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Energy from planted forest and its residues characterization in Brazil

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ABSTRACT

An overview of planted forest and its use for energy generation in Brazil is presented. Historical and current data on planted area, productivity and consumption of planted wood is presented. Planted wood was responsible for 7.8% of primary energy consumed in Brazil during 2016, mainly as charcoal for steel industry. Eucalyptus and pine are the main planted species in Brazil. Favourable climate and soil quality enhance productivity of planted forest in Brazil, reaching 30–36 m^3 ha^{-1} y^{-1} thus representing the world's highest productivity, with better managed forests producing up to 70 m^3 ha^{-1}. Forest residues reach 20% for eucalyptus and 40% for pine as compared to the amount of wood produced. Residues of a particular eucalyptus planted forest were collected directly on the field, considered for fuel and analyzed determining composition, heat value, ash content and thermogravimetric analysis. It is estimated a yearly generation of 20×10^6 t of forest residues and 15×10^6 t of wood industry residues.

1. Introduction

Biomass is a source of renewable primary energy that can be used for the production of thermal and electric energy or even for the production of biofuels through energy converting processes. Forest biomass encompass wood, charcoal, leaves, branches, wood litter, roots, fruits, extracts, solid residues from the forest-based industries and black liquor from pulp and paper industries. Using biomass for the generation of heat and energy can substitute fossils fuels and reduce the emissions of greenhouse gases, thus making up an environmental advantage [1]. The increasing use of forest biomass for energy generation has been enhanced through the enforcement of environmental policies and from the increase in price of the fossils fuels [2]. Planted forests can be defined as short rotation plantations with a high number of planted trees per hectare, thus producing a high volume of biomass in the shorter time possible [3]. Wood from planted forests can be used for several purposes as energy generation, pulp and paper industry, wood for building engineering, furniture, and charcoal among others.

The generation of energy through biomass, currently responsible for 25% of Brazil's primary energy, can be increased if planted forest waste is also used as an energy source. Considerations about the potential of the energy production through planted forests and their residues are not unique to Brazil alone. Other countries with similar characteristics to Brazil, in Africa, Asia and Oceania, have the same potential. Such features include climate and large tracts of land. Planted forests have lower agronomic requirements regarding soil and water availability, so that the best arable land can still be devoted only to food production. Few countries in the tropical and sub-tropical range use planted forest for power generation. Studies on assessing the economic and energy potential of planted forests mainly focus on cases in countries in the northern hemisphere, outside the subtropical and tropical region [4]. An overview of Brazil should be useful for extending its results to developing countries.

However, introducing the forest energy in countries with little or no tradition on its use is more difficult as compared to others where forestry industry is well developed. One of the key factors for this is that current use of mechanization for both harvesting and wood processing is well established. Countries that already domain an efficient use of technology have great advantage in the introducing new and further developed methodologies [5].

Up to 1967, fuelwood was the primary source of energy in Brazil, only surpassed by oil, and in 1978 by hydroelectricity. However, by that time most of the firewood was produced from native forests [6]. Planted forests in Brazil were first introduced in early 20th

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century with eucalyptus species from Australia and primarily for railways infrastructure [6]. Later on, pine was introduced in the Brazilian silviculture. In 1966 Brazil started a program for reforestation with tax incentives aiming to recover areas of native forests and to produce wood for industrial uses [7]. That program ended by 1987, but planted forests have been increasing in area since then. Main sectors investing in planted forests are the industries of pulp and paper and the production of charcoal for steel-making.

Most countries worldwide are using or considering the use of wood from planted forests and its residues for energy generation. Using biomass as an energy source depends on the natural resources available, on the demand for energy and also on technological development. Data and statistics from International Energy Agency (2018) shows that developing countries can have their energy supply from biomass in the order of 94.6% in Congo, 82.5% in Tanzania, 58.0% in Guatemala, 20.1% in India and 31.4% in Brazil. Some developed countries already have their energy matrix with a strong presence of biomass, such as Denmark (27.7%), Finland (29.8%) and Sweden (25.7%), but typical figures of biomass use as energy source in developed countries are United States 4.8%, Germany 10.0%, France 7.2% [8].

Many countries have studied the feasibility of using forest waste to generate energy. Sweden has a large forest resource per capita and produces 25–30% of the total energy consumed from planted forests. De Jong et al. [9] conducted a review study to understand the impact of collecting wood residues as slash and stump from planted forest activities. Unprocessed wood for bioenergy conversion, which includes bark, sawdust, shavings, slash, round-wood, small diameter trees etc., handles the generation of 180 PJ per year. Increasing the use of slash and stump the generation might reach 240 PJ per year, although environmental risks with such intensification are not precisely evaluated. López-Rodríguez et al. [10] evaluated the bioenergy potential from forest residues, in the province of Caceres, west Spain, where the main species could provide 1 t ha^{-1} y^{-1} of residues from *Pinus pinaster* and 7.5 t^{-1} y^{-1} from *Eucalyptus camaldulensis*. Gómez et al. [11] evaluated the potential for electricity generation from forests and agriculture residues, resulting in an equivalent to 11% of all electrical energy generated in Spain during 2008.

The repeated removal of residues from a planted forest can have a negative impact on forest productivity, and several authors have investigated this theme. Jones et al. [12] identified a substantially lesser growth than expected, with the removal of residues from planted forests of *Eucalyptus globulus*. However, the effects showed different magnitudes between the analyzed sites. The reduction in productivity may be because of the reduction in the availability of organic matter and nutrients in the soil. Biomass waste retention in the soil varies widely depending on soil texture and other characteristics, and in the long run the impact may not be as negative, as long as the soil surface remains intact [13].

In order to quantify the consequences of removing residues from the soil of planted forests, Achat et al. [14] analyzed data from 168 sites. They concluded that removing waste can reduce 10–40% of organic matter on the soil surface and reduce tree growth by 3–7% over a 33-year period. However, in this study, only 9% of the sites were in a tropical or subtropical region. Sherman and Coleman [15], when studying the impact on forest soil respiration and enzyme activity, suggest that removing residues in over-stocked forests of organic matter (for example, low-turnover forests) should not cause short-term damage. They conclude that long-term studies are still needed [16].

The reduction in productivity has been identified, for example, in a *Pinus patula* forest in Africa, losing 9% after 10 years, reaching up to 33% due to slash removal [17]. With eucalyptus in southwestern Australia, studies to predict the impact on nutrient availability (specifically N) due to waste removal, resulted in a significant reduction in growth from 45 to 13 m^3 ha^{-1} y^{-1} [18]. In Australia, a study developed by Mendham et al. [19], revealed that repeatedly collecting the harvesting residues can cause lowering the productivity of *Eucalyptus globulus*, mainly on the third rotation. The authors suggest that the removal of waste should be carefully studied, in order to not affect the total productivity of biomass. Likewise, some authors propose it is possible to mitigate negative impacts, selecting and controlling the amount and type of waste to be removed. Usually the impact is greater if the ground cover is also removed, since the foliage and the forest floor have a large amount of nutrients [13].

The additional biomass gain, through the collection of forest residues, may not be compensated because of the reduction in forest productivity, caused by the repeated removal of these residues. However, careful collection management, through the selection of the type of waste to be collected, and fertilizer compensation measures, can cause greater utilization of forest biomass for energy generation.

The characterization of a solid fuel is an important and fundamental step for the investigation and analysis of the application of this fuel [20]. Such characterization involves the determination of chemical and physical properties that apply to thermal processes, in order to make it possible to predict the behavior of the fuel in the process to be used, the quantification of the energy to be generated, the composition of the combustion products, the possibility of hot corrosion and fouling on heat transfer surfaces and other parts of the combustion system [21].

A few studies present the characterization of forest residues in order to assess the energy potential of using these residues as fuel, as performed by Pérez et al. [22]. They characterized the residues of pine and eucalyptus in northern Spain. Mateos et al. [23] also made a similar study for forest waste in Biscay (Spain), and Sette Jr et al. [24] studied the residues from acacia and eucalyptus plantations in Brazil. Enes et al. [25] characterized pine, eucalyptus and shrubs residues in northern Portugal.

Although data on the characterization of planted wood for energy are already widely available, studies on the characterization of forest residues related to their different parts (leaf, branches, bark) are still scarce. Characterization studies rarely determine beyond the calorific value and the proximate analysis of the residues, which limits the application of these results in the detailed design of the thermal equipment and in the occurrence's prediction of hot corrosion, fouling and slagging. In addition, there are also few studies that determine in detail the composition of ash from forest residues, which can be useful for application to the soil as a supplier of mineral nutrients.

Using wood waste in Brazil is not widespread. A few applications are known, such as the use of processing residues in the timber industry, and the use of bark in some pulp and paper industries. In this article we present an overview of the production and use of wood planted in Brazil, with a focus on the potential use of planted forest waste for energy generation. Although there is much research in planted forest in Brazil, most of these results are published only in Portuguese.

Here, a compilation of wood productivity data and its various types of residues from the two main genera planted in Brazil, eucalyptus and pine, is presented. Furthermore, considering that eucalyptus is the main species planted in Brazil for energy, we present a detailed characterization of its residues as fuel, to gather data and presenting knowledge to be used in the planning and design of energy generation from planted wood and its forest residues.

2. Planted forests in Brazil

In this section, we present an overview of planted forests in Brazil, considering the production and consumption of wood in the industry, and also the use of planted wood for energy generation. Then, we present a compilation of productivity data for eucalyptus and pine wood, and its forest residues.

