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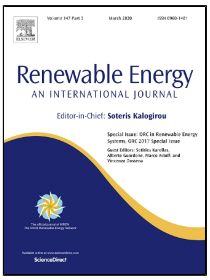

Apple pruning residues: potential for burning in boiler systems and pellet production

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Corrected article - Final version

Apple pruning residues: potential for burning in boiler systems and pellet production

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ABSTRACT

Residues from management activities of fruit growing can be an important source of biomass for energy generation. The aim of this study was to determine the potential use of apple pruning residues for energy generation as process steam or power energy. To this end, branches from the pruning of commercial apple orchards have been evaluated in the Santa Catarina State, Brazil. To compare with the traditional biomass used for energetic purposes, particles of *Pinus* sp. from the industrial timber processing have also been analyzed. Homogeneous pellets of the two types of biomass were produced, and three more mixes containing the two raw materials were made. Pellets have been evaluated according to their physical and energetic properties. The results have been compared to the ISO 17225-2 Standard. Apple pruning residues have the potential for energy generation in boilers, that is, for the production of process steam and electric power. Their potential can vary from 12,649.54 MWh y^{-1} to 115,442.44 MWh y^{-1}. The physical and energetic properties varied between the analysed residues, except the gross calorific value (19.69 MJ kg^{-1} for pine wood particles and 20.27MJ kg^{-1} for apple pruning). Comparing with the pine wood (87 $kg.m^{-3}$), the apple pruning (141 $kg.m^{-3}$) has a higher amount of biomass per unit volume processed for energy and less residence time in the burning systems (17.54% fixed carbon for apple pruning and 18.91% fixed carbon

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for pine wood). However, it generates more wastes (ashes) after burning (3.25% for apple pruning and 0.46% for pine wood). The pellets' energy density increased by 3.35 times the energy density of the apple pruning particles after pelletizing. The homogeneous apple pruning pellets can only be applied to industrial use (I3), mainly because of its high ash content (2.27%). The pine wood with apple pruning mix used for pellet production reduces the ash content and increases the bulk density and energy density, which improves the quality of the pellets.

Keywords: Apple growing; *Pinus* sp.; biomass for energy; ISO 17225-2.

INTRODUCTION

Among the 33,583 ha of apple orchards in Brazil, the southern region has 33,159 ha (98.74% of the planted area), which are distributed between Santa Catarina (SC) (16,364 ha), Rio Grande do Sul (RS) (15,695 ha), and Paraná (PR) (1,100 ha). According to IBGE's latest data, in 2017, South Brazil contributed with 99.30% of the national apple production. The state of Santa Catarina is the greatest national producer (50.88% of the production), followed by the Rio Grande do Sul (46.05%) and Paraná (2.37%) [1] (Figure 1).

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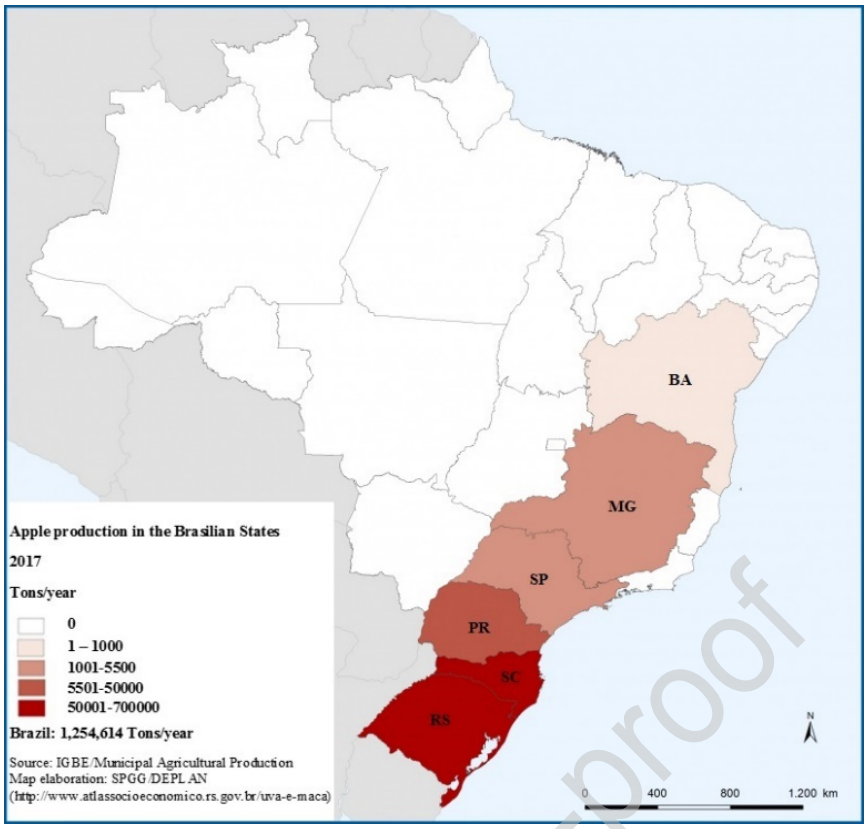

