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Pyrolysis gases burners: Sustainability for integrated production of charcoal, heat and electricity

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ABSTRACT

Brazil is the largest producer of charcoal, specifically for obtaining pig iron, basic raw material for the production of steel. Charcoal production is an economically important activity for Brazil, but there are challenges that impede its sustainable production throughout the length of the production chain. A major bottleneck in the charcoal chain is relative to higher emissions of pollutants and gases causing the greenhouse effect. These emissions can, moreover, be mitigated by incineration of the gases, thus reducing emissions into carbon dioxide and water. Incineration of gases opens new business opportunities, because the energy generated during the incineration process can be transformed into electricity, generating more revenue for producers, and can also be used in the drying of the wood to be carbonized, reducing the production cycle time, increasing production capacity and hence producers' income. However, to date, these technologies failed to achieve the entire production chain, consistently and comprehensively, mainly due to technical barriers to be overcome, requiring researches that validate and improve these systems. Therefore, the general goal was to identify the key critical factors in the Brazilian production chain of charcoal and to investigate major issues related to the combustion of the gases generated during the carbonization process. The charcoal chain study was performed by SWOT analysis and the comprehensive literature review allowed addressing the challenges of burning the emission from charcoal kilns and the status of gas burner technologies. Policies are required to motivate the use of technologies for reducing the emission from charcoal production. Investment in research in partnership to the charcoal companies will ensure the improvement of the gas burning technologies. Also, credit lines to farmers would encourage the implementation of these technologies.

1. Introduction

Charcoal is an energy source of great importance in Brazil, not only because it is renewable, but also for its historical and economic importance for the country. Currently, Brazil is the largest producer and consumer of charcoal, producing and consuming 5.6 million and 4.27 million tons, respectively [1,2]. Thus, the production and use of charcoal along with the ethanol from sugarcane are perhaps the best known examples of Brazilian success in bioenergy [3].

The main destinations for charcoal produced include the pig iron and steel sectors, which consume 76% of charcoal; ferroalloys, which use 10%; followed by residential, with 9.7% (household cooking and heating), and commercial and industrial (excluding the steel industry) sectors, especially for the production of cement and for the chemical and food industries [4]. The State of Minas Gerais has the largest charcoal-based steel industry in the world and has emerged as the largest producer and consumer of this energy source [5].

The use of charcoal has many advantages over coal and coke breeze, such as it is renewable, less polluting and almost free of sulfur and phosphorus. Coal combustion in the steel industry contributes with approximately 90% of the total CO_2 emissions [6]. Thus, partial or complete substitution of coal by a renewable fuel in the ironmaking process is an attractive technique for reducing CO_2 emissions and gaseous pollutants [7,8]. CO_2 mitigation in the iron-ore sintering process were shown by Abreu et. al [9], who investigated the replacement of coke and anthracite with 0%, 10%, 25%, 50% and 100% of charcoal in two different granulometry. Experimental results indicated that up to 50% charcoal substitution showed to be viable, resulting in a 50% reduction on greenhouse gas emission.

In contrast to Brazil that uses charcoal primarily as an input in

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industrial processes, in other charcoal-producing regions like sub-Saharan Africa, charcoal is mainly used for subsistence needs [10]. In 2004, 560 million households in developing countries relied on traditional biomass (fuelwood, charcoal or dung) for cooking. This corresponds to a total of 2.68 billion people, 40% of the global population [11]. Countries like Kenya have a yearly consumption of about 2.4 million tons of charcoal [12]. Estimates of Kenya's charcoal consumption vary widely, but it is likely one of the largest charcoal consumers globally in absolute and per capita terms [13]. Charcoal in Europe is mainly used for the barbecue market [14], more than 800,000 t of charcoal is used in Europe every year. Nigeria is the biggest charcoal supplier in Europe, with Namibia, South Africa, Egypt, and Ivory Coast also exporting to Europe. In total, Africa accounts for 40% of all European charcoal imports [15].

Although Brazil is the largest producer and consumer of charcoal, it has been observed that its production is facing numerous challenges, from the market fluctuations to technical problems, kilns operation, low productivity, variable quality of raw material and lack of skilled labor. A major problem faced by the sector is the greenhouse gas emissions resulting from the transformation of wood into charcoal, causing a large and negative social and environmental impact.

The carbonization process releases noxious gases into the atmosphere, such as CH_4, greenhouse gas with high global warming potential, and CO; their inhalation may trigger respiratory diseases and carcinomas [16]. The emission factor of these gases was estimated in several studies [16–20]. Observations made in 11 ovens of these studies indicated an emission factor (g greenhouse gas/kg charcoal produced) at 1788 ± 337 for CO_2 and CH_4 is 32 ± 5. Additionally, the biomass carbonization process also releases PAHs, both liquid and in gaseous phases, which is highly toxic and requires special attention. Barbosa et al. [21], for example, detected 16 PAHs associated with the particulate material from slow pyrolysis of *Eucalyptus* sp.