2.1. Planted forest in Brazil, production and consumption of wood for industry

Planted forests in Brazil by 2016 are mainly eucalyptus covering 5.7×10^6 ha, pine 1.6×10^6 ha and 0.54×10^6 ha of other genera as teak, acacia, rubber and parica (*Shizolobium amazonicum*) all making 7.84×10^6 ha [26]. The main species of eucalyptus and pine are *Eucalyptus saligna*, *E. grandis*, *E. urophyla* and their clones, *Pinus taeda* and *P. caribea*.

Table 1 shows the planted area for eucalyptus and pine in the year 2016 by geographical regions of Brazil, these shown in Fig. 1. The South East presents biggest area for eucalyptus with Center West is increasing the planted area for this specie during the last 5 years, while the South has the biggest area of planted pine. Brazilian planted forests presents the highest productivity in the world, with short rotation, and average productivity in 2016 being 35.7 $m^3\ ha^{-1}\ y^{-1}$ (14.2 $t\ ha^{-1}\ y^{-1}$) for eucalyptus and 30.5 $m^3\ ha^{-1}\ y^{-1}$ (9.36 $t\ ha^{-1}\ y^{-1}$) for pine [26]. Fig. 2 presents the evolution of planted area during 10 years from 2006 to 2016, showing an increase of 51% on the area for eucalyptus and a 10% decrease on pine.

Table 2 shows the area of planted forests for the countries that are the major producers. Brazil is the ninth country in the world in terms of planted area, but planted forests occupy only 0.9% of its territory. China has the largest planted area in the world, occupying 8.2% of its territory. Other countries occupy a larger part of their territory, such as Sweden with 30.7%, Japan with 28.2% and Finland occupying 20% of its territory with planted forests.

The industrial consumption of wood in natura from planted forests in Brazil during 2016 reached $206.3 \times 10^6\ m^3$ [26]. In Brazil, pulp and paper industries handle the biggest planted area, with 72.5% of the eucalyptus and 53.3% of pine, as presented in Table 3. Table 4 shows that eucalyptus is the major species used for paper, pulp, industrial firewood and charcoal, and pine is used mainly for lumber. The industry of pulp and paper is the major consumer, the order of 40% of planted forests [26].

Brazilian production of pulp during 2016 reached 18.8×10^6 t. Chemical processes for short fiber using eucalyptus accounted for 86% and pine for long fiber was 11.1% of the total production. Brazil is presently the second biggest producer of cellulose pulp, directing 69% for exports and 31% for internal consumption. The USA is the biggest producer with 48.5×10^6 t. Production of paper in Brazil during 2016 reached 10.3×10^6 t with 80% being for internal market and the 8th producer of paper; China was the leader producing $111.2 \times 10^6\ t\ y^{-1}$. Production of pulp and paper is increasing in Brazil during the past 14 years, although paper is nearly constant during the past 6 years as shown in Fig. 3.

Table 1
Distribution of the planted area of eucalyptus and pine in Brazil in 2016 (adapted from Ibá [26]).

Region	Eucalyptus (ha)	(%)	Pine (ha)	(%)
Southeast	2,575,897	45.4	163,186	10.3
South	726,244	12.8	1,403,719	88.6
Center West	1,304,970	23.0	14,259	0.9
Northeast	862,415	15.2	3168	0.2
North	204,256	3.6	–	–

The amount of charcoal used in Brazil during 2016 was 4.5×10^6 t being 84.4% from planted and the rest from native forests. In 2008, the amount of charcoal produced from native forests was slightly over 50% of the total production [26]. Most of the charcoal from planted forests of eucalyptus were used for the production of pig iron and steel. Fig. 3 presents the production of charcoal in Brazil for the last 20 years.

Charcoal is increasingly been used in steel and iron industry substituting coke as thermo-reducing agent. It costs less and produces lower polluting emissions and greenhouse gases as compared to fossil coke [28]. In Brazil many iron industries, around 120, mostly producing pig iron are using charcoal. The production of charcoal for pig-iron industry encompass the whole chain from planting the wood, harvesting, transporting, producing the charcoal and using it in the blast furnaces as a thermo-reducing at industries producing pig iron, steel, silicon and other metallic alloys [26]. In the steel industries, coke and charcoal are used as fuels and reducing agents in the blast furnaces, where carbon is added to the iron ore. From the beginning of steel making, charcoal is a source of thermal energy and reducing agent, and because it is free from sulfur a better quality may be attained [29].

The production of wood panels in Brazil from reconstituted wood reached $7.3 \times 10^6\ m^3$ during 2016. House furnishing is the main user of panel wood and $1.1 \times 10^6\ m^3$ were exported during that year. Brazil is 8th in the world ranking of producers, with 18 large industries located mainly in the South and South East. Production of plywood panels from planted trees reached $2.7 \times 10^6\ m^3$ and 66.7% were exported. Production of laminate flooring is related to the industry of panels and reached $11.8 \times 10^6\ m^2$ during 2016 [26]. Timber production from planted forests reached $8.6 \times 10^6\ m^3$ during 2016, with $6.4 \times 10^6\ m^3$ for internal use and 34.4% exported [26].

2.2. Utilization of planted wood for energy in Brazil

Energy from biomass has a great potential in Brazil. During 2016, biomass produced 25% of primary energy in Brazil and 8.2% of electricity. Wood as firewood and black liquor accounted for 7.8% of the primary energy and 2.4% of electricity generated in the industrial sector of paper and pulp. Renewable sources contributed with 41.4% of primary energy and 80.4% of the electricity generated as shown in Table 5, according to EPE [30].

Wood consumption in Brazil during 2016 was 74.5×10^6 t, but it used to be 92×10^6 t 10 years ago. This evolution is shown in Fig. 4. Main consumers of wood are charcoal producers, industries and domestic/commercial users, although most residential use is wood from natural forests [31]. Pulp and paper industries are large consumers of wood as raw material for their own processes, and are also generators of electricity using black liquor for fuel. Black liquor is a byproduct from digestion process of the pulp and paper industry, dissolved residues (lignin) from wood and other organic matter separated from the kraft cooking process. Production and therefore consumption of black liquor during 2016 in Brazil was 29.5×10^6 t generating 12,000 GWh which is 2% of all electricity generated [30].

The installed capacity for electricity generation from biomass in Brazil is shown in Table 6. The total contribution from planted forests is 2333 MW due to black liquor, 432 MW due to wood waste and 169 MW from charcoal, while generation from sugar cane bagasse is 5 times bigger than that from wood. These figures show that energy generated from forest products is still small, even though planted forests are highly productive. This also confirms that there is great potential for energy generation from the planted forest and its waste.

Fig. 1. Geographical regions of Brazil, related to Table 1.

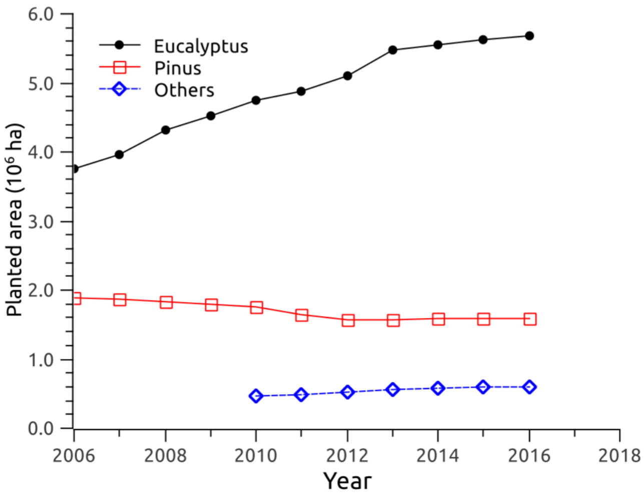

Fig. 2. Planted area of main species in Brazil, recent evolution (Source: Ibá [26]).

Table 2
Planted forests in countries that are main producers (Source: Food and Agriculture Organization of the United Nations, 2015).

Country	Area planted forest (1000 ha)	% of country area
China	78,982	8.2
United States of America	26,364	2.6
Russian Federation	19,841	1.1
Canada	15,784	1.6
Sweden	13,737	30.7
India	12,031	3.6
Japan	10,270	27.2
Poland	8957	28.6
Brazil	7736	0.9
Finland	6775	20.0
Sudan	6121	3.2
Germany	5295	14.8

2.3. Productivity of planted forests and its residues in Brazil

Productivity of planted forests is influenced by environmental conditions and management practice, the former represented by soil and climate and the last by plant distance, irrigation, fertilizers and pest control [32]. Several researches have been carried out to

Table 3
Planted area by industrial sector in Brazil (from ABRAF [27]).

Industrial sector	Share (%)	
	eucalyptus	pine
pulp and paper	72.5	53.5
charcoal	19.	6.1
lumber	7.3	24.4
wood independent producers	0.7	15.9

Table 4
Wood consumption for industrial use in Brazil in 2016 (adapted from Ibá [26]).

Industrial sector	volume (10^6 m^3)		Others	Total
	Eucalyptus	Pine		
Pulp and Paper	70.74	9.25	0.09	80.07
Industrial firewood	46.94	3.72	4.31	54.97
Charcoal	21.46	–	–	21.46
Panels	5.93	6.70	0.37	13.00
Lumber	5.86	27.37	0.35	33.58
Treated wood	1.46	–	–	1.46
Others	1.57	0.15	–	1.72
Total	153.96	47.19	5.12	206.26

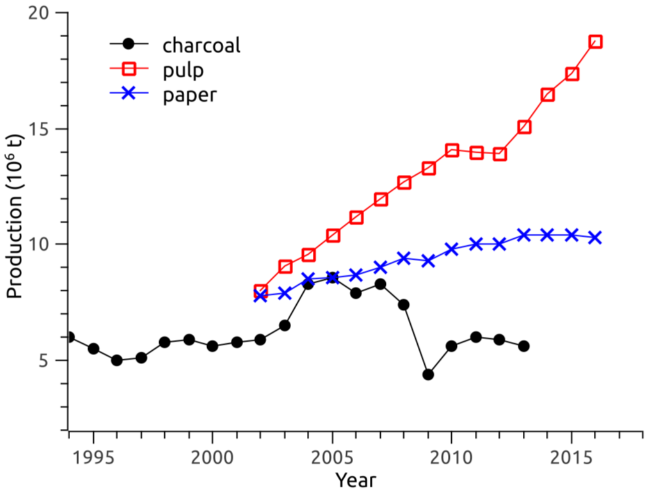

Fig. 3. Historical production of pulp and paper in Brazil since 1994 to 2016 (from Ibá [26]).

increase and evaluate the productivity of planted forest biomass in Brazil, but many of the results are published only in Portuguese. Table 7 shows a compilation of published works on the evaluation of productivity for the two main genera planted in Brazil: eucalyptus and pine. Data refers to productivity of dry wood without bark and original unities are maintained as presented in the papers cited.

