


## Article

# Comparison of Waste Biomass from Pine, Eucalyptus, and Acacia and the Biochar Elaborated Using Pyrolysis in a Simple Double Chamber Biomass Reactor

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**Abstract:** Using waste biomass is considered one of the ways to reduce climate change. Arboreal waste biomass from pine, eucalyptus, and particularly invasive plants (*Acacias*) would make it possible to transform this natural resource, but needs to be adjusted to current and innovative technologies. The production of high fixed carbon biochar with this biomass would improve not only environmental aspects, but also the use of currently not susceptible materials for other types of exploitation. The objective of this study is to develop biochar from three different waste biomass materials and compare their parameters with those of the original biomass. Thermochemical conversion processes were used in a simple double chamber reactor developed for this study. Temperatures between 400 and 500 °C during 280 min were achieved and allowed to transform the initial biomass in a biochar with a high content of fixed carbon. By comparing the original biomass with the final biochar through tests of humidity, density, calorific values, fixed carbon, and cationic and elemental analysis, an increase in the parameters was confirmed. Fixed carbon of 70%, 77%, and 71% with pine, acacia, and eucalyptus biomass have been obtained, respectively, with yields between 30% and 40%. The results are favorable, particularly with acacia invasive plants, and could help in their difficult silviculture management.

**Keywords:** bioenergy; bioproducts; invasive species; waste biomass; pyrolysis; biochar; acacia



**Citation:** González-Prieto, Ó.; Ortiz Torres, L.; Vazquez Torres, A. Comparison of Waste Biomass from Pine, Eucalyptus, and Acacia and the Biochar Elaborated Using Pyrolysis in a Simple Double Chamber Biomass Reactor. *Appl. Sci.* **2024**, *14*, 1851. <https://doi.org/10.3390/app14051851>

Academic Editor: Dino Musmarra

Received: 29 January 2024

Revised: 19 February 2024

Accepted: 21 February 2024

Published: 23 February 2024



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## 1. Introduction

According to data from the National Forest Inventory of Spain (4th) [1,2], more than 600,000 ha of the northwest forestry surface is occupied by *Eucalyptus globulus* and *Pinus pinaster*. On the other hand, *Acacia* spp. is considered an invasive species in Spain by authorities and although it is not very clear in its extension, some studies suggest an increase in the dominance area of these species, which is more important in the case of *Acacia dealbata* and *Acacia melanoxylon* [2,3]. The proposal for the appropriate utilization of the biomass remains of these invasive acacias, as well as of eucalyptus and pine waste, is highly necessary. This renewable biomass is an energy source that has the potential to replace petroleum-derived fuels. Furthermore, it can support local agricultural and forestry industries, given that these approaches typically use the lignocellulosic materials found in forestry residues or forest by products' waste. Additionally, using an invasive plant which is highly difficult to manage or eliminate can lead to more sustainable forest management with economic returns [4,5]. However, the low adoption of innovative technologies and the limitations for the development of new products continue to represent untapped opportunities that have not been adequately addressed.

One approach to processing this biomass waste is through thermal treatment in order to produce charcoal, syngas, or another derivative. To produce biochar, several processes were used, typically categorized as torrefaction [6], pyrolysis [7], hydrothermal carbonization-HTC [8], and microwave carbonization [9]. Recently, pyrolytic processes for charcoal production have gained significant attention [6]. In addition to its typical use as fuel, new applications have emerged in the agricultural sector, where it is currently employed in order to improve

the physical and chemical properties of soils [10]. The utilization of this material, commonly referred to as biochar (charcoal of vegetable biomasses origin), enhances soil organic matter content while modifying acidity levels (pH). Likewise, it alters the cation exchange coefficients, allowing to improve the yield in diverse types of crops. Due to its porous structure, biochar is also used as an additive in low rainfall regions, where it effectively stabilizes soil moisture levels [11]. Additionally, the incorporation of biochar as a structuring agent and base material for nutrients during the composting process has optimized the degradation of organic matter while reducing emissions of ammonia and greenhouse gases. It is also known for its effectiveness in reducing the absorption of heavy metals in contaminated agricultural soils, and as an additive it is considered a climate change mitigation strategy given its ability to sequester solid carbon in agricultural fields for hundreds and even thousands of years [12]. Among the currently available technologies, pyrolysis constitutes an important alternative for the recovery of these biomasses, offering the flexibility to produce various products. This process yields solid compounds (carbonaceous materials), gaseous components (syn-gases), liquid fractions (bio-oils), or combinations thereof. There is a growing interest in the use of biochar derived from biomass across diverse disciplines to tackle significant environmental challenges [13].

Pyrolysis involves the thermal decomposition of the biomass under inert atmospheres (with either absence or low oxygen levels) and temperatures exceeding 300 °C [14]. It is the most common method for producing biochar and also converting the initial biomass waste into other clean sources, such as oil and gas [15]. Within the pyrolysis process, distinctions are made between a slow, fast, and very-fast system [16,17]. Several authors have successfully employed similar pyrolysis processes with different agricultural rest, yielding positive results [18–20], and also from pine chips [21], obtaining a high-performance biochar.

There are numerous parameters in the process with influence on the physicochemical properties of biochar, including the original raw material, reaction temperature, heating rate, residence time, and reaction atmosphere. However, it is particularly important that the system and reactor used involve simple manufacturing, employ affordable materials, are mobile (to be utilized near the biomass source), and feature straightforward operation without the need for non-renewable energy. The primary focus lies in enabling usage in rural areas of the wide world, especially in third-world regions with limited economic resources.

