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Preventing wildfires through smart management and valorisation of residual forest biomass into biochar: experiences from the BioValChar project

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Abstract

Forest management operations adequately integrated in the forestry value-chain are the gold standard in wildfire prevention. However, these operations generate considerable amounts of residual forest biomass (RFB) that cannot be legally disposed in land and further require suitable management. Residual biomass also includes highly flammable plants existing in the Portuguese forest such as gorse, broom, giant reed and acacia. Quite often wildfires in Portugal are linked with spreading of this residual biomass that promotes fuel accumulation. Besides deleterious impacts on rural and forestry economy, wildfires are also a driver for desertification and soil degradation.

Alternative uses for this residual biomass to promote its valorisation and enable proper models of management of forest areas are needed, thus providing economic and environmental benefits towards decreasing of the fuel load. Though this biomass has reasonable carbon content and heating value, they also present inorganic composition (e.g. Na, K, Cl) that promotes operating problems in thermochemical conversion processes as combustion and gasification for useful energy production because of ash related problems (e.g., sintering/fouling), thus restricting their use in such applications.

As such, biochar production by pyrolysis is a potential alternative to generate added-value. During pyrolysis the volatile matter of biomass is released to the gaseous phase, resulting a solid product, biochar, which is carbon-rich and contains most of the inorganics (nutrients) of the raw biomass. Exposure of biomass inorganics as free ashes is prevented in this process, and hence pyrolysis mitigates their negative effects. Nonetheless, the efficient pyrolysis of these types of biomass requires development of novel solutions optimized for energy and environmental performance. Enhancing of the energetic sustainability of the process and minimizing of the environmental impacts associated to the emission of gaseous pollutants are aspects of major relevance. Additionally, the biochar quality depends on biomass type, technology and operating conditions used.

The BioValChar project (https://biovalchar.web.ua.pt/en/) seeks to answer these challenges related to valorisation of low-quality residual biomass through production of biochar by pyrolysis, which can return back to forest and rural soils. This approach will provide both carbon/nutrient cycling and synergies within forestry management, wildfire prevention, improvement of soil quality and rural development, under the circular economy principle. The research focus valorisation of residual forest biomass in full-control pyrolytic batch and continuous (auger-type reactor) processes, and testing of the resulting biochar performance as soil amendment. Moreover, a prototype of an integrated mobile unit for auto-thermal and continuous biochar production by pyrolysis of biomass is also being developed, by using the pyrolysis gases to provide the energetic needs of the process. Here we present the project overview, as well as some preliminary results on pyrolytic valorisation of one selected biomass (acacia) into biochar through distinct operating modes and conditions.

1. Context

Portugal territory has a significant fraction of forest supporting economic activity. However, as a result of improper forestry management, forest and rural areas have been subjected to strong pressure from wildfires, with negative impacts on natural resources (ecosystem degradation) and human life (socio-economic threats). The Portuguese Government launched a commitment program to develop Scientific and Technological

Research (S&TR) related to forest management and valorisation and prevention of forest fires (Conselho de Ministros, 2017), in line with the National Strategy for Forest (Conselho de Ministros, 2015). The goal is to generate applied knowledge to integrate perspectives of management and valorisation of forest resources, and underlying prevention to forest fires. Valorisation of residual biomass in rural areas is of the most relevant topics requiring applied S&TR.

Previous studies have identified distinct types of residual biomass from forestry operations with potential to be valorised to energy (Lopes *et al.*, 2013). In turn, forest cleaning for wildfires prevention also results in significant amounts of residual biomass without quality enough to be valorised into energy. This includes shrubs (acacia, gorse, broom, giant reed), which inorganic contents (e.g. K, Cl, Na) and resulting ash pose operating problems during combustion or gasification (van Loo and Koppejan, 2008; Niu *et al.*, 2016). These shrubs are highly flammable and have been identified recently as drivers for wildfire propagation in Portugal, as the Independent Technical Commission that investigated the wildfires that occurred in 2017 recommend their proper management towards wildfire prevention (Comissão Técnica Independente, 2017).