Brazil has the highest average productivity as compared to the rest of the world, presenting an average of 35.7 m^3 ha^{-1} y^{-1} for eucalyptus and 30.5 m^3 ha^{-1} y^{-1} for pine, and a comparison to other countries is presented in Fig. 5 [27].

Adequate climatic conditions are favourable in enhancing fast growing rates and therefore shortening rotation. Average rotation for eucalyptus in Brazil is 7 years, and for pine is 18 years. In countries located at higher latitudes, rotation can reach 20–35 years for eucalyptus, and 35–70 years for pine, depending on the purpose of the plantation and local conditions [26].

Table 5
Production of primary energy and electricity in Brazil, 2016 (from EPE [30]).

Non-renewable	Primary energy		Electricity	
	1000 toe	Percent	GWh	Percent
Petroleum	130,373	44.2	12,103	2.1
Natural gas	37,610	12.7	56,485	9.8
Coal	2636	0.9	18,043	3.1
Nuclear	512	0.2	15,864	2.7
Other	1921	0.7	10,877	1.9
Total non-renewable	173,052	58.6	113,372	19.6
Renewable				
Hydraulic	32,758	11.1	380,911	65.8
Firewood	23,095	7.8	1970	0.3
Black liquor[a]			12,031	2.1
Sugar cane products	50,658	17.2	35,236	6.1
Wind	2880	1.0	33,489	5.8
Solar	7	0.0	85	0.1
Other	12,781	4.3	1804	0.3
Total renewable	122,179	41.4	465,526	80.4
Total	295,231	100	578,898	100

[a] black liquor included in firewood as primary energy.

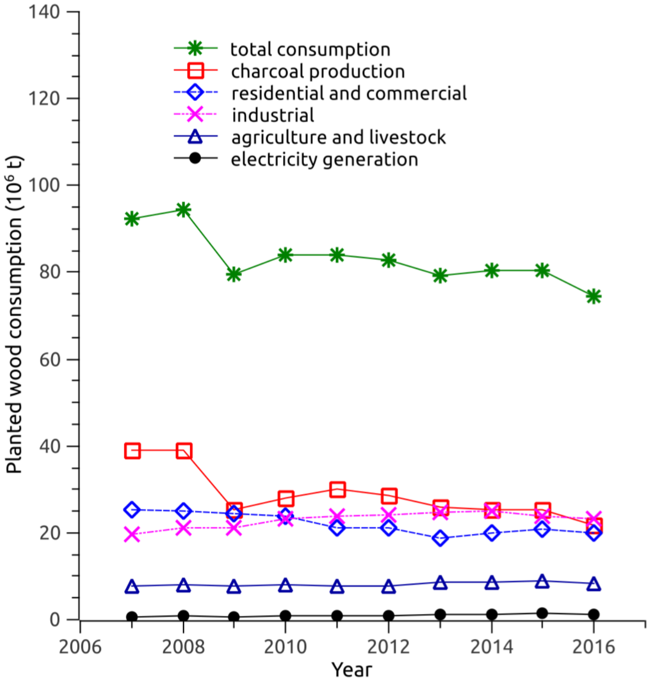

Fig. 4. Consumption of planted firewood last ten years, in Brazil. (Source: EPE [30]).

Table 6
Installed capacity of electricity generation by biomass in Brazil, 2016 (From: EPE [30]).

Fuel	MW
Bagasse	10,979
Biogas	119
Elephant grass	66
Charcoal	54
Rice husk	45
Charcoal gas	115
Vegetable oil	4
Wood waste	432
Black liquor	2333
Total	14,147

Table 7
Productivity data as dry wood from planted forests in Brazil.

Species	Latitude	Minimum	Average	Maximum	Units	Rotation (years)	Reference
Eucalyptus	Brazil		41		$m^3\ ha^{-1}\ y^{-1}$		[33]
Eucalyptus spp.	18°38′ S to 19°59′ S	21.8	28.1	34.4	$t\ ha^{-1}\ y^{-1}$	6	[34]
Eucalyptus clones	19°49′ S	14		15.8	$t\ ha^{-1}\ y^{-1}$	6.5 to 7	[35]
Eucalyptus clones	22°21′ S	21		22.6	$t\ ha^{-1}\ y^{-1}$	6.5 to 7	[35]
Eucalyptus clones	18°02′ S	18.1		19.3	$t\ ha^{-1}\ y^{-1}$	6.5 to 7	[35]
Eucalyptus clones	16°21′ S	27.8		29.6	$t\ ha^{-1}\ y^{-1}$	6.5 to 7	[35]
Eucalyptus clones	17°20′ S	20.8		38	$t\ ha^{-1}\ y^{-1}$	4.5	[36]
Eucalyptus clones	18°35′ S	21.3		26.5	$t\ ha^{-1}\ y^{-1}$	5.3	[36]
Eucalyptus clones	19°49′ S	18.3		28.2	$t\ ha^{-1}\ y^{-1}$	6	[36]
Eucalyptus grandis	18°38′ to 19°59′ S	7.4		21.3	$t\ ha^{-1}\ y^{-1}$	7	[34]
Eucalyptus grandis	27°22′ S;	38		55.8	$t\ ha^{-1}\ y^{-1}$	5	[37]
Eucalyptus grandis	19°44′ S,	56		77.6	$m^3\ ha^{-1}\ y^{-1}$	5	[38]
Eucalyptus grandis hybrid	16°45′ S to 20°15′ S	23		42	$m^3\ ha^{-1}\ y^{-1}$	7	[39]
Eucalyptus urograndis	19°57′ S	21	28	39	$m^3\ ha^{-1}\ y^{-1}$	7	[40]
Eucalyptus urograndis	0°53′ S	22.5	40.8	49	$m^3\ ha^{-1}\ y^{-1}$	6	[41]
Pinus caribea	22°22′ S	12		14	$t\ ha^{-1}\ y^{-1}$	11	[42]
Pinus taeda	25°05′ S to 26°06′ S	6		13	$t\ ha^{-1}\ y^{-1}$	10	[43]
Pinus taeda	26°42′ S	15	26	35	$m^3\ ha^{-1}\ y^{-1}$	11 to 15	[44]
Pinus taeda	25°27′ S	10		40	$m^3\ ha^{-1}\ y^{-1}$	4	[45]
Pinus taeda	25°0′ S	23		30.6	$m^3\ ha^{-1}\ y^{-1}$	7 to 14	[46]
Pinus taeda	24°15′ S	19.7		28.6	$m^3\ ha^{-1}\ y^{-1}$	24.4	[47]

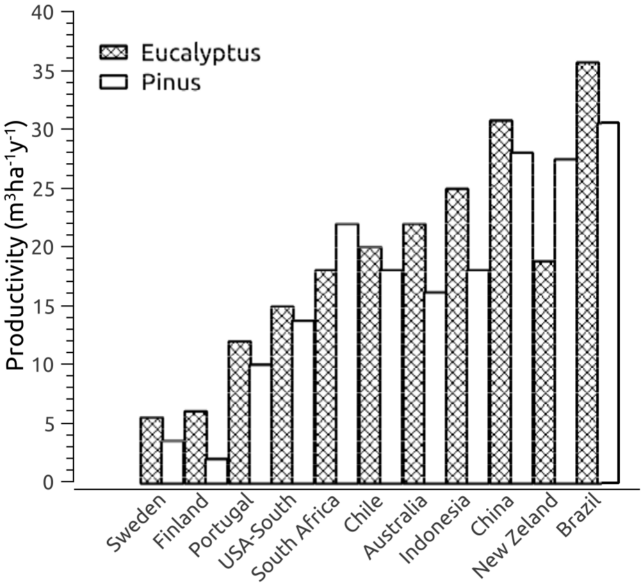

Fig. 5. Productivity of planted trees in Brazil, comparing with other significant players worldwide. (Source: Ibá [26] and ABRAF [27]).

Production of wood without bark represents only part of all biomass that is produced from planted forests. Typical productivity of forest residues like bark, branches and leaves are shown in Table 8. Eucalyptus residues represent 17–38% when compared to wood biomass, while for pine they are 13–44%. These values depend on the age of the tree, and can also result from variations in the measurement method used in each estimate. For eucalyptus, the largest portions of the residues correspond to the bark and branches, with the leaves representing only 2–6% of the wood biomass. Because of this small value, the collection of leaves may not be interesting for energy use. In addition, leaving the leaves in the forest can return nutrients and organic matter to the soil. Thus, with the use of eucalyptus barks and branches, or only part of them, the potential for energy generation can be increased in the order of 15–30% with the use of forest residues.