Figure 1 - Distribution of the Brazilian apple production in 2017.

Source: IBGE [1]. RS (Rio Grande do Sul State); SC (Santa Catarina State); PR (Paraná State); MG (Minas Gerais State); BA (Bahia State).

The apple orchards (*Malus domestica* Borkh) require annual and cyclical operations (annual pruning and tree cutting at the end of the fruit production cycle). These activities produce woody biomass materials such as branches, trunks, and rootstocks [2]. The annual pruning generates a substantial amount of residues, which must be disposed of [3,4].

After being collected, most of these wastes are burnt in the orchards [5]. These residues are often considered wastes and not resources [4]. Therefore, finding uses for the orchard pruning residues would allow converting a disposal problem into a supplemental production, which can have revenue potential or reduce management costs [3].

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Prando et al. [6] quantified the pruning residues and the wood from removed trees in the management of apple orchards in the province of South Tyrol (Northern Italy) and concluded that the average pruning weight on dry basis is 1.15 t ha^{-1}, with an average moisture content of 56.7%. In the studied region, the authors claim that the pruning residues are available at a rate of 14,950 t y^{-1}. Similarly, Boschiero et al. [2] raised an amount of 1.03 t ha^{-1} of apple pruning residues with a moisture content of 51% in Northern Italy. Nakomcic-Smaragdakis et al. [7] stated that the yield of apple pruning residues with a moisture content of 14% is around 3.40 t ha^{-1}. Taking into account that 18,402 ha of land are used for fruit cultivation in the Autonomous Province of Vojvodina, the annual yield of this type of biomass in the region is 62,548 t ha^{-1}. Moreover, when analysing different collection systems of apple pruning residues, Magagnotti et al. [4] found that the production can vary from 2.1 to 9.8 t ha^{-1} of the total production, but due to losses in the collection process the production of residues varies from 1.8 to 9.4 t ha^{-1}, with a mean moisture content of 44%.

Nowadays, the trunks of felled trees are used as firewood to feed house-stoves or boilers in farmers' houses. Pruning residues are grinded and left on the field and rootstocks are sent to composting plants landfills. Therefore, the exploitation of this residual biomass for energetic purposes could represent an alternative income for farmers and the possibility to limit the use of fossil fuels [2].

The agronomic sector based on apple cultivation (*Malus domestica*) represents a promising option for the use of an alternative biomass that is currently underestimated [2, 8]. This biomass can supply relatively cheap bioenergy feedstock [6, 8]. In fact, pruning residues could replace traditional wood assortments for energy and industrial uses [9], and they may play an important role in supplying bioenergy plants with renewable fuels [10]. The energetic use potential of apple pruning residues was evaluated by Ekinci [11].

The author concluded that the quantity of technically available apple pruning residues in the province of Isparta is 69,835.55 dry tons per year. He claims that the Combined Heat and Power (CHP) system has a capacity of 7.8 MWe and it can produce a net annual electricity of 59,754,426.5 kWh, which covers approximately 82% of the annual electricity consumption of the district of Egirdir. Regarding heat generation from CHP plants, 24.17% of the annual heat consumption of the district of Egirdir could be met by the proposed biomass CHP with the capacity of 21.08 MWth.

The steps to turn this biomass into a fuel for energetic use consist of harvesting, transforming it into chips and transporting it to the energy conversion plant [2]. The use of modern technologies under favourable field conditions allows tapping this new resource at a limited cost, well within the price limits offered for raw biomass. As field conditions or logistics become less favourable, the cost of recovery increases and the operation may lose financial sustainability. Even so, recovery is generally less expensive than disposal and should be pursued [4].