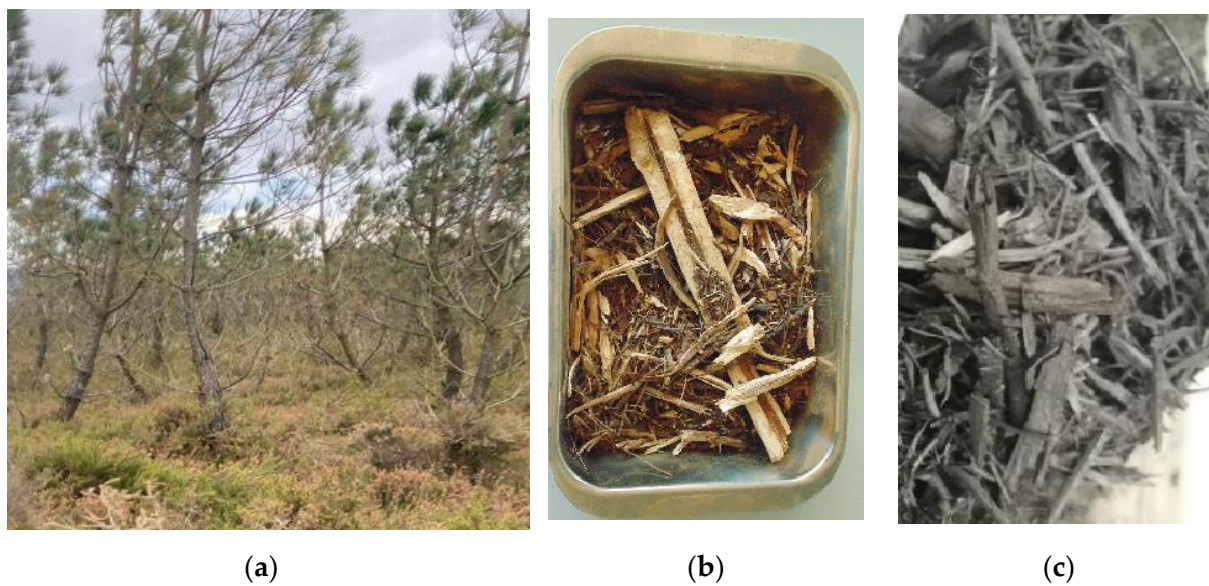
Following these criteria, this study employed a slow pyrolysis system in a straightforward vertical reactor with two parallel chambers. To achieve the desired temperature, a co-fuel process with biomass waste was utilized. Previously, studies [22] elaborated biochar from acacia wood using a slow pyrolysis process, achieving satisfactory results with temperatures ranging between 300 and 500 °C, with an optimum temperature of 434.8 °C for 1 h using a laboratory electrical furnace. Similarly, Sriburi and Sohi et al. [23,24] used a slow pyrolysis process under a low–moderate temperature (450–500 °C) with an extended residence time (2–3 h) in the absence of oxygen to produce biochar from different waste materials, yielding satisfactory results for soil improvement purposes.

This study aims to develop biochar from three different biomass waste materials and compare the parameters from the original biomass and final charcoal. Through the application of thermochemical conversion processes, specifically slow pyrolysis using a simple double grate reactor, it is possible to transform the initial biomass into biochar with a high content of fixed carbon. This heating process does not rely on energy from electricity or fossil sources. Moreover, the syngas produced is redirected back into the heating process, thereby preventing energy and emission into the atmosphere. Additionally, the integration of consecutive processes allows for the utilization of residual heat, further enhancing efficiency. These principles fit into the research and application of biochar in Europe [25] and takes into account that the diverse physicochemical traits of biochars profoundly influence their broad spectrum of applications [26].

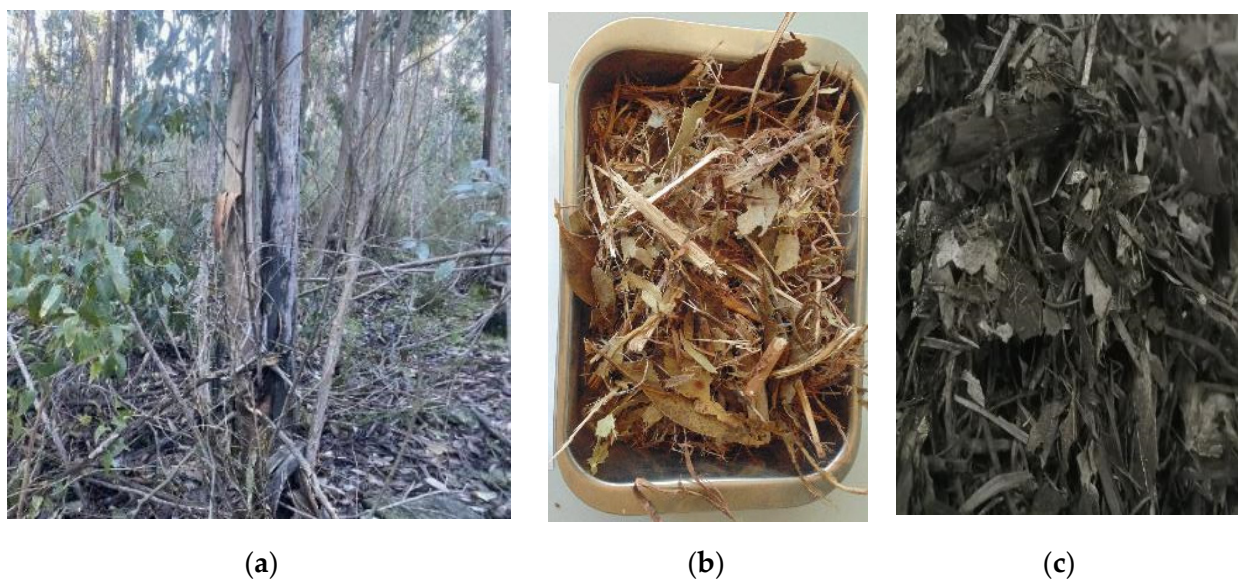
This is of high interest as it adds value to residual biomass, including invasive plants, thereby increasing their overall value. Comparing the original lignocellulosic biomass with the final biochar obtained after the thermal process allows to observe the enhancements in the original properties and parameters.

## 2. Materials and Methods

Biochar was produced from three types of waste biomass: 12-year-old *Pinus pinaster* from a failure plantation (due to unsuitable silviculture conditions), 5-year-old *Eucalyptus globulus* affected by a fire and weevil infestation, and biomass from a mass of invasive *A. dealbata*. Figures 1–3 show the original biomass material in forestry (a), processed waste material (b), and final biochar (c). The study thus involves two hardwoods and one softwood, comprising lignocellulosic biomass from widely distributed trees. The three primary components of these lignocellulosic biomasses are cellulose, hemicellulose, and lignin [27], together with inorganic chemicals and organic extractives, as well as a significant amount of free and bound water.