Roots biomass is not considered here because of practical difficulties for its use and lack of information. Pérez et al. [52] estimated that the wastes amounted to around 25% by weight in relation to the weight of the wood produced in eucalyptus forests, while Mateos et al. [23] found a value of 20% for the case of pine and eucalyptus forests. The collection and handling of waste can generate additional energy consumption, but studies on the crushing of eucalyptus tree tops at the plantations sites, for improving transportation, demonstrated an equivalent diesel oil consumption of 0.6–1.0% of the energy content in the residue, referred to its low calorific value [53].

Table 8
Productivity of forest residues related to dry wood in Brazil.

specie	waste/wood						reference
	tree age (years)	wood	bark	branches	leaves	total waste	
Eucalyptus grandis	5	1.0	0.04	0.07	0.06	0.17	[37]
Eucalyptus spp	5	1.0	0.11	0.05	0.028	0.19	[34]
Eucalyptus Urograndis	6.5	1.0	0.08	0.029	0.02	0.129	[48]
Eucalyptus saligna	8.5	1.0	0.17	0.21	*[a]	0.38	[49]
Pinus taeda	16	1.0	*[b]	0.11	0.024	0.134	[50]
Pinus taeda	27	1.0	0.097	0.3	0.049[c]	0.446	[51]

[a] leaves included in branches.
[b] bark included in branches and leaves.
[c] needles.

Residues generation in the industries processing forest products must be considered regarding its use for energy production. Brand et al. [54] found that 2.62 m^3 of logs are used to produce 1 m^3 of lumber in sawmills, resulting in 38% lumber and 62% residues.

Brazilian industries using wood from planted forests were responsible 47.8 millions of tons of solid waste during the year of 2016, being 70.5% (33 millions of tons) generated directly at the forests as bark, branches, leaves and tops, and 29.5% (14 millions of tons) at the industrial sites as chips, saw dust, black liquor, etc. In the forest activity, 99.7% of the residues is left in the field. From the residues at the industries, 66% (9.3 millions of tons) were used for energy generation in steam boilers with part of this in electricity generation for the industry plant [26].

3. Characterization of residues from planted forest

The residues from the planted forest may have different characteristics from the wood. And among the residues themselves (bark, branches, tops, leaves) these characteristics can also differ. In addition, with the residues being on the ground, subject to the weather, their characteristics may also vary over the time they remain on the forest floor. In this section, samples of the various residues from the planted forest with eucalyptus were collected shortly after harvesting the wood, after 32 days of harvest and after 94 days of harvest, in order to be characterized as fuel.

3.1. Methods

Residues were collected in a planted forest of Eucalyptus, clone Urograndis, in the State of São Paulo (28° Latitude S and 760 m over sea level). Forest was planted in the year 2007 with spacing of 3.2 m × 2.5 m (density of 1250 plants per hectare) and harvested at the 6th year of age, with a productivity of 55 $m^3\ ha^{-1}\ y^{-1}$ of log with bark. Residues on the forest site are branches, leaves, tree tops and bark. Samples were collected during three stages: on the harvesting day, after 32 and after 94 days laying on the soil. Chips from processing industry were also collected in order to take a comparison with regarding the forest residues. Preparation of samples were conducted according to ASTM Standard E1757. Samples were oven dried at 60 °C to determine natural moisture content and then reduced in size with a knife mill. Ashes of biomass were prepared in muffle at 575 °C.

Proximate analysis (moisture, volatile matter, fixed carbon and ash content) were conducted according to ASTM E−871, E−872 and D-1102 (575 °C) respectively. Contents of carbon (C), hydrogen (H), nitrogen (N) and sulfur (S) were measured directly from dry samples with Elementary CHNS analyser according to ASTM E−775, E−777 and E−778. Calorific value was determined in a calorimetric pump PAAR 6300 according to ASTM D-240. Cellulose, hemicellulose, lignin and extractives were determined with a HPLC PAD according to TAPPI 264 cm-97, TAPPI UM 250 and TAPPI 222 om-98.

Thermal analysis was conducted in a SDT Q600 analyzer with samples weighting 10.5 ± 0.5 mg, under heating rate of 10 K min^{-1}, inert atmosphere (N_2) with a flow rate of 100 mL min^{-1}, in a temperature range from 25 to 900 °C for the biomasses and from 500 to 1200 °C for the ashes, in crucibles of alumina and platinum. Elementary composition analysis of ashes was conducted using SEM/EDS Microscope System comprising FEI Inspect F-50 High Resolution SEM and an EDS of high sensitivity and speed.

In order to predict the occurrence of phenomena like ash fouling and slagging, three parameters were worked out based on ashes composition: *AI*, $R_{b/a}$ and *BAI*. *AI*, the alkali index, expresses the quantity of alkali oxides in the fuel per unit of fuel energy; $R_{b/a}$ is the base-to-acid ratio; and *BAI* is the bed agglomeration index applying to fluidized bed reactors [21]. Fouling and slagging are probable when alkali index is in the range 0.17−0.34 kg GJ^{-1} and is certain to occur for a value greater then 0.34. As the base-to-acid ratio increases, the fouling tendency of a fuel ash also increases, and bed agglomeration occurs when the *BAI* is lower than 0.15. Definitions of these indexes are:

$$AI = \frac{K_2O + Na_2O}{GJ} \tag{1}$$

where $K_2O + Na_2O$ is the total mass (kg) of these oxides in 1 kg of dry fuel, and *GJ* is the higher calorific value of the fuel (GJ kg^{-1}).

$$R_{b/a} = \frac{Fe_2O_3 + CaO + MgO + K_2O + Na_2O}{SiO_2 + TiO_2 + Al_2O_3} \tag{2}$$

$$BAI = \frac{Fe_2O_3}{K_2O + Na_2O} \tag{3}$$

where $R_{b/a}$ and *BAI* are the ratios of mass fractions of these oxides in the dry fuel.

3.2. Results and discussion

Table 9 presents the moisture content of samples. The results are presented on a wet basis (percentage of water in relation to the total mass), and as expected, the moisture content of the residues on the day of the harvest is high. Bark shows the highest moisture with 61.7%, Leaves, branches and tree tops showed 48.4, 40.4 and 50.0% respectively. High moisture content represents a great trouble for the use of biomass if to be used for energy generation [55]. However, moisture content lowers fast with time, as shown in Table 9. According to the measured results, moisture reduces greatly and after 32 days on the field the wood reached a level of 5−8% of moisture wet basis and this value seemed to be stabilized from then on. Natural drying on the field depends on many causes as environmental features, climate, rainfall and conditions under which the logs are arranged as well as residues elements on the piles [55]. Results of moisture content at levels of 8% might result from logs been spread instead of piled and the period of collecting of samples be in August, typically a dry season at that site.

As can be seen in Table 10 results on a dry basis for volatiles of the order of 78−90% and 10−17% for fixed carbon agree with literature [52, 57−61] Bark holds highest ash content, 4.5%, then leaves 3.2%, branches 1% and tree tops and chips 0.2−0.7%, all on

Table 9
Forestry residues moisture *in natura* (%, w.b.) (From: Vergara et al. [56]).

	day 1	day 32	day 94
Leaves	48.4	5.8	7.9
Bark	61.7	4.5	7.2
Branches	40.4	8.5	8.0
Tops	50.0	8.2	–

Table 10
Proximate composition (%, d.b.) and Higher heating value (MJ kg^{-1}) (From: Vergara et al. [56]).

Sample	Volatile Matter	Fixed Carbon	Ash	HHV
Leaves - day 1	80.1 ± 0.7	16.6 ± 0.7	3.2 ± 0.1	21.1
Leaves - day 32	83.0 ± 1.6	14.7 ± 1.6	2.4 ± 0.1	20.4
Leaves - day 94	82.1 ± 1.3	15.3 ± 1.3	2.6 ± 0.1	20.5
Bark - day 1	80.4 ± 0.9	15.1 ± 0.9	4.5 ± 0.2	17.1
Bark - day 32	86.2 ± 7.1	8.9 ± 7.1	4.9 ± 0.1	17.0
Bark - day 94	78.9 ± 0.9	17.1 ± 0.9	4.0 ± 0.1	17.1
Branches - day 1	84.3 ± 3.9	14.8 ± 3.9	0.9 ± 0.1	19.4
Branches - day 32	88.3 ± 1.1	10.6 ± 1.1	1.2 ± 0.1	19.4
Branches - day 94	83.7 ± 1.5	15.6 ± 1.5	0.8 ± 0.1	19.2
Tops - day 1	89.5 ± 1.2	10.2 ± 1.2	0.3 ± 0.1	19.1
Tops - day 32	87.4 ± 0.2	11.9 ± 0.2	0.7 ± 0.2	19.2
Wood chips	87.0 ± 0.90	12.8 ± 0.9	0.3 ± 0.1	19.1

Table 12
Elemental composition (d.b.) (From: Vergara et al. [56]).

Sample	C (%)	H (%)	O (%)	N (%)	S (%)	Chloride (ppm)
Leaves - day 1	54.7	6.0	34.7	1.2	0.2	1339
Leaves - day 32	54.9	5.9	35.8	0.8	0.2	366
Leaves - day 94	55.1	6.0	35.1	1.0	0.2	112
Bark - day 1	48.1	5.5	41.7	0.1	0.1	4329
Bark - day 32	47.7	5.4	41.8	0.1	0.1	864
Bark - day 94	47.5	5.5	42.7	0.2	0.1	231
Branches - day 1	53.3	5.8	39.9	0.0	0.1	760
Branches - day 32	52.9	5.9	39.9	0.1	0.1	686
Branches - day 94	52.2	5.9	41.0	0.0	0.1	368
Tops - day 1	52.9	6.1	40.6	0.0	0.1	484
Tops - day 32	52.5	5.9	40.6	0.2	0.1	263
Wood chips	52.3	5.9	41.4	0.0	0.1	376

O (%) by difference.

dry basis. Those are levels reported in the bibliography and an ample variability is observed according to the eucalyptus species [58]. Ash content is a major parameter affecting those residues in terms of fuel quality because low level is desirable.