In Brazil, the National Solid Waste Policy (PNRS), that is regulated by Law 12,035 [12], establishes legal bans on the disposal of solid wastes. It prohibits the burning in open areas. On the other hand, the PNRS has as one of its principles the recognition of the reusable and recyclable solid waste as an economic good with social value, generator of work and income, and promoter of citizenship. This law also encourages the integrated management of solid waste, including its recovery and energy use. In this way, using the wastes from the apple orchards to generate energy in different ways is in accordance with the national guidelines for solid waste management in the agricultural sector.

Residual biomass often has some characteristics such as heterogeneous particle size, high moisture content and low energy density, which make its use as solid biofuel difficult [13]. However, pruning residues from fruit trees have low moisture and high

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cellulose and lignin contents [5], which is an advantage for energy use. It is also advisable to blend agricultural residues with other biomass fuels; such as sawmill or forest residues. The resulting mix would benefit from the low water mass fraction of the agricultural residues and the low ash content and reduced undesired elements of the forest residues [14].

Besides using the residual biomass in the direct burning, for thermal and electric power generation, its compaction through the production of pellets can constitute a viable technology to obtain a dense and uniform biofuel with low moisture content that can be used in domestic stoves, industrial boilers and electric power plants [13]. However, problems related to the low density of the different types of biomass, transportation, and storage, have led to the need to find a solid fuel with higher density and greater hardness, such as pellets and briquettes [15]. Within the energetic context, the use of waste pellets as a sustainable energy alternative is an effective tool in the fight against climate changes [16].

In this context, the hypothesis of this research is that the apple pruning residues can be an important biomass source for the production of process steam, power energy, and pellets in South Brazil. The aim of this study was to determine the potential use of apple pruning residues for energy generation as process steam or power energy. In order to do so, the energetic quality of apple pruning residues was compared to the pine wood particles. Also, pellets produced with both apple pruning residues and pine wood particles, and with different mixtures of them were compared to the ISO 17225-2 standard.

MATERIALS AND METHODS

The apple pruning residues were collected from apple orchards located in Urubici, Santa Catarina, Brazil (28º 00 '54 "S 49º 35' 30" W). The city has an altitude of 915 m. Pinus sp. wood particles were used to compose the mixtures for pellet production. Their source was a door's industry located in Lages, Santa Catarina, Brazil (27º 48 '58 "S 50º 19' 34" W), which has an altitude of 915 m.

In South Brazil, the raw materials used for combustion in industrial boilers and pellet production are residues from *Pinus taeda* L. and *Pinus elliottii* Engelm processing industries, residues from commercial plantations. Therefore, the pine wood particles have been evaluated along with the apple pruning residues.

After pruning, the leafless branches are gathered and placed in piles in the orchard and then burned. We have collected the branches shortly after the pruning. Then, the apple branches were shattered in an industrial hammer mill, with a 6 mm screen size. The pine wood particles have been used as they were received from the industry, without receiving any prior treatment before the pelletizing process. After receiving the pine wood particles and grinding the apple branches we have determined the particle size distribution, the bulk density, and the moisture content of the biofuels in natura (Table 1).

Table 1 - Standards used to determine the chemical, physical and energetic properties of pine wood particles and apple pruning residues before the pelletizing process.

Properties	Standard	Number of repetitions
Moisture content (%)	EN 14774 [17]	3
Bulk density (kg m^{-3})	EN 15103 [18]	5

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Proximate analysis (%)	ASTM 1762 [19]	3
Gross calorific value and net calorific value (MJ kg^{-1})	DIN 51900 [20]	3
Chemical analysis (%)	TAPPI T257 [21] TAPPI T264 [22] TAPPI T222 [23]	4
Determination of particle size distribution (%)	EN 15149-1 [24]	3

Proximate analysis: volatile matter (%), fixed carbon (%), and ash content (%). Chemical analysis: extractives in ethanol-toluene (%), extractives in ethanol (%), extractives in hot water (%), total extractives (%), and acid-insoluble lignin content (%).