**Figure 1.** *P. pinaster* (a) waste material in the forestry, (b) crushed material, and (c) final biochar.



**Figure 2.** *E. globulus* (a) waste material in the forestry, (b) crushed material, and (c) final biochar.





**Figure 3.** *A. dealbata* (a) waste material in the forestry, (b) crushed material, and (c) final biochar.

Biomass and biochars exhibit a multitude of physical, chemical, and mechanical characteristics, which vary depending on the raw material and pyrolysis conditions, making their characterization essential [28]. For the characterization of the biomass and biochar, different standards of solid biofuels were used to prepare the material [29] and determine the following: moisture content (%) [30,31], density ( $\text{kg}/\text{m}^3$ ) [32–34], calorific value ( $\text{kJ}/\text{kg}$ ) [35], volatile matter (%) [36], ash content (%) [37], fixed carbon content (%), total carbon, hydrogen, and nitrogen content (%) [38], and principal major and minor elements of composition (%) [39–41]. The biochar yield was determined as the ratio of the prepared biochar weight in relation to the weight of the initial biomass subjected to pyrolysis, according to Equation (1).

$$\text{Biochar yield} = (w_2/w_1) \times 100 \quad (1)$$

where  $w_1$  is the weight of the biomass at the moisture content on a wet base before pyrolysis and  $w_2$  is the biochar weight at the end of the thermal transformation process.

Fixed carbon is the solid carbon in the biomass and biochar that remains in the pyrolysis process after devolatilization. It is determined from the following Equation (2).

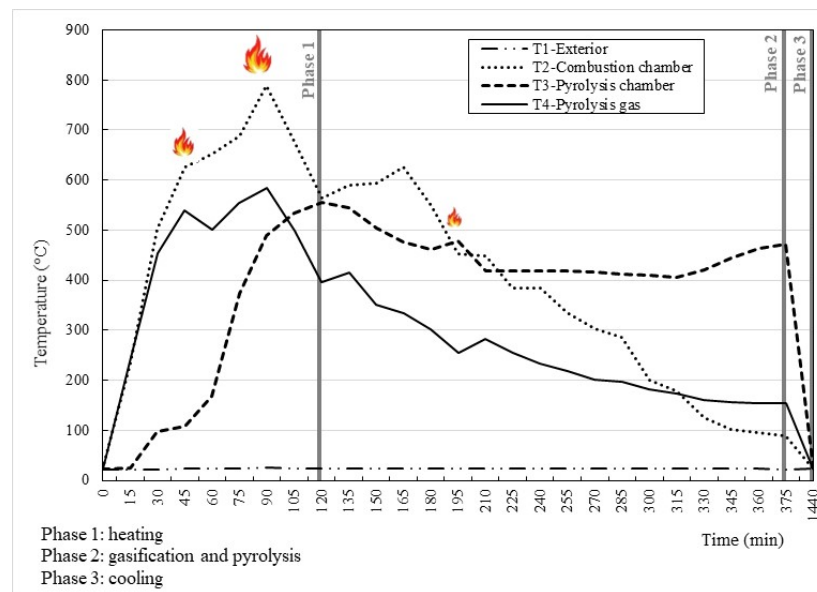
$$\text{Fixed Carbon} = 1 - V_d - A_d \quad (2)$$

where  $V_d$  and  $A_d$  were the volatile matter content and the percentage of ashes on a dry basis.

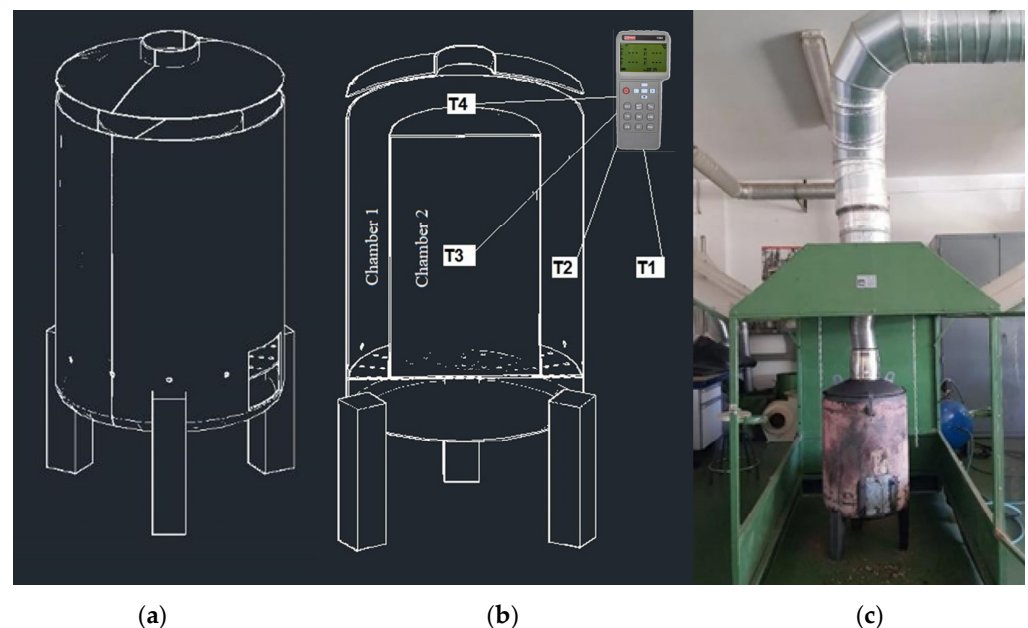
In relation to the thermal process employed for biomass transformation and biochar production, Figure 4 shows the conditions of the slow pyrolysis process, divided into three phases. The first phase involves water content evaporation and biomass heating, with an increase in the temperature at a rate close to  $4.5\text{ }^\circ\text{C}/\text{min}$  for the first 40 min, reaching a maximum temperature of  $540\text{ }^\circ\text{C}$  over the next 90 min. In the second phase, pyrolysis occurs with the emission of syngas, with the temperature ranging between  $540$  and  $480\text{ }^\circ\text{C}$  for the subsequent 255 min inside the pyrolysis chamber, considering a long residence time [13]. Finally, there is a third phase of cooling, during which the high residual temperature decreases to room temperature ( $15\text{ }^\circ\text{C}$ ) over a span of 15 h.