Table 10 shows changes in volatile matter and ash content over time in leaves, bark and branches. The three samples showed a reduction in ash content after 94 days in the field. This reduction may be because of the leaching of the minerals by the rainwater, with this making a selective extraction or solubilization of some chemical constituents of the ashes [62]. The results for volatile and fixed carbon content are like other biomasses used as fuel, such as sugarcane bagasse and rice husk. However, agricultural (or agro-industrial) residues have significant differences in relation to eucalyptus wood, as regards ash content, where bagasse has ash content similar to forest residues (3.0%) and rice husk can reach much higher values (19%).

Higher calorific value showed values from 17.0 to 21.1 MJ kg^{-1}, as presented in Table 10, where leaves are at the top showing a light loss with time. Branches, tree tops and chips do not show much difference among them and bark shows the lowest level of lower calorific level being also the residue with higher ash content. Eucalyptus, as biomass fuel, when compared to sugarcane bagasse, pine and rice hull exhibits an equivalent, or even higher, calorific value [52,59,61].

Samples' structural composition is shown in Table 11. Wood used for pulp and paper industry represent the major part of the trees. Chips from this wood presented the highest cellulose content (46.5%) and the contents of hemicellulose, lignin and extractives were respectively 13.3%, 29.9% and 2.7%, all dry basis. These are normal values for trees species used for the pulp and paper industry, high cellulose content and low lignin and extractives. Residues show a wide distribution of structural contents among the many parts of the trees. Leaves have a lower cellulose content (16–25%) as compared to bark, branches and tree tops (38–44%). Total cellulose contents from all other parts is lower than the wood of the main trunk. The content of hemicellulose is nearly the same for all parts of the tree (11–15%). Leaves showed higher content of lignin (37%) followed by tree tops, branches and bark with respectively 32, 31 and 22%. Extractives showed the same trend as lignin with decreasing content for leaves > bark > Branches > tree tops. Noticeable that green leaves sowed ten fold extractives content as compared to the wood chips. Important to point that extractives are lost at a very high time rate in the material that remains in the ground. With 32 days a loss of 60% in leaves and 70–75% in bark and branches is detected, in agreement with bibliography [63]. Extractives are the volatile fraction, presenting higher degradation or leaching.

Data for elementary analysis of biomass are shown in Table 12. Carbon content is 55% in leaves, 48% in bark and 52–53% in branches, tree tops and chips. Hydrogen is nearly the same in all parts of the biomass representing 5–6% on a dry basis. Nitrogen present in leaves reaches 1%, while all the rest of the biomass contains less than 0.2% of both nitrogen and sulfur, although the content of these components is much dependent on the forest fertilization. Low concentration of nitrogen is environmentally important for biomass to be used for energy generation through thermal processes [52, 58]. There is little change respective to time in the concentration of C, H and N but chlorine, as chloride, showed

Table 11
Structural composition (%, d.b.) (From: Vergara et al. [56]).

Sample	Cellulose	Hemicellulose	Lignin	Extractives	Ash	Not Ident.
Leaves - day 1	15.73	11.01	37.45	32.74	3.07	–
Leaves - day 32	24.57	14.11	37.06	18.95	2.35	2.97
Leaves - day 94	22.92	13.09	38.10	18.25	2.63	5.03
Bark - day 1	44.08	11.92	21.92	14.24	4.54	3.31
Bark - day 32	39.98	11.69	25.10	10.77	4.91	7.56
Bark - day 94	44.36	13.01	23.73	10.24	3.97	4.70
Branches - day 1	38.24	14.67	31.42	6.66	0.88	8.13
Branches - day 32	38.26	14.61	31.36	4.76	1.15	9.87
Branches - day 94	39.55	14.83	30.88	4.69	0.79	9.26
Tops - day 1	37.92	14.80	31.98	6.83	0.31	8.16
Tops - day 32	42.78	13.77	30.99	3.10	0.70	8.67
Wood chips	46.52	13.30	29.90	2.73	0.31	7.25

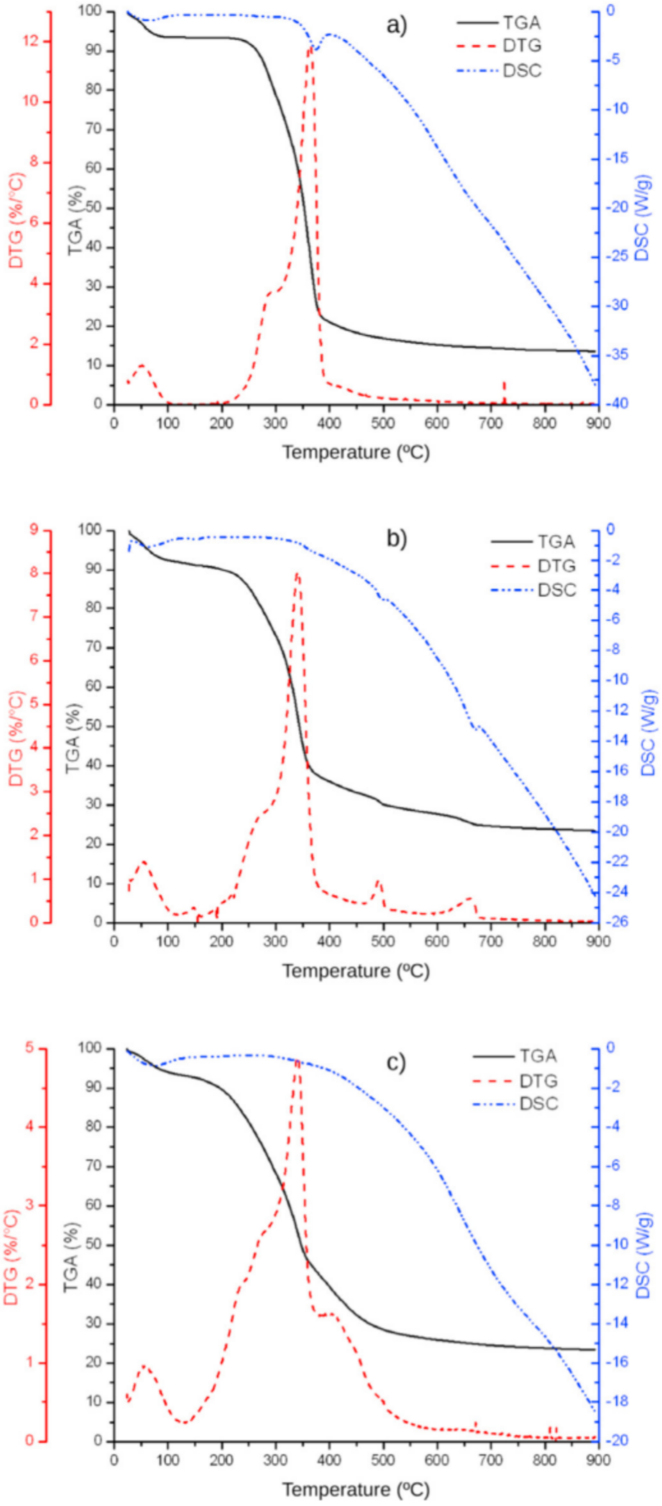

Fig. 6. Thermal analysis of the biomasses. a)Wood chip b)Bark c)Leaves.

an important reduction in all samples of up to 90% from its original concentration. This reduction could have been caused by leaching of the residues while on the soil. Chlorine increases hot corrosion on heat transfer surfaces of combustion equipments.

Thermal analysis were conducted under inert atmosphere (N_2) for three samples of biomass and three of ashes (wood chips, bark and leaves) producing the plots for loss of mass with temperature (TGA), its derivative (DTG) and the differential scanning calorimetry (DSC). Results for thermogravimetric analysis of wood chips indicate similitude with data for eucalyptus and other biomasses [57,64–66]. Mass loss (TGA and DTG) showed two peaks, Fig. 6(a). The first at temperature below 100 °C indicates evaporation of the moisture content and is the same for all biomass. The second, beginning around 250 °C and a maximum at 360 °C has a “shoulder” at 280 °C, considered representing the degradation of hemicellulose, and the point of 360 °C is the degradation of cellulose [66]. Lignin presents a smaller degradation rate at a higher temperature range, 400–500 °C, and the tail at the end of the higher peak represents this degradation. The work of Yang et al. [66], on pyrolysis of each biomass component, individually, showed those peaks at the DTG curves. DSC curves present a drift, thus interfering in the analysis. For the chips this drift is noticeable from 420 °C, presenting a decrease in the heat flux which is not generated by thermal reactions. The same happens for all parts of the biomass and ashes. Even though is possible to identify two peaks of endothermal reactions, the first due to moisture evaporation and the second, around 365 °C, shifted up by 5 °C respective to the pyrolysis of cellulose.

Bark have three minor peaks of mass loss at temperatures of 150, 590 and 660 °C, besides the peaks described above, Fig. 6(b). These localized increases in the thermal degradation rate have associated endothermic reactions each. The first of these smaller peaks may be related to pyrolysis of extractives. Thermogravimetric analysis of the leaves is quite different when compared to the analysis of the wood chips (Fig. 6(c)). Degradation begins at a lower temperature (150 °C), reaching up to 550 ~ 600 °C. A large peak is identified, with the maximum at 350 °C, two small shoulders at temperatures less than the maximum (220 and 270 °C) and a larger shoulder (or peak) at 410 °C. The thermal degradation of extractives generated the first shoulder, the second can be attributed to the degradation of hemicellulose, the highest peak because of degradation of cellulose and the last shoulder because of lignin. Considering that the leaves have a high content of both extractives and lignin, the overlap of the degradation of these compounds, with the degradation of hemicellulose and cellulose, can generate this great peak.