The following physical and chemical biomass properties have been assessed, moisture content, bulk density, particle size distribution, proximate analysis, gross calorific value, extractive content, and lignin content. In order to characterize the pruning residues and the pine wood particles, the materials have been turned into sawdust. The sawdust then passed through the 40 mesh sieve and it was retained in a 60 mesh sieve (Table 1), which was used to determine the chemical and energetic properties of the raw materials before the pelletizing process.

For pelletizing, the treatments have been prepared based on the weight of each material on the wet basis moisture content, which has been measured at the time of pelletizing (Table 2). After the composition of the mixtures, the particle-size distribution was performed based on EN 15149-1 [24] to verify possible particle-size changes as a function of the compositions of the treatments.

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Table 2 - Experimental design for the pelletization of different mixtures of apple pruning residues and pine wood particles.

Treatment	Apple pruning residues* (%)	*Pinus* sp wood* (%)
Ap100	100	-
Ap75P25	75	25
Ap50P50	50	50
Ap25P75	5	75
P100	-	100

* Percentage of the total mass of the experiment. Ap (apple pruning residues), P (pine wood particles)

The pelletizing process has been performed by a pilot laboratory pelletizer with a flat pellet matrix (Figure 2) and a production capacity of 400 $kg.h^{-1}$.

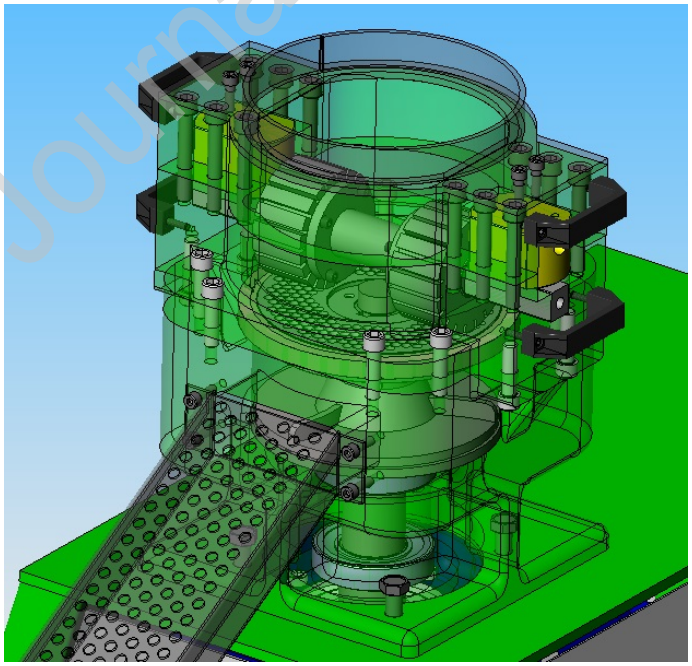

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Figure 2 - Flat pellet matrix of the pilot laboratory pelletizer (Lippel Metal Mecânica Ltda - Equipment Manufacturer)

Source: Brand et al. [25]

The equipment has frequency inverters in (a) the electric motor that moves the pelletizing matrix, (b) the motor of the biomass feed silo, and (c) the pellet-cooling station's motor. The temperature variations are read by two sets of thermocouple type sensors, one before the biomass enters the pelletizing matrix and then another one in the matrix's pelletizing area.

For each treatment, the pelletizer has been heated to 80°C. The pelletizing parameters, pressure (80 to 110 Bar), feed velocity (139 to 200 revolutions per minute for apple pruning and 492 revolutions per minute for pine particles), and speed of the conveyor feeder (59.60 Hz) were adjusted until the pellets maintained their consistency and compression after exiting the matrix and after cooling down (Figure 3).

Figure 3 - Pellets of different mixtures of apple pruning residues and pine wood particles. A: P100 – pine wood particles 100%; B: P75Ap25 - pine wood particles 75% and apple pruning residues 25%; C: P50Ap50 – pine wood particles 50% and apple pruning residues 50%; D: P25Ap75 – pine wood particles 25% and apple pruning residues 75%; E: Ap100 - apple pruning residues 100%.

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Moreover, the pellets were left in an air-conditioning chamber (65% of relative humidity and 22°C of temperature) after the pelletizing process, and in the aftermath their physical (pellets' dimensions, bulk density, and moisture content), mechanical (durability and fines content), and energetic properties (gross calorific value and proximate analysis) were determined (Table 3).