The reactor employed operates at a semi-industrial scale conducted by the research group. Figure 5 shows the exterior (a) and interior view (b) of the reactor, along with a real image of the installed unit (c). Figure 5b shows the double chamber: “chamber 1” where high temperatures are generated using biomass, with a volume of  $0.17\text{ m}^3$  and outlet chimney for gas and smoke; and “chamber 2”, contained inside chamber 1, where the biomass is transformed into biochar, with a capacity of  $0.10\text{ m}^3$ , and is sealed from the outside with a

5 mm gas outlet hole. To simplify construction and avoid the need for complex welding, machining, or casting methods, locally available materials and supplies were utilized, allowing for quick and agile assembly while facilitating potential subsequent recycling.



**Figure 4.** Temperature and time in the reactor to transform the biomass in biochar.



**Figure 5.** (a) External schematic representation of the reactor; (b) internal schematic representation of the reactor, with identification of the two chambers and the points where process temperatures are recorded; (c) real reactor and installation in the laboratory.

In chamber 1, two types of fuel-biomasses are employed: low-density materials in the upper part of the chamber, comprising residual remains of pine solid wood from pallets with high flammability, and higher-density materials, consisting of pelletized biomass, which provide sustained temperatures over time. The combination of these two types of biomasses, along with the regulation of the combustion air entry through controlled holes in chamber 1, enables the control of the system temperature.

During the process inside chamber 1, combustion occurs as the biomass is heated in the presence of oxygen. Chemically, this exothermic oxidation of material generates high temperatures in the presence of oxygen, producing CO<sub>2</sub> and H<sub>2</sub>O along with the hot flue gas that is transmitted to chamber 2. The combustion in chamber 1 produces the temperature for the reactor but is not optimal for producing biochar since it converts most carbon in the biomass to CO<sub>2</sub>. However, in chamber 2, a rise in the temperature occurs with a deficiency in oxygen as a consequence of a gas-pressure increment inside. This pressure is expelled outside through a hole dimensioned accordingly. The gas pressure generated inside by the syngas is so high that it prevents the entry of oxygen from the outside. As a result, a thermal process and material flows within the reactor are achieved, comprising three phases, as depicted in Figure 4. The external flame in chamber 1 never comes into contact with the material undergoing conversion to biochar in chamber 2. The syngas of chamber 2 has been reintroduced into the heating process, contributing to the increase in temperature and preventing the emission of gases into the atmosphere. Temperature profiles were measured with a set of 4 type K thermocouples and a data logger RS in the positions indicated in Figure 5b.

### 3. Results

#### 3.1. Biochar Yields

A yield between 30% and 40% was obtained in the production of the biochar. Table 1 shows the weight losses and the mean efficiency recorded in the conducted tests. The results indicate that approximately 1 kg of biomass is required to produce 0.21 and 0.42 kg of biochar, depending on the biomass used.

**Table 1.** Product yields of pyrolysis.

	Dry Biomass Weight (kg)	Biochar (kg)	Biochar (%)	Syngas and Bio-Oil (%)
<i>P. pinaster</i>	2.4	0.9	40 ± [2.17]	60.4
<i>A. dealbata</i>	2.3	0.8	34 ± [1.09]	66.2
<i>E. globulus</i>	2.2	0.7	30 ± [8.32]	70.2

[standard deviation].

#### 3.2. Moisture Content of Biomass and Biochar

The average moisture content (MC) of the three different biomasses and biochar was determined. The MC of the biomasses studied varied depending on their source conditions. During the collection of the materials, the meteorological season was cold, humid, and characterized by frequent rains, resulting in high average MC values for each biomass, as shown in Table 2. The MC measured in the biochar is residual, resulting from the thermal process during the pyrolyzation, which transforms it into an anhydrous material. Therefore, MC values of 0.3% were measured, making it unnecessary to distinguish between wet or anhydrous states.

**Table 2.** Moisture content of biomasses and biochar (%).

	Original Biomass		Final Biochar
	Wet Basis (%)	Anhydrous Basis (%)	Wet and Anhydrous Basis (%)
<i>P. pinaster</i>	43.1 ± [2.04]	76.0 ± [1.23]	0.3 ± [5.59]
<i>A. dealbata</i>	33.5 ± [1.06]	50.4 ± [0.96]	0.3 ± [5.73]
<i>E. globulus</i>	27.0 ± [1.76]	37.1 ± [1.02]	0.3 ± [8.56]

[standard deviation].

#### 3.3. Caloric Values

The Gross Calorific Value (GCV) refers to the heat released from the fuel combustion, including the energy released from water vaporization. On the other hand, the Lower Calorific Value (LCV) is based on steam as the product, meaning that its vaporization energy is not considered as heat [42]. The values obtained from the characterization of the calorific power of the biomass and biochar are summarized in Table 3.

**Table 3.** Original biomass and final biochar heating values.

	Original Biomass (kJ/kg) at MC <sup>1</sup> = 0%		Final Biochar (kJ/kg) at MC <sup>1</sup> = 0%	
	GCV <sup>2</sup>	LCV <sup>3</sup>	GCV <sup>2</sup>	LCV <sup>3</sup>
<i>P. pinaster</i>	20,597.1 ± [865.6]	19,100.8 ± [865.6]	28,760.8 ± [1446.5]	27,264.4 ± [1446.5]
<i>A. dealbata</i>	19,644.6 ± [1022.6]	18,148.3 ± [1022.6]	30,407.5 ± [915.6]	28,911.2 ± [915.6]
<i>E. globulus</i>	20,314.7 ± [765.6]	18,818.4 ± [765.6]	29,361.5 ± [387.6]	27,865.1 ± [387.6]

[standard deviation]; <sup>1</sup> MC = Moisture content (%). <sup>2</sup> GCV = Gross Calorific Value. <sup>3</sup> LCV = Lower Calorific Value.

### 3.4. Volatile Matter and Ash Content

Volatile matter refers to the percentage loss in mass, adjusted for moisture. In biomass, it primarily consists of combustible gases, such as hydrocarbons, hydrogen, oxygen, and carbon monoxide, and non-combustible gases, among others. On the other hand, a significant fraction of the biomass comprises inorganic constituents, commonly referred to as ash. Table 4 shows the average results obtained. Notably, in the results obtained, the acacia exhibits the highest values of volatile matter and the lowest values of ash content.