The ashes of the three biomasses were prepared at 575 °C. They presented a slight loss of mass at temperatures lower than this one. Ashes of wood chips and leaves are the ones that present greater loss of mass in the heating to 1200 °C, reaching up to 76 and 77% of the initial mass, respectively. The bark ash was reduced to 93% of its initial mass. In the Fig. 7, plots of the thermal analyzes of the ashes are presented. Because of the large ash loss from leaves, and considering the high ash content of the leaves, it is estimated that leaf ash may present a higher occurrence of fouling or slagging on heat transfer surfaces in a boiler because volatilized portions of the ashes can condense and solidify on colder surfaces. The peaks in the DTG of all the samples have associated variations in the DSC, which indicates the volatilization of some compound from the ashes. However, it is not observed variations in the DSC associated with the maintenance of constant mass, making it difficult to determine the occurrence of ash melting. It is noteworthy that, in all the ashes, two peaks are observed in the DTG at temperature ranges from 650 to 750 °C and from 750 to 900 °C. The ashes are mainly composed of

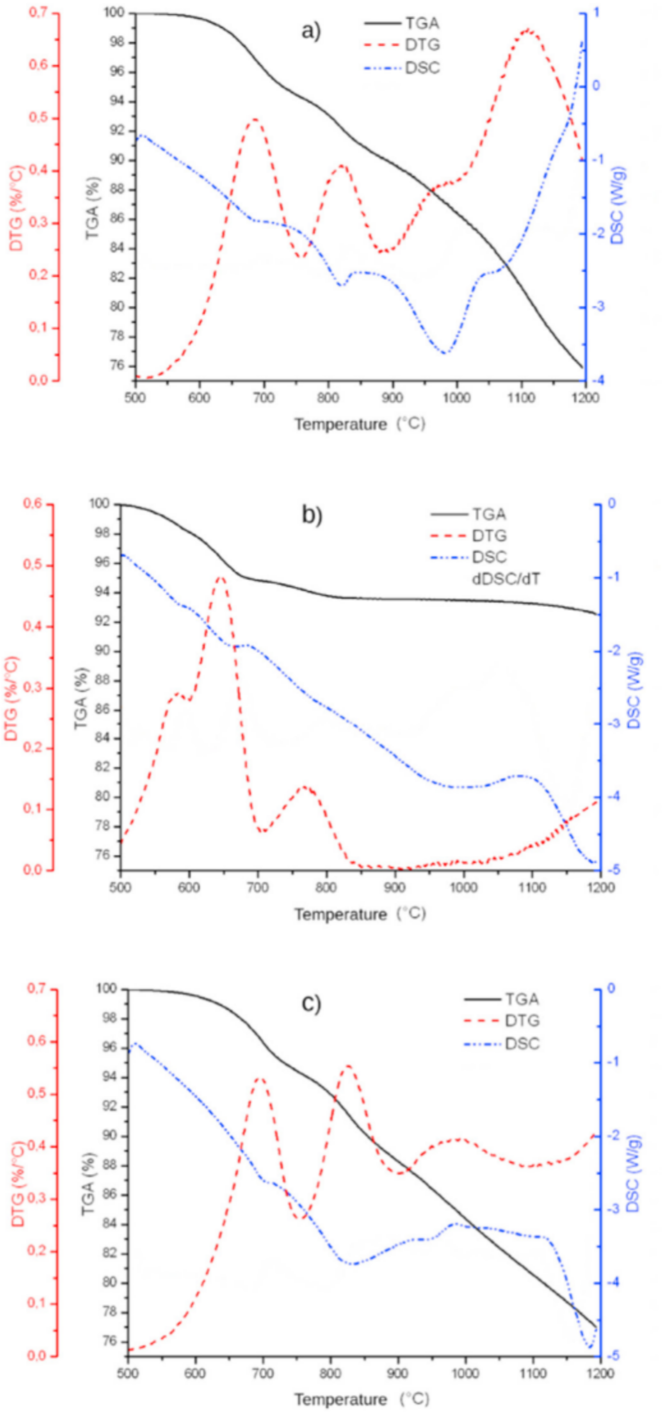

Fig. 7. Thermal analysis of the ashes. a)Wood chip ash b)Bark ash c)Leaves ash.

Ca (Table 13), and the calcium carbonate ($CaCO_3$) degrades at 840 °C, releasing CO_2. This phenomenon may be linked to the second peak mentioned above [67].

Calcium is one of the major elements present in biomass ashes, with higher content in the bark and overall content remains nearly constant with time, with little return to the soil. Alkaline metals Na and K, earthy alkaline Mg and Ca, silicon Si, sulfur S and chlorine Cl are the less desirable elements to be present in ashes because contribute strongly for the occurrence of fouling, slagging and corrosion on thermal equipment. Table 13 shows the amount of each element (Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Mn and Fe) found in the samples through the EDS analysis. The two main elements present in the ashes are K and Ca, followed by Mg and little P and Na. The remaining are of little significance. Chlorine that is an important element influencing corrosion, is mainly present in leaves and bark but the amount decays with time when the biomass is left on the ground, which is a favourable if the material is to be used for energy generation. The alkaline group has sodium (Na) present with 4–6% in the ashes from leaves, branches, tree tops, wood chips, and a little less in bark, 2%. This element remains in the biomass or presents minor loss when left on ground. Potassium content is affected by the conditions on the ground and decreases with time either through degradation or leaching. Bark ash showed a decrease in potassium from 12 to less than 4%. Ash from leaves, branches and tree tops showed a decrease in potassium of the order of 44 to 15% during the period of 94 days while exposed to the environment on the ground.

Table 14 shows the results for ash fouling indexes from each of the samples analyzed. According to these parameters and criteria presented by Vamvuka and Zografos [21], the combustion of all biomass considered in this study are prone to fouling, slagging and clustering. Occurrence of fouling and/or slagging is more probable when burning bark and leaves, with a tendency to decrease as far as the material stays longer on the ground, because the *AI* index decreases to values below critical (0.17 kg GJ^{-1} for leaves and 0.09 kg GJ^{-1} for bark).

According to the parameter *AI*, burning branches, tree tops and wood chips should not produce phenomena of fouling and/or slagging. Results of *AI* and $R_{b/a}$ are not compatible, therefore calculations conducted here are to be considered as a first approach to the phenomena considered.

4. Conclusions

An overview of planted forest and its use for energy generation in Brazil is presented. Brazil ranks world 9th in area of planted forest using only 0.9% of the national territory, exhibiting high expansion potential considering land availability adequate for agriculture. Favourable climate and soil quality enhance productivity of planted forest in Brazil, reaching 30–36 m^3 ha y^{-1} for eucalyptus and pine, thus representing the world's highest productivity, with better managed forests producing up to 70 m^3 ha y^{-1}.

Planted wood provides 7.8% of primary energy generation, mainly as charcoal for the steel industry. Electricity generation from planted wood represents only 2.4% of the total national generation and firewood contributes with a mere 0.3%, while the rest 2.1% is generated from black liquor in pulp and paper industry. Forest residues reach 20% for eucalyptus and 40% for pine as compared to the amount of wood produced. These values represent a potential of 16–20 $\times$ 10^6 t y^{-1} of forest residues from a production of 80 $\times$ 10^6 t y^{-1} from planted wood with 70% being eucalyptus. Considering residues from wood industry, lumber and panels, 33 $\times$ 10^6 m^3 (15 $\times$ 10^6 t y^{-1}) is produced because 72% of all processed wood turns into residues.

Residues of a particular eucalyptus planted forest after 30 days on the field, had their average moisture lowered to 5–8% from a typical 40–60% at harvesting time. Wood chips showed ash content

Table 13
Ash elemental composition (% mass), excluded oxygen.

Sample	*Na*	*Mg*	*Al*	*Si*	*P*	*S*	*Cl*	*K*	*Ca*	*Ti*	*Mn*	*Fe*
Leaves - day 1	4.19	8.93	1.20	1.77	5.42	1.55	4.59	43.72	24.35	0	3.39	0.90
Leaves - day 32	4.98	9.49	1.12	1.83	5.56	1.76	0.80	41.46	30.29	0	1.43	1.27
Leaves - day 94	1.73	9.19	1.45	2.16	5.11	2.14	0	15.06	61.30	0	0.76	1.09
Bark - day 1	2.10	8.19	7.89	0.41	1.59	0.71	3.50	12.40	62.49	0	0.73	0
Bark - day 32	1.15	9.46	0	0	1.53	0.40	0	5.75	81.21	0	0.49	0
Bark - day 94	0.91	4.72	2.05	0.44	1.47	0.37	0	3.74	85.91	0	0.40	0
Branches - day 1	3.40	8.86	10.32	0.55	2.94	1.01	0	27.16	43.27	0	2.50	0
Branches - day 32	4.37	15.65	1.00	3.07	8.10	1.27	0	34.64	29.68	0.42	0.85	0.95
Branches - day 94	3.12	11.29	0.64	0.64	4.17	1.30	0	14.97	63.07	0	0.81	0
Tops - day 1	4.31	6.79	0.95	0.93	7.05	1.24	0	55.89	19.59	0	2.57	0.67
Tops - day 32	6.11	17.66	0	0	6.33	1.32	0	35.72	31.82	0	1.03	0
Wood chips	6.02	5.76	1.09	1.25	4.48	2.21	0	34.28	43.03	0	0.78	1.09

Table 14
Ash fouling indexes.