Since some of this residual biomass has considerable carbon content and heating value (van Loo and Koppejan, 2008), alternative valorisation must be developed. Biochar production by pyrolysis is an option. The pyrolysis process allows generation of distinct products, namely gases, liquids (bio-oils) and solids (biochar), with relative yields and composition depending on biomass type, pyrolysis reactor and operating conditions (Neves *et al.*, 2011). During pyrolysis the volatile matter of the biomass is released to the gas phase, thus remaining a solid fraction (biochar) where most of the inorganic content (ash constituents) of the raw biomass is embedded onto a carbon-rich matrix (Neves *et al.*, 2011; Neves *et al.*, 2017; Tarelho *et al.*, 2020), thus minimizing ash related problems that otherwise would be experienced during combustion or gasification.

The appropriate process for biochar production is slow pyrolysis (or carbonization), and several technologies have been referred as applicable, yet most of them derive from those applied to charcoal production from woody biomass (Neves *et al.*, 2011; Tarelho *et al.*, 2020) to be used as fuel. These technologies are mostly of type batch operated, large size, with low energy efficiency and high environmental impact. Considering the characteristics of residual biomass, more appropriate reactor configurations need development (Qureshi *et al.*, 2018) by addressing fuel flexibility, continuous operation, energy efficiency, portability/mobility, and this is a major challenge since existing information on technologies for biochar production relies on conventional configurations. New standards of product quality and energy efficiency can only be achieved with high level of process integration, e.g. by using the pyrolysis gas as fuel to satisfy the process energy needs (Salgado *et al.*, 2020; European Biochar Certificate, 2022). As such, these subjects require further applied research and technological development (R&TD), as most of the knowledge on biochar production concerns laboratorial small-scale.

Biochar produced from this low-grade residual biomass has no interest as fuel (charcoal) in typical energy applications due to its inorganics content and particle size, so alternative applications to boost its added-value have been suggested (Qureshi *et al.*, 2018; Salgado *et al.*, 2020; European Biochar Certificate, 2022; Lehmann and Joseph, 2015) yet lacking of technical evaluation and scale-up. The pyrolysis variables (e.g. feedstock, reactor type, heating rate, peak temperature, residence time) should be defined in order to obtain biochar with suitable characteristics (e.g. surface area, porosity and chemical composition) for specific applications and with economic profits, and that depends on biomass and pyrolysis conditions (Tarelho *et al.*, 2020; Salgado *et al.*, 2020; Lehmann and Joseph, 2015). As a way of improve physico-chemical and biological properties of soils, it has been shown that biochar significantly increases soil water holding capacity (Qian *et al.*, 2015; Verheijen *et al.*, 2019), while increased infiltration in Mediterranean soil can increase available soil moisture during dry periods (Abrol *et al.*, 2016). Biochar in soil contributes to carbon sequestration and nutrient recycling (European Biochar Certificate, 2022; Lehmann and Joseph, 2015). Biochar contains (in)organic forms of N and P that can improve the nutrient use efficiency in plant-soil systems. This feature can provide N/P recycling and enhanced crop nutrition and yield, thus decreasing the application of inorganic fertilisers (Gul and Whalen, 2013) with associated environmental and economic gains. However, besides soil type, the agronomic value of biochar also relies on its redox chemistry that rules nutrient dynamics (Gul and Whalen, 2013; Palansooriya *et al.*, 2019), which in turn strongly depends on feedstock and process conditions. Therefore, trade-offs between pyrolysis conditions, biochar characteristics and impact on soil nutrient pools of specific agro-ecosystems require deeper research to boost the agronomic value of biochar.

Applied knowledge on biochar production from pyrolysis of residual biomass in a decentralised (in-situ) and energy sustainable process, and its valorisation in soil, is a key subject requiring innovative R&TD to support proper management and valorisation of residual biomass in rural areas. Demonstration of this integrated approach will both assist wildfires prevention and enable business models based on circular economy.