**Table 4.** Content of volatile matter and ash content (% d.w.).

	Original Biomass		Final Biochar	
	Volatile Matter	Ash Content	Volatile Matter	Ash Content
<i>P. pinaster</i>	80.3 ± [9.91]	2.8 ± [0.95]	19.9 ± [7.91]	10.1 ± [0.36]
<i>A. dealbata</i>	83.2 ± [6.91]	0.6 ± [0.52]	18.0 ± [1.26]	4.7 ± [1.24]
<i>E. globulus</i>	81.2 ± [4.72]	2.6 ± [1.05]	20.6 ± [3.79]	8.3 ± [1.48]

[standard deviation].

### 3.5. Fixed Carbon

Fixed carbon is the solid carbon in the biomass that remains as residue after the pyrolysis process and devolatilization. It is determined from the following Equation;

$$\text{Fixed Carbon} = 100 - \% \text{ Moisture Content} - \% \text{ Volatile Matter} - \% \text{ Ash content}$$

For each of the biomasses and biochar elaborated and studied, the average fixed carbon value is determined. Table 5 shows the results obtained.

**Table 5.** Fixed carbon (%).

	Original Biomass	Final Biochar
<i>P. pinaster</i>	16.2 ± [2.20]	70.0 ± [9.17]
<i>A. dealbata</i>	16.9 ± [1.97]	77.3 ± [2.51]
<i>E. globulus</i>	16.1 ± [1.52]	71.1 ± [2.31]

[standard deviation].

### 3.6. Bulk Density of Biomass and Biochar

The values obtained with the acacia material are higher in both the biomass format and the biochar format. Table 6 shows the average bulk density values obtained for both the biomass and biochar. A distinction is made between density values based on wet and anhydrous conditions for the biomass material. In the case of biochar, being already an anhydrous product, a single value is determined.

**Table 6.** Bulk density.

	Original Biomass (kg/m <sup>3</sup> )		Final Biochar (kg/m <sup>3</sup> )
	Wet Basis	Anhydrous Basis	Wet and Anhydrous Basis
<i>P. pinaster</i>	203.1 ± [2.57]	115.5 ± [1.46]	147.0 ± [10.59]
<i>A. dealbata</i>	213.1 ± [16.46]	141.7 ± [9.27]	127.1 ± [2.34]
<i>E. globulus</i>	125.0 ± [12.70]	91.3 ± [10.94]	104.5 ± [7.12]



### 3.7. Total Content of Carbon, Hydrogen, and Nitrogen

The total content of carbon, hydrogen, and nitrogen is determined. Table 7 summarizes the results obtained for each material.

**Table 7.** Elementary analysis of N = Nitrogen, C = Carbon, H = Hydrogen, and S = Sulfide.

	Original Biomass				Final Biochar			
	N (%)	C (%)	H (%)	S (%)	N (%)	C (%)	H (%)	S (%)
<i>P. pinaster</i>	0.89	48.21	6.71	<0.30	0.84	77.62	2.59	<0.30
<i>A. dealbata</i>	0.82	49.51	6.90	<0.30	1.63	81.06	2.66	<0.30
<i>E. globulus</i>	0.92	49.91	6.88	<0.30	1.19	76.17	2.85	<0.30

### 3.8. Principal Major and Minor Elements of Composition

Optical emission spectrometry (ICP-OES) produces excited atoms and ions with different emissions of electromagnetic radiation at different wavelengths, enabling the determination of trace elements. The elements were differentiated as major and minor elements in both the biomass and biochar. Table 8 summarizes the values obtained.

**Table 8.** Cationic analysis.

Cationic Analysis (mg/kg)	<i>P. pinaster</i>		<i>A. dealbata</i>		<i>E. globulus</i>	
	Biomass	Biochar	Biomass	Biochar	Biomass	Biochar
Ca	2280	14,560	1760	13,880	4960	16,600
Na	360	526	376	580	1960	3700
K	2800	8870	1720	5480	3880	14,200
Mn	148	459	120	378	200	880
Cu	8	265	2.4	36	4	40
P	1216	2590	960	2120	1320	3320
Mg	680	3620	520	2640	2080	5520
Fe	680	2290	64	680	124	580
Zn	16	90.5	8	38	8	52
Cr	12	14	<1	6	<1	4.4
Ti	36	420	2	516	8	70
Co	0.1	3.3	<0.1	1.05	<0.1	1.2
Ni	5.6	12.2	<0.5	4	2	4.8
Si	1320	2860	<50	972	320	1360
Al	1280	4280	84	512	360	1020
S	480	980	400	382	660	580
Cl	233	402	1589	1480	585	541

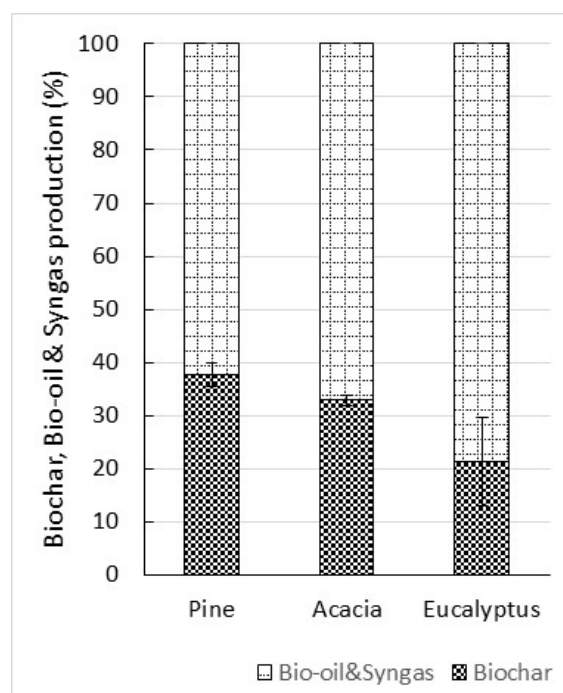
## 4. Discussion

### 4.1. Biochar Yields

According to the results, the lowest biochar production output was observed for the eucalyptus biomass. This could be attributed to the presence of abundant fine and small fractions such as leaves and branches, leading to a significant amount of material that volatilizes faster than wood itself [43]. Figure 6 shows a comparison of values for the three different biomasses. The obtained values are consistent with previous experiences conducted with biomass, particularly slow pyrolysis [44]. Nevertheless, achieving performance rates of less than 50%, which is typical in the case of solid wood, is primarily due to the inherent nature and variability of the biomass used, characterized by residual heterogeneous materials varying in size, constituents, and granulometry [45]. Previously, studies have reported yields ranging from 26% to 58% for pine within a temperature range of 300 to 450 °C [42].