Sample	*AI* (kg GJ^{-1})	$R_{b/a}$	*BAI*
Leaves - day 1	0.61	18.1	0.44
Leaves - day 32	0.45	19.6	0.064
Leaves - day 94	0.17	16.9	0.153
Bark - day 1	0.32	7.5	0
Bark - day 32	0.17	∞	0
Bark - day 94	0.09	27.8	0
Branches - day 1	0.12	5.4	0
Branches - day 32	0.19	12.9	0.057
Branches - day 94	0.06	50.3	0
Tops - day 1	0.08	30.0	0.026
Tops - day 32	0.13	∞	0
Wood chips	0.06	25.8	0.063

of 0.3% and bark 4–5%. Ash elementary composition exhibited low Si and high K and Ca content. Ash from leaves and bark showed high Cl content at harvest, but this element lowered significantly after 32 days, possibly leached by rain. The ssh content from residues indicated probable effects of fouling and slagging in combustion chambers, although calculations seemed inconclusive.

Planted forest wood is an important biomass for power generation in Brazil because of its high productivity. Using forest residues can add on the order of 20–30% of the energy generated, if proper management is implemented in order to not reduce productivity by repeated harvesting of these residues.

Credit author statement

Gabriel Pena Vergara: Methodology, Validation, Formal analysis, Investigation, Writing – original draft. Luis Roberto Castro: Validation, Formal analysis, Writing – original draft. Carlos Alberto Gasparetto: Methodology, Validation, Writing – original draft. Waldir Antonio Bizzo: Supervision, Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Leslie AD, Mencuccini M, Perks M. The potential for Eucalyptus as a wood fuel in the UK. Appl Energy 2012;89(1):176–82. https://doi.org/10.1016/j.apenergy.2011.07.037.
[2] Rothe A, Moroni M, Neyland M, Wilnhammer M. Current and Potential Use of Forest Biomass for Energy in Tasmania, Biomass and Bioenergy 2015;80: 162–72. https://doi.org/10.1016/j.biombioe.2015.04.021.
[3] Brand MA. Energia de biomassa florestal. Rio de Janeiro, Brazil: Editora Interciência; 2010. ISBN 978-85-7193-244-9.
[4] Cambero C, Sowlati T. Assessment and optimization of forest biomass supply chains from economic, social and environmental perspectives – a review of literature. Renew Sustain Energy Rev 2014;36:62–73. https://doi.org/10.1016/j.rser.2014.04.041.
[5] Röser D, Sikanen L, Asikainen A, Parikka H, Väätäinen K. Productivity and cost of mechanized energy wood harvesting in northern scotland. Biomass Bioenergy 2011;35(11):4570–80. https://doi.org/10.1016/j.biombioe.2011.06.028.
[6] Brito J. Fuelwood utilization in Brazil. Biomass Bioenergy 1997;12(1):69–74. https://doi.org/10.1016/S0961-9534(96)00052-9.
[7] Suchek VI. The role of the planted forest in the pulp and paper industry in Brazil. For Chron 1991;67(6):636–48. https://doi.org/10.5558/tfc67636-6.
[8] Agency IE. Data and statistics. Tech. Rep.; 2018. https://www.iea.org/data-and-statistics.
[9] de Jong J, Akselsson C, Egnell G, Löfgren S, Olsson BA. Realizing the energy potential of forest biomass in Sweden – how much is environmentally sustainable? For Ecol Manag 2017;383:3–16. https://doi.org/10.1016/j.foreco.2016.06.028.
[10] López-Rodríguez F, Atanet CP, Blázquez FC, Celma AR. Spatial assessment of the bioenergy potential of forest residues in the western province of Spain. Caceres, Biomass and Bioenergy 2009;33(10):1358–66. https://doi.org/10.1016/j.biombioe.2009.05.026.
[11] Gómez A, Rodrigues M, Montañés C, Dopazo C, Fueyo N. The potential for electricity generation from crop and forestry residues in Spain. Biomass Bioenergy 2010;34(5):703–19. https://doi.org/10.1016/j.biombioe.2010.01.013.
[12] Jones HE, Madeira M, Herraez L, Dighton J, Fabião A, González-Rio F, Fernandez Marcos M, Gomez C, Tomé M, Feith H, Magalhâes MC, Howson G. The effect of organic-matter management on the productivity of Eucalyptus globulus stands in Spain and Portugal: tree growth and harvest residue decomposition in relation to site and treatment. For Ecol Manag 1999;122(1):

73–86. https://doi.org/10.1016/S0378-1127(99)00033-X.

[13] Eisenbies MH, Vance ED, Aust WM, Seiler JR. Intensive utilization of harvest residues in southern pine plantations: quantities available and implications for nutrient budgets and sustainable site productivity. Bioenerg. Res 2009;2(3):90–8. https://doi.org/10.1007/s12155-009-9036-z.

[14] Achat DL, Deleuze C, Landmann G, Pousse N, Ranger J, Augusto L. Quantifying consequences of removing harvesting residues on forest soils and tree growth – a meta-analysis. For Ecol Manag 2015;348:124–41. https://doi.org/10.1016/j.foreco.2015.03.042.

[15] Sherman L, Coleman MD. Forest soil respiration and exoenzyme activity in western north America following thinning, residue removal for biofuel production, and compensatory soil amendments. GCB Bioenergy 2020;12(3):223–36. https://doi.org/10.1111/gcbb.12668.

[16] Sherman LA, Page-Dumroese DS, Coleman MD. Idaho forest growth response to post-thinning energy biomass removal and complementary soil amendments. GCB Bioenergy 2018;10(4):246–61. https://doi.org/10.1111/gcbb.12486.

[17] Mavimbela LZ, Crous JW, Morris AR, Chirwa PW. The importance of harvest residue and fertiliser on productivity of pinus patula across various sites in their first, second and third rotations, at usutu Swaziland, N. Z. j. of For. Sci. 2018;48(1):5. https://doi.org/10.1186/s40490-018-0110-1.

[18] Corbeels M, McMurtrie RE, Pepper DA, Mendham DS, Grove TS, O'Connell AM. Long-term changes in productivity of eucalypt plantations under different harvest residue and nitrogen management practices: a modelling analysis. For Ecol Manag 2005;217(1):1–18. https://doi.org/10.1016/j.foreco.2005.05.057.

[19] Mendham DS, Ogden GN, Short T, O'Connell TM, Grove TS, Rance SJ. Repeated harvest residue removal reduces E. Globulus productivity in the 3rd rotation in south-western Australia. For Ecol Manag 2014;329:279–86. https://doi.org/10.1016/j.foreco.2014.06.033.

[20] Saidur R, Abdelaziz EA, Demirbas A, Hossain MS, Mekhilef S. A review on biomass as a fuel for boilers. Renew Sustain Energy Rev 2011;15(5):2262–89. https://doi.org/10.1016/j.rser.2011.02.015.

[21] Vamvuka D, Zografos D. Predicting the behaviour of ash from agricultural wastes during combustion. Fuel 2004;83(14):2051–7. https://doi.org/10.1016/j.fuel.2004.04.012.

[22] Pérez S, Renedo CJ, Ortiz A, Mañana M. Energy potential of waste from 10 forest species in the north of Spain (cantabria). Bioresour Technol 2008;99(14):6339–45. https://doi.org/10.1016/j.biortech.2007.12.014.

[23] Mateos E, Garrido F, Ormaetxea L. Assessment of biomass energy potential and forest carbon stocks in Biscay (Spain). Forests 2016;7(4):75. https://doi.org/10.3390/f7040075.

[24] Sette Jr CR, de Moraes MDA, Coneglian A, Ribeiro RM, Hansted ALS, Yamaji FM. Forest harvest byproducts: use of waste as energy. Waste Manag 2020;114:196–201. https://doi.org/10.1016/j.wasman.2020.07.001.

[25] Enes T, Aranha J, Fonseca T, Lopes D, Alves A, Lousada J. Thermal properties of residual agroforestry biomass of northern Portugal. Energies 2019;12(8):1418. https://doi.org/10.3390/en12081418.

[26] Ibá Report. Setorial, industria brasileira de Árvores - ibá. 2017. Brasília, Brazil, 2017.

[27] ABRAF. Anuário estatístico ABRAF 2013 ano base 2012, tech. Rep. Brasília, Brazil: Associação Brasileira de Produtores de Florestas Plantadas - ABRAF; 2013.

[28] Piketty M-G, Wichert M, Fallot A, Aimola L. Assessing land availability to produce biomass for energy: the case of Brazilian charcoal for steel making. Biomass Bioenergy 2009;33(2):180–90. https://doi.org/10.1016/j.biombioe.2008.06.002.

[29] Uhlig A, Goldemberg J, Coelho ST. O Uso de Carvão Vegetal Na Indústria Siderúrgica Brasileira e o Impacto Sobre as Mudanças Climáticas. Revista Brasileira de Energia 2008;14(2):67–85.

[30] Epe EdPE. Brazilian Energy Balance 2017 Year 2016, Tech. Rep., Ministério das Minas e Energia. 2017. Brasília, Brazil.

[31] Moreira JMMAP. Potential e participação das florestas na matriz energética. Pesquisa Florestal Brasileira 2011;31(68):363.

[32] Caron BO, Eloy E, de Souza VQ, Schmidt D, Balbinot R, Behling A, Monteiro GC. Quantificação da Biomassa florestal em plantios de curta rotação com diferentes espaçamentos. Comun Sci 2015;6(1):106–12.

[33] de Carvalho KHA, da Silva ML, Soares NS. Efeito Da Área e Da Produtividade Na Produção de Celulose No Brasil. Rev Árvore 2012;36(6):1119–28. https://doi.org/10.1590/S0100-67622012000600012.

[34] A. Gatto, N. Félix de Barros, R. Ferreira de Novais, I. Ribeiro da Silva, H. Garcia Leite, E. M. de Albuquerque Villani, Estoque de carbono na biomassa de plantações de eucalipto na região centro-leste do estado de Minas Gerais, Rev Árvore 35 (4).