2. Project objectives and overview

The BioValChar project is public-funded and aims at valorisation of low-grade residual forest biomass (RFB) resulting from forestry maintenance operations for wildfire prevention. The valorisation process involves biochar production by pyrolysis, followed by biochar use as soil amendment and demonstration of the economic gains of the process towards development of sustainable business models. The methodology gathers scientific competences related to thermochemical conversion processes of biomass to energy vectors and organic products, waste management, biochar application, restoration of soil functions and energy/engineering economics, as well as collaborating companies. Furthermore, project demonstration targets two contrasting edaphoclimatic study areas in Portugal (north-central coast and central inland) in which wildfires often occur and where one of the partner companies has on-going forestry cleaning activities. This way the project outputs and impacts become validated to possibly apply to other countries experiencing wildfire issues.

The BioValChar research is being developed over four integrated axes:

1) Development and characterisation of the pyrolysis process at bench-scale under batch (fixed-bed reactors) and continuous (auger-type reactor) modes of operation. It will allow evaluate the influence of processes conditions (e.g. peak temperature, heating rate and soak time) in the yields and properties of each of the products (biochar, bio-oil and gas). Both fixed-bed and auger-type reactors were designed and developed at the University of Aveiro.
2) Design and construction of a prototype of a mobile integrated pyrolysis unit with a biomass processing capacity up to 10 kg h^{-1}, including a continuous pyrolysis reactor integrated with a combustion reactor to deliver heat for the pyrolysis process. It will be optimised for considering energy efficiency and environment performance. This will advance significant innovation and scientific knowledge on energy efficiency and mitigation of emission of air pollutants during biochar production in integrated pyrolysis-combustion systems, in order to suppress the existing knowledge gaps in this field.
3) Valorisation of the biochar produced by studying its performance as soil amendment at bench- and field-scale. This will allow obtaining dose-response curves in several variables (e.g. pH, CEC, organic matter/carbon/nutrient contents, geochemical reactive content, respiration, biomass productivity, among others), aiming at determining and demonstrating the biochar agronomic value. Ultimately it will help to close the loop between biomass pyrolysis and return of carbon and nutrients to soil.
4) Techno-economic analysis of the several operations (e.g., biomass collection and processing, pyrolysis unit construction and operation, biochar application costs, and greenhouse gas offset) involved in the solution proposed towards establishment of feasible business models applied to the forestry sector. It will also comprise field-scale demonstration activities to stakeholders to upscale and transfer of the key-results.

3. Preliminary results

Since most of the work packages are currently still on-going, we present here an example of results obtained during the work progress in Axis 1 (bench-scale pyrolysis) applied to one of the selected biomass species (acacia). Biomass was collected from a coastal pine forest in north-central Portugal, as a result from forest cleaning operations for wildfires prevention. It was further chopped till a maximum particle size of c.a. 1 cm, and characterised for proximate and elemental analysis.

Pyrolysis experiments took place in both batch and continuous modes with full control and monitoring of the operating variables. For the batch experiments, a fixed-bed tubular quartz reactor with 20 mm internal diameter, 23 mm outer diameter and 350 mm length, and a tubular furnace with 25 mm internal diameter and 300 mm length was used. The tubular furnace is operated by means of a control and data acquisition electronic system that allows the definition of heating rate and peak temperature of the tubular quartz reactor. For the continuous experiments, an auger reactor was used. The experimental facility is composed of a biomass silo, a screw-type reactor made in stainless steel with 0.05 m internal diameter and an overall length of 2 m (including biomass feeding section, pyrolysis section and biochar discharge). The reactor comprises three sections, namely biomass feeding section, pyrolysis section, and biochar and gas discharge section. The biochar is discharged by means of a continuous screw feeder, and the pyrolysis gas produced is burned in a downstream combustion reactor.

Two peak temperatures were tested (450 and 550 ºC). In the batch process, soaking time and heating rate were set it 30 min and 20 ºC min^{-1}, respectively. In the continuous process, residence time (in the pyrolysis section) was set in 5 min. Biochar yields and proximate analysis are presented in Figure 1.