Previously, studies [46,47] have found that the yield biochar varies significantly depending on the pyrolysis technique used. Slow pyrolysis conducted in an oxygen-free environment yields approximately 30% more charcoal compared to fast pyrolysis (12%) or gasification (10%). The results obtained are consistent with those of slow pyrolysis. Extended reaction times promote polymerization, thereby increasing production [13], while moderate temperatures and a short residence time typically result in more liquids [48].

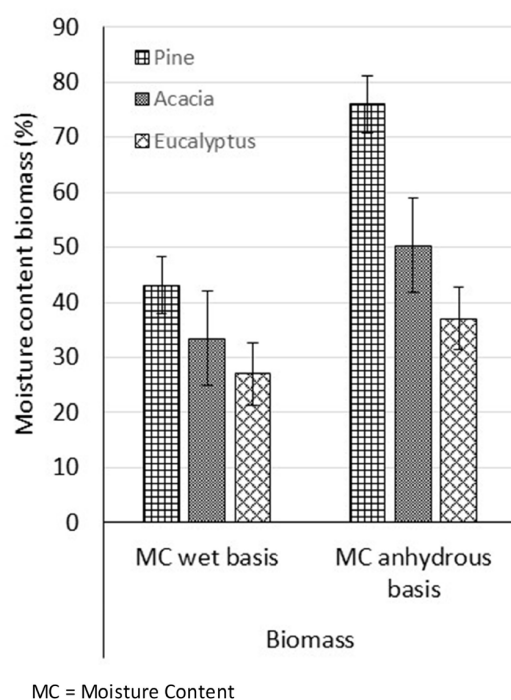




**Figure 6.** Comparison of quantity of the biochar and pyrolysis oil + syngas production.

#### 4.2. Moisture Content of Biomass and Biochar

The MC values of biomass vary significantly in a real supply compared to its initial MC depending on the collection conditions. This factor and this variability can influence the transformation process, as well as the handling and storage of biomass, potentially leading to decomposition, fungal growth, and spore formation [49]. The values obtained in this study correspond to the biomass collected in the mountainous areas during the spring season in northern Spain (Figure 7).

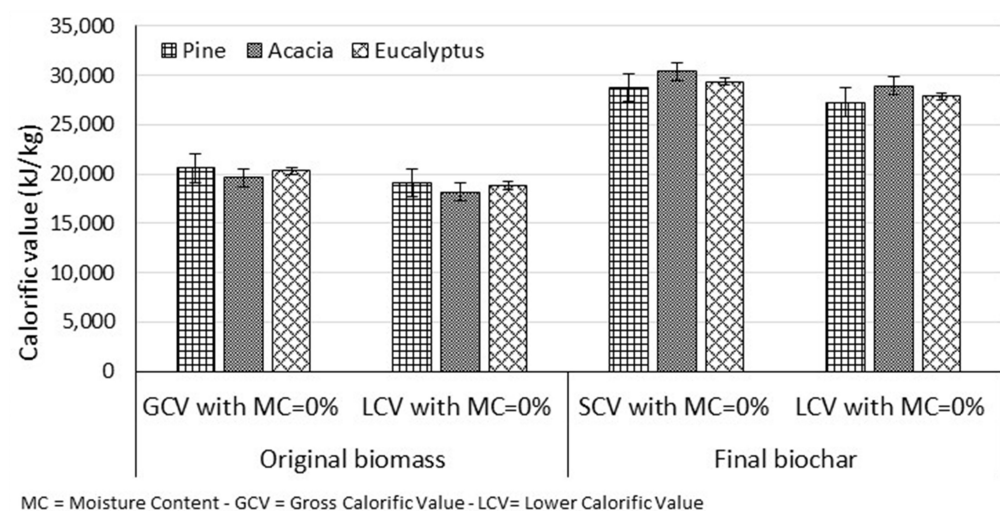


**Figure 7.** Moisture content of the biomass.

Previously, studies have found that pyrolysis typically involves relatively dry materials, usually with a moisture content below 30% w.b., although levels of up to 10% are considered acceptable [50]. The increase in biomass moisture content requires additional energy to achieve higher heat of vaporization as the biomass is heated to a pyrolysis temperature.

#### 4.3. Caloric Values

The values coincide with previous studies conducted on similar biomasses [51]. The data obtained for *A. dealbata* are particularly surprising, as they clearly exceed the value of *P. pinaster* and *E. globulus*, reaching the biochar values typical of woods of a certain quality (such as firewood). In any case, it is evident that the charred remains can be utilized for combustion with much better thermal characteristics than untreated biomass samples (Figure 8). Due to its high carbon content, biochar can serve as a valuable fuel source for power generation [52].



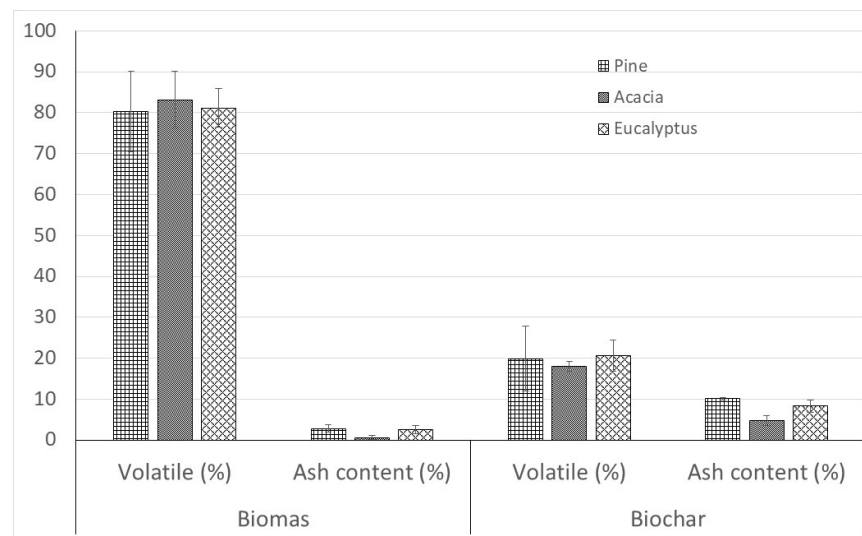
**Figure 8.** Calorific values of the three biomasses and biochar material.