[35] Binkley D, Stape JL, Bauerle WL, Ryan MG. Explaining growth of individual trees: light interception and efficiency of light use by Eucalyptus at four sites in Brazil. For Ecol Manag 2010;259(9):1704–13. https://doi.org/10.1016/j.foreco.2009.05.037.

[36] Stape JL, Binkley D, Ryan MG, Fonseca S, Loos RA, Takahashi EN, Silva CR, Silva SR, Hakamada RE, Ferreira JMdA, Lima AMN, Gava JL, Leite FP, Andrade HB, Alves JM, Silva GGC, Azevedo MR. The Brazil Eucalyptus potential productivity project: influence of water, nutrients and stand uniformity on wood production. For Ecol Manag 2010;259(9):1684–94. https://doi.org/10.1016/j.foreco.2010.01.012.

[37] Eloy E, da Silva DA, Schmidt D, Trevisan R, Caron BO, Elli EF. Effect of planting age and spacing on energy properties of Eucalyptus grandis w. Hill ex maiden. Rev Árvore 2016;40(4):749–58. https://doi.org/10.1590/0100-67622016000400019.

[38] Fernandes ALT, Thála de M F, de Faria MF. Análise biométrica de florestas irrigadas de eucalipto nos cinco anos iniciais de desenvolvimento. Rev Bras Eng Agrícola Ambient 2012;16(5):505–13. https://doi.org/10.1590/S1415-43662012000500006.

[39] Baesso RCE, Ribeiro A, Silva MP. Impacto Das Mudanças Climáticas Na Produtividade Do Eucalipto Na Região Norte Do Espírito Santo e Sul Da Bahia. Ciência Florest 2010;20(2):335–44. https://doi.org/10.5902/198050981856.

[40] Leite H, Castro R, Silva A, Júnior C, Binoti D, Castro AF, Binoti M. Classificação da capacidade produtiva de Povoamentos de Eucalipto utilizando diâmetro dominante. Silva Lusit 2011;19(2):181–95.

[41] Castro RVO, Soares CPB, Martins FB, Leite HG. Crescimento e produção de plantios comerciais de eucalipto estimados por duas categorias de modelos. Pesqui Agropecuária Bras 2013;48(3):287–95.

[42] de Rezende MA, Aroni AS, Costa VE, Severo ETD, Latorraca JVdF. Densidade e produtividade da madeira de híbrido e seminal de Pinus caribaea. Floresta e Ambiente 2008;15(2):8–17.

[43] Munhoz JSB. Caracterização da produtividade florestal e dos padrões de crescimento de Pinus taeda L. no sul do Brasil através de análise de tronco, Doutorado, Universidade de São Paulo, Escola Superior de Agricultura Luiz de Queiroz. 2011. Piracicaba - SP - Brazil.

[44] I. A. Bognola, P. J. R. Junior, E. A. A. da Silva, C. Lingnau, A. R. Higa, Modelagem uni e bivariada da variabilidade espacial de rendimento de Pinus taeda L., Floresta 38 (2), doi:10.5380/rf.v38i2.11632.

[45] Lima R, Inoue MT, Figueiredo A, de Araujo AJ, Machado SdA. Efeito do espaçamento no desenvolvimento volumétrico de Pinus taeda L. Floresta e Ambiente 2013;20(2):223–30. https://doi.org/10.4322/floram.2013.001.

[46] Oliveira EB. Planejamento e manejo da plantação de pinus. In: Shimizu JY, editor. Pínus na silvicultura brasileira; 2008. Embrapa Florestas, Colombo, PR, Brazil, ISBN 978-85-89281-26-3, 111–130.

[47] Cardoso DJ, Lacerda AEB, Rosot MAD, Garrastazú MC, Lima RT. Influence of spacing regimes on the development of loblolly pine (pinus taeda L.) in southern Brazil. For Ecol Manag 2013;310:761–9. https://doi.org/10.1016/j.foreco.2013.09.021.

[48] Castro AFNM, Castro RVO, Carneiro AdCO, Carvalho AMML, da Silva CHF, Cândido WL, dos Santos RC. Quantification of forestry and carbonization waste. Renew Energy 2017;103:432–8. https://doi.org/10.1016/j.renene.2016.11.050.

[49] do Couto H, Brito J, Tomazello Filho M, Corradini L, Fazzio E. Quantificação de Resíduos Florestais Para Produção de Energia Em Povoamento de Eucalyptus Saligna. IPEF (Inst Pesqui Estud Florest) 1984;(26):19–23.

[50] Casagrande NB, Brand MA, Lopes GPRD, Henne RA, Giesel G. Otimização do uso de Resíduos em florestas de Pinus sp. Para a geração de Energia. Anais eletrônicos, florianópolis, brasil, vols. 1–11; 2017.

[51] Schumacher MV, Witschoreck R, Calil FN, Lopes VG. Biomassa e nutrientes no corte raso de um povoamento de Pinus taeda L. de 27 anos de idade em Cambará do Sul – RS. Ciência Florest 2013;23(2):321–32. https://doi.org/10.5902/198050989278.

[52] Pérez S, Renedo CJ, Ortiz A, Mañana M, Silió D. Energy evaluation of the Eucalyptus globulus and the Eucalyptus nitens in the north of Spain (cantabria). Thermochim Acta 2006;451(1):57–64. https://doi.org/10.1016/j.tca.2006.08.009.

[53] J. Lorensi do Canto, C. Cardoso Machado, F. Seixas, A. P. de Souza, C. de Mello Sant' Anna, Avaliação de um sistema de cavaqueamento de ponteiras de eucalipto para aproveitamento energético, Rev Árvore 35 (6).

[54] M. A. Brand, G. I. B. de Muñiz, D. A. da Silva, U. Klock, Caracterização do rendimento e quantificação dos resíduos gerados em serraria através do balanço de materiais, Floresta 32 (2), doi:10.5380/rf.v32i2.2288.

[55] Ortíz L, Tejada A, Vázquez A, Veiras GP. Aprovechamiento de La biomasa forestal producida por La cadena monte-industria. Parte III: producción de Elementos densificados. Revista CIS-Madera; 2003. p. 17–32.

[56] Vergara GP, Gomes FB, Colodette J, Bizzo W. Characterization and energy potential assessment of the forestry residues from the paper and pulp industry. In: Proceedings of the 5 th international conference on engineering for waste and biomass valorisation (WasteEng2014). Rio de Janeiro, Brazil: Mines d'Albi; 2014. p. 1674–91.

[57] Musinguzi WB, Okure MAE, Wang L, Sebbit A, Løvås T. Thermal characterization of Uganda's Acacia hockii, combretum molle, Eucalyptus grandis and Terminalia glaucescens for gasification. Biomass Bioenergy 2012;46:402–8. https://doi.org/10.1016/j.biombioe.2012.08.001.

[58] Kumar R, Pandey KK, Chandrashekar N, Mohan S. Study of age and height wise variability on calorific value and other fuel properties of Eucalyptus hybrid. Acacia Auriculaeformis and Casuarina Equisetifolia, Biomass and Bioenergy 2011;35(3):1339–44. https://doi.org/10.1016/j.biombioe.2010.12.031.

[59] García R, Pizarro C, Lavín AG, Bueno JL. Spanish biofuels heating value estimation. Part II: proximate analysis data. Fuel 2014;117:1139–47. https://doi.org/10.1016/j.fuel.2013.08.049.

[60] Heidari A, Stahl R, Younesi H, Rashidi A, Troeger N, Ghoreyshi AA. Effect of process conditions on product yield and composition of fast pyrolysis of Eucalyptus grandis in fluidized bed reactor. J Ind Eng Chem 2014;20(4):2594–602. https://doi.org/10.1016/j.jiec.2013.10.046.

[61] Almeida G, Brito JO, Perré P. Alterations in energy properties of Eucalyptus wood and bark subjected to torrefaction: the potential of mass loss as a synthetic indicator. Bioresour Technol 2010;101(24):9778–84. https://doi.org/10.1016/j.biortech.2010.07.026.

[62] Turn SQ, Kinoshita CM, Ishimura DM. Removal of inorganic constituents of biomass feedstocks by mechanical dewatering and leaching. Biomass Bioenergy 1997;12(4):241–52. https://doi.org/10.1016/S0961-9534(97)00005-6.

[63] Silvério FO, Barbosa LCA, Maltha CRA, Fidêncio PH, Cruz MP, Veloso DP, Milanez AF. Effect of storage time on the composition and content of wood extractives in Eucalyptus cultivated in Brazil. Bioresour Technol 2008;99(11):4878–86. https://doi.org/10.1016/j.biortech.2007.09.066.

[64] Barneto AG, Vila C, Ariza J. Eucalyptus kraft pulp production: thermogravimetry monitoring. Thermochim Acta 2011;520(1):110–20. https://doi.org/10.1016/j.tca.2011.03.027.

[65] Mortari D, Ávila I, Crnkovic P. Study of thermal decomposition of sugarcane bagasse and ignition temperature of coal/bagasse blends using thermogravimetry. In: Proceedings of the 21th Brazilian congress of mechanical engineering. vol. 1; 2011. p. 1–8. Natal, RN, Brazil.

[66] Yang H, Yan R, Chen H, Lee DH, Zheng C. Characteristics of hemicellulose, cellulose and lignin pyrolysis. Fuel 2007;86(12–13):1781–8. https://doi.org/10.1016/j.fuel.2006.12.013.

[67] Arvelakis S, Jensen PA, Dam-Johansen K. Simultaneous thermal analysis (STA) on ash from high-alkali biomass. Energy Fuels 2004;18(4):1066–76. https://doi.org/10.1021/ef034065+.