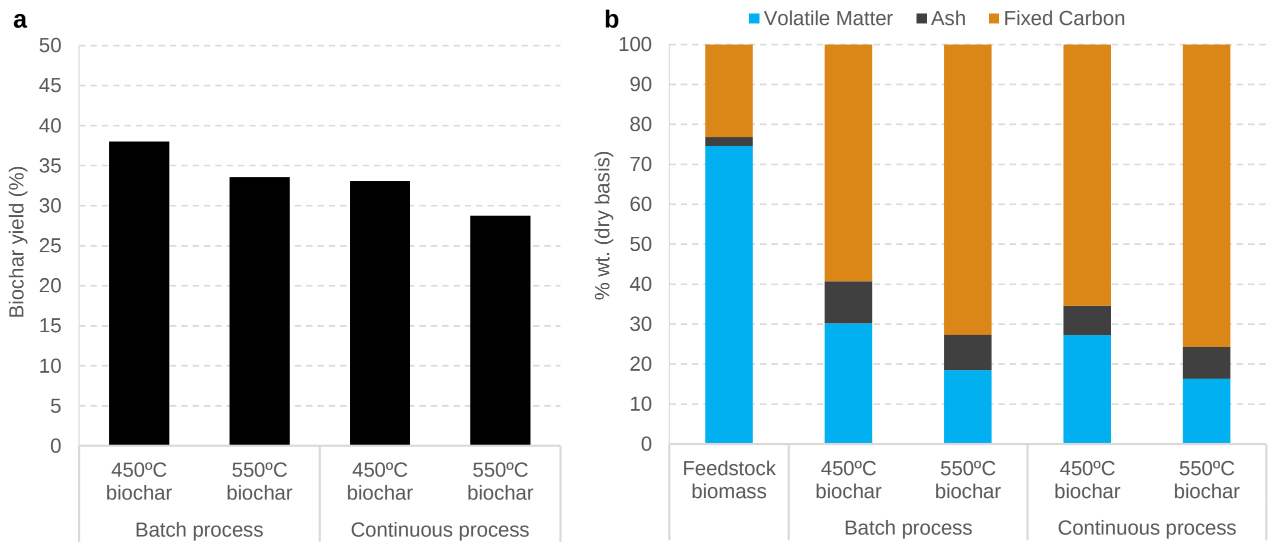

Figure 1- Biochar yield and properties, from batch and continuous pyrolysis of acacia: (a) biochar yield; (b) biochar proximate analysis

Biochar yields over the tested conditions and processes varied in the range 29 to 38%wt (Figure 1a). The biochar yield was influenced by both temperature and process mode. Peak temperatures of 450 ºC yielded 13 to 15% more biochar than 550 ºC peak temperatures, regardless of the process type. In turn, when reproducing pyrolysis batch processes in the auger reactor, a 13 to 14% drop in biochar yield was observed, regardless of the process temperature tested. The reasoning for this effect is under study, and its understanding is of upmost relevance to consider when designing scale-up of pyrolysis processes.

Regarding biochar proximate analysis (Figure 1b), similar trends are observed regardless of the pyrolysis operation mode. In both cases, the fraction of fixed carbon is substantially higher in the highest process temperature (73 to 76%wt) when compared to the lowest process temperature (59 to 65%wt), with the opposite trend observed in the volatile matter content. When comparing the process mode, continuous pyrolysis resulted in biochar with 4 to 10% higher fixed carbon content and 10 to 12% lower volatile matter than in the batch processes.

The ash content is systematically greater in the biochar resulting from the batch processes (9 to 11%wt) when compared to that produced through continuous processes (7 to 8%wt). When comparing process temperature, the increasing of 450 to 550 ºC resulted in a 15% decrease in the biochar ash content produced through batch pyrolysis. In turn, the same temperature shift in the continuous process resulted in a slight increase (5%) of the biochar ash content.

These preliminary results highlight the influence of the pyrolysis conditions and parameters in the key characteristics of the resulting biochar, and hence its further behaviour and feasibility as an added-value product in selected applications. Therefore, ensuring of a full control of the pyrolysis process, not only at prototype-scale, but especially considering upscaling scenarios, is of major importance to effectively provide a strategy to manage and valorise residual forest biomass, and thus enabling both wildfires prevention and profitable business models in the forestry sector. Moreover, the scope and outcomes of the BioValChar project are expected to provide a comprehensive basis towards replication of the models for management of residual forest biomass.

Its valorisation into biochar that can be applied to increase soil quality is of most relevance in ecosystems affected by recurrent wildfires and soil quality issues, such as the Mediterranean region.

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