Based on these results, there is no difference in the energy values between one of the hardwoods (eucalyptus) and the softwood (pine). However, the results for acacia are particularly noteworthy, surpassing even those of pine.

#### 4.4. Volatile Matter and Ash Content

Lignocellulosic biomass contains both inorganic chemicals and organic extractives. These inorganic chemicals, which account for less than 10% of the biomass by weight [13], are mainly transformed into ash during pyrolysis. Previous studies with hardwoods [53] reported ash content values of 9.86%.

While all initial mineral matter remains the same after pyrolysis is completed, the total mass is reduced by more than 60%, resulting in a significant increase in the recorded percentage of ash. Similarly, volatiles are drastically reduced since carbonization precisely begins with devolatilization. The values obtained for *A. dealbata* (Figure 9) are consistent with previous research, which reported values of 79.70% for volatile matter and 0.66% for ash content [42].

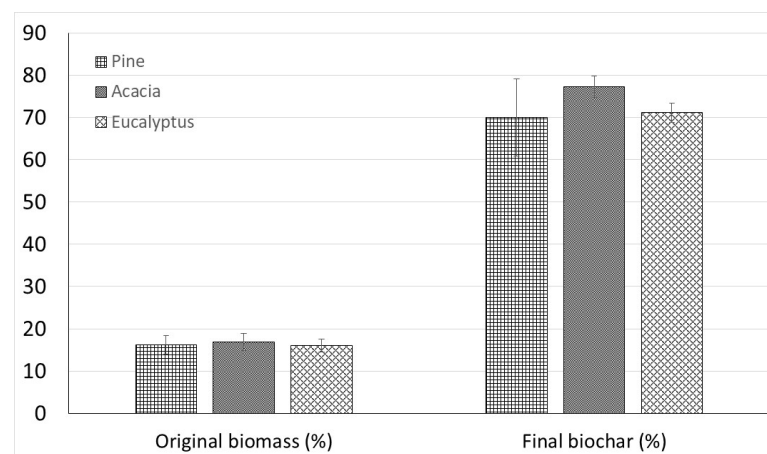


**Figure 9.** Volatile and ash content results.

#### 4.5. Fixed Carbon

The most significant and striking data correspond to fixed carbon.

According to previous studies [54], slow pyrolysis with a slow heating rate combined with moderate pyrolysis heat produces primary and secondary char rich in fixed carbon, depending mainly on the reactor and the original biomass. Lower H/C ratios result in the loss of more oxygen and hydrogen during combustion [55], resulting in a product with unique elemental carbon content. In this study, more than 70% has been reached in all cases, and in the case of acacia, this is close to 80%, which is remarkably interesting (Figure 10). From the biomass, the obtained values are in accordance with the general results for this type of biomass [42], but acacia waste biochar had carbon yields of about 77%, while the two other materials had values in the range of 70–71%.

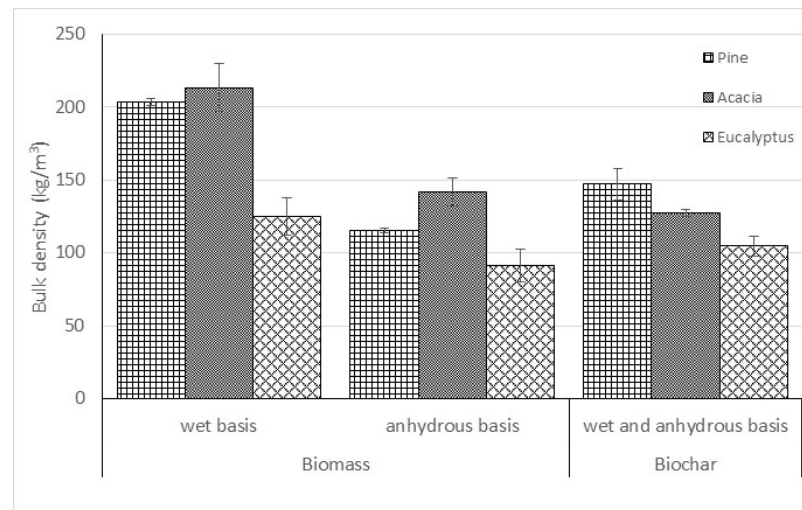


**Figure 10.** Fixed carbon (%) for the three biomasses and biochar material.

#### 4.6. Bulk Density of Biomass and Biochar

The average values of the density of the biochar are situated in intermediate values between the reference of the humid base and anhydrous base of the biomass.

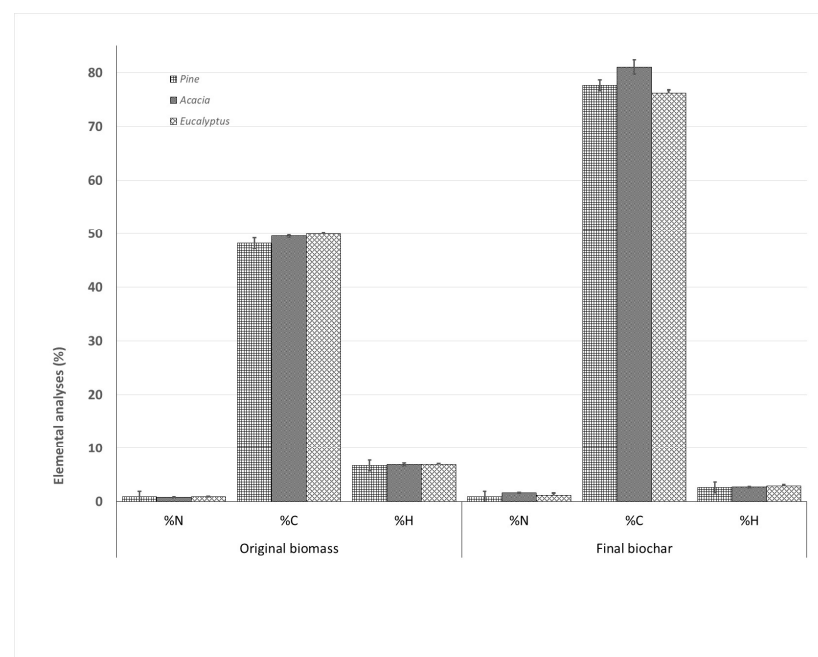
As can be seen in Figure 11, the density in the anhydrous state is slightly more than that of the original biomass. This is due to the fact that when small and more fragile fragments decompose after having been charred, fine particles and dust are generated and, therefore, the apparent density data are increased. The results obtained indicate a reduction in the density of biochar compared to wet biomass and show a loss of mass and volume.



