrogen production from wood chips through gasification.

2.2. Functional unit

According to Iribarren et al., [15], one cubic meter of hydrogen is
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