Given this scenario, technologies for burning such gases, which enables the reduction of emission of these pollutants is a viable alternative for the sustainable production of charcoal. Burners coupled to charcoal kilns are designed to burn the gases generated during the process, turning pollution into energy in the form of heat. This energy provided by burners can be utilized for drying the wood to be introduced into the kilns and for generation of electricity for use in the charcoal production unit itself or even distributed across the electricity network. According to Miranda et al. [22], cogeneration of electricity from charcoal production is a promising technology with worldwide application, since it could offer several benefits including entrepreneurial opportunities, livelihood diversification and increased income in rural areas for charcoal entrepreneurs, as well as reduction of greenhouse gases emissions and additional renewable energy capacity.

Despite advances in the field of combustion of the carbonization gases and the implementation of some burners by companies, studies are still required to achieve the best cost-effective system, as there are technical and economic barriers to be overcome. This study aimed to survey the main critical factors inherent to the charcoal production chain in Brazil. This article also extensively discusses the technology of burning of pyrolysis gases, analyzing the history of this technology and listing the main challenges and opportunities for its use.

2. The process of charcoal production

The charcoal production takes place indoors under controlled oxygen conditions, by applying heat to the wood for its distillation and breakdown of its constituents into non-condensable gases (carbon dioxide, carbon monoxide, hydrogen, etc.), condensable gases (tar and pyroligneous acid) and solid (charcoal) [23].

The amount of solid (charcoal), liquid (pyroligneous extract) and gas (pyrolysis gas) generated depends on several process parameters, including temperature, time, pressure and design of the kiln [14,24,25]. Solar et al. [26] studied the influence of temperature and residence time in the quality of the charcoal obtained in the pyrolysis of biomass waste (*Pinus pinaster*). They found pyrolysis yields in the range 20–30 wt% charcoal, 6–22 wt% liquids and > 47 wt% gases at high pyrolysis temperatures (1023 and 1173 K) with 32 and 64 min of residence.

Under normal conditions, considering wood with 20% moisture, approximately 30% original wood mass is processed into charcoal and 70% into pyrolysis gas. These gases, which are usually released into the atmosphere, contain about 50% initial energy incorporated into the wood raw material [27].

Carbonization is a slow pyrolysis process, whose main goal is to eliminate most of the oxygen and hydrogen by the action of heat and, therefore, enable the carbon concentration in the residual structure, which is the charcoal. The transformation of wood into charcoal is a process of irreversible physicochemical thermal decomposition, which starts with drying, loss of free or capillary water and bound water. After water removal, the pyrolysis stage begins with production of condensable and non-condensable gases [28].

According to Oliveira [29], the carbonization process is divided into four steps, although only the first three steps are included for charcoal production:

Drying of wood: evaporation of all the water contained inside the wood. Temperatures remain below 180 °C. In the most traditional kilns, heat required to maintain the proper temperature is supplied by burning part of the wood in the kiln.

Pre-carbonization: between 180 and 290 °C. It is an endothermic process, at which begins the release of volatiles. Wood starts to decompose, releasing CO, CO_2, acetic acid and methanol.

Carbonization: between 300 and 500 °C. The reaction becomes exothermic and self-sustaining. The thermal decomposition process accelerates and releases more heat, so that the temperature does not decrease while carbonization continues. There is great elimination of gases such as CO, CO_2, H_2, CH_4 and condensable vapors. The release of tar and pyroligneous acid reaches its maximum, as well as the wood decomposition rate. The final residue of this step is charcoal, which, when heated to near 500 °C, has a low volatile content and a high fixed carbon content.

Gasification: above 500 °C, the charcoal starts to thermally degrade, initiating the gasification, which is not interesting in the process of conversion of wood into charcoal.

Gases produced during the carbonization process are the result from thermal decomposition of the main chemical components of wood, hemicellulose, cellulose and lignin. Each wood component decomposes more intensely in different temperature ranges, and variable, according to ranges cited by several authors.

According to Alho [30], during pyrolysis, hemicelluloses are the least stable components to thermal degradation due to their amorphous nature. The degradation starts around 250 °C, and is almost complete around 325 °C. The hemicelluloses produce more non-combustible gases and more tar than cellulose. Most of the acetic acid produced during pyrolysis is assigned to hemicelluloses. Cellulose, the main chemical component of wood, decomposes at temperatures between 260 and 350 °C, being responsible for the production of most flammable volatiles. The products formed during initial pyrolysis of cellulose, the primary pyrolysis, undergoes a secondary pyrolysis. As an example, levoglucosan decomposition at temperatures above 270 °C, in water, formaldehyde, acetic acid and phenols.

The lignin as high resistance to thermal degradation as compared to cellulose and hemicellulose, due to its high level of aromaticity, to the size and arrangement of its structure [31]. According to Yang et al. [32], its decomposition occurs slowly, from 100 to 900 °C, with an exothermic reaction, with peak energy release at 305 °C.Lignin is responsible for the presence of phenols and other aromatic compounds in the pyrolytic liquids in addition to contributing to the production of charcoal, carboxylic acids, methanol and other products.