**Figure 11.** Bulk density ( $\text{kg/m}^3$ ) for biomass and biochar material.

#### 4.7. Total Content of Carbon, Hydrogen, and Nitrogen

The molar hydrogen-to-carbon (H/C) ratio serves as a crucial parameter in characterizing biochar, as it reflects the material's level of carbonization and stability. These results are favorable, as the molar ratios of H/C in lignocellulosic biomass are considered optimal with values below 1.5 [13], indicating that hydrogen is preferentially absorbed over carbon. H/C ratios tend to decrease when the biomass is converted to biochar, as observed in this case. The values obtained for acacia are once again consistent with previous studies [42] and are represented in Figure 12. The relatively high ratios of H/C for biomasses of 0.13, and for the biochar of 0.03, could be attributed to the residual organic matter, such as carbohydrates [56], and shows no significant differences between them. H/C ratios exceeding 0.7 signal low-quality biochar and potential limitations in the pyrolysis process [13]. The H/C ratio obtained shows suitable aromaticity and maturation [57]. The International Biochar Initiative (IBI) specifies an optimum molar H/C ratio of 0.7 to differentiate biochar from unmodified or slightly modified biomass [58].



**Figure 12.** Elementary analysis of N = Nitrogen, C = Carbon, H = Hydrogen.



#### 4.8. Principal Major and Minor Elements of Composition

The interpretation of these elements allows to evaluate the behavior of the ash in a thermal conversion process or to evaluate the future use of the ash. They also allow the interpretation of the presence of pollutants in the original biomass, such as soil rests, sand, or inert materials, especially when high values of certain elements are evident. The results obtained are shown in Table 8. Calcium (Ca), silica (Si), aluminum (Al), and potassium (K) were common elements in biochar, and their concentrations had increased in biochar in relation to the original biomass, similar to a previous study [42]. The interpretation of these elements allows to evaluate the behavior of the ash in a thermal conversion process or to evaluate the future use of the ash.

Figure 13 shows a cationic analysis of biomass and biochar, representing the main elements that have an influence on their use as solid additives, such as calcium (Ca) and potassium (K) [10]. Biochar exhibits higher values than biomass, indicating an increase in the respective parameters compared to the original biomass. The results obtained do not show a higher concentration of heavy metals and heteroatoms such as nitrogen, phosphorus, and sulfur, coinciding with previous results [59], in contrast to the high content of heavy metals found on non-lignocellulosic biomass. Therefore, they do not show toxic metals, as found in some cases in non-lignocellulosic biomass, which can dissolve in water and lead to contamination and accumulation in food chains [60].

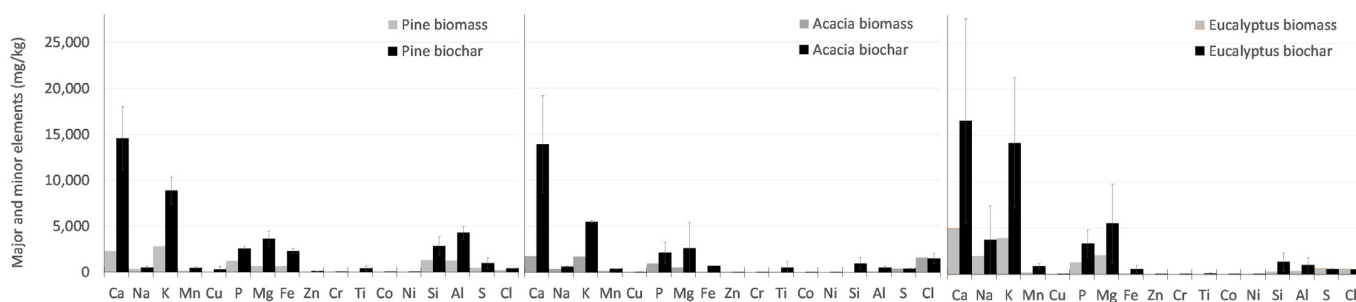


Figure 13. Cationic analysis of biomass and biochar material.

## 5. Conclusions

This study demonstrates the feasibility of producing biochar with favorable properties using renewable and sustainable biomass, employing a simple double-chamber reactor and utilizing biomass as a source of thermal energy. The results indicate that all three types of lignocellulosic biomass provide suitable parameters for energy utilization and the production of high-quality biochar, with the biomass of acacia particularly standing out among the three.

The results of biochar produced via slow pyrolysis at temperatures between 400 and 500 °C demonstrate improvements over the values obtained from the original biomass. Biochar yields ranged between 30% and 40%, with a high fixed carbon content, showing the highest value at  $77 \pm [2.51]\%$  with acacia biomass. The H/C ratio of 0.03 in all three biochars, compared to 0.13 in the biomass, indicates suitable aromaticity and maturation. The main inorganic elements in the three biochars show an increase compared to the original biomass. The high presence of calcium (Ca) and potassium (K) evidence an advantage for use in soil.

The high fixed carbon values enable the biochar utilization for soil remediation and enrichment, carbon sequestration, as filtering elements or another versatile application, as composting organic solid waste, decontaminating water and wastewater, serving as catalysts and activators, as well as in electrode materials and modifiers. The studied lignocellulosic biomass material, along with the selected working conditions and technologies, facilitated the production of high-quality biochar.

**Author Contributions:** Ó.G.-P.: conceptualization, methodology, validation, formal analysis, investigation, writing—original draft preparation, supervision. L.O.T.: conceptualization, methodology, validation, resources, writing—original draft preparation, funding acquisition, supervision. A.V.T.: methodology, formal analysis. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Operational Group for the development of new products, practices, processes, and technologies in the agroforestry field, co-financed with the European Agricultural Fund for Rural Development (EAFRD) within the framework of the Rural Development Program (PDR) of Galicia 2014–2020.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data are available to interested parties upon explicit request to the corresponding author. Data will be available within five years of the publication date.

**Acknowledgments:** The authors thank all the organizations involved as well as the scientific colleagues who in some ways have contributed to this work. Special thanks to GO BioforePlus and GO Ecochar groups, involved in the national projects FEADER 202/031A and FEADER 2023/011B, respectively.

**Conflicts of Interest:** The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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