Table 3 - Quality analysis of pellets obtained from different mixtures of apple pruning residues and pine wood particles.

Analysed properties	Standard	Repetitions
Length and diameter of pellets and Unity density	EN 16127 [26]	100
Bulk density (kg m^{-3})	EN 15103 [18]	5
Mechanical durability and fines content	EN 15210-1 [27]	4
Moisture content (%)	EN 14774 [17]	3
Gross calorific value and net calorific value	DIN 51900 [20]	3
Proximate analysis	ASTM 1762 [19]	3

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Energy density represents the amount of energy that can be released after the complete combustion of a given fuel volume [28]. This variable is also used to compare the energy conversion efficiency of different types of biofuels. Thus, the energy density ($GJ.m^{-3}$) was calculated by multiplying the gross calorific value ($MJ.kg^{-1}$) by the bulk density ($kg.m^{-3}$) of the pellets.

The results obtained from the laboratory were compared to the parameters of the ISO 17225-2 Standard [29]. In Europe and North America, countries used to have their

own national regulations regarding the use of biomass for energy generation. This variety of standards have generated some problems for the domestic and foreign trades of biofuels. Thus, in 2014, the ISO 17225-2 was established to determine the wood-pellet-quality criteria for different uses. The implementation of this standard sought to create regulations that could be accepted and used by all European countries. Since in Brazil there is no legal mechanism that controls the quality and the use of the biomass fuels, this work has adopted the ISO 17225-2 [29] because this standard is accepted worldwide and, therefore, it can also be applied in Brazil.

The data have been analysed by using the analysis of variance (ANOVA) and the F test. In addition, the Scott-Knott test ($p < 0.05$) have been carried out by using the SISVAR statistical software. The Scott-Knott test was used because it separates averages into distinct groups, by minimizing variation within and maximizing variation between groups. The results are easily read because of the lack of ambiguity. In this way, this test results in greater objectivity and clarity [30]. To study the correlation between the bulk density and the energy density and between the gross calorific value and the energy density, it was used the Pearson correlation coefficient (r), which reflects the intensity of a linear relationship between two data sets.

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RESULTS AND DISCUSSION

The literature data show that the amount of pruning residues can vary from 1.03 t $ha^{-1}y^{1}$ with 51% of moisture content [2] to 9.4 $t.ha^{-1}y^{-1}$ with 44% of moisture content [4]. Therefore, considering that the apple orchards cover 33,159 ha [1], the potential production of apple pruning residues in South Brazil can vary from 34,153.77 t y^{-1} to 31,1694.60 t y^{-1}.

These residues could be used in boiler systems or Thermal Power Stations (TSP) for energy generation. They would have an annual energy output of 12649.54 MWh to 115442.44 MWh if they were used in fixed-bed boilers for power generation. These results have been calculated from data of a thermoelectric plant in the study region (Lages, Santa Catarina, Brazil), where 2.7 tons of forest biomass are needed to generate 1 MWh.

The apple pruning residues showed a moisture content close to the desired one (30%) for combustion in boilers [31] even after pruning and gathering the branches (Table 4). These results were lower than the ones presented by Magagnotti et al. [4] (44%), Boschiero et al. [2] (51%), and by Prando et al. [6] (56.7%) under the same harvest conditions.

Table 4 - Physical and energetic properties of apple pruning residues and pine wood particles in natura (before the pelletizing process).

Types of biomass	Pine wood particles	Apple pruning residues
Wet basis moisture content (%)	14.63 B	32.14 A
Bulk density (kg m^{-3})	87 B	141 A
Fixed carbon (%)	18.91 A	17.54 B
Volatile matter (%)	80.63 A	79.21 B
Ash content (%)	0.46 B	3.25 A
Gross calorific value (MJ kg^{-1})	19.69 A	20.27 A
Net calorific value (MJ kg^{-1})	15.25 A	12.02 B
Total extractives (%)	10.01 B	13.72 A

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Lignin content (%)	30.10 B	33.18 A

Means followed by the same letter IN LINE (Capital letter) do not differ statistically between them by the Scott-Knott test ($p > 0.05$).

The moisture content of the pine wood particles was low due to their source, a door manufacturing company. In its production process, the wood is dried before the manufacture of the doors. The pine wood particles could be directly pelletized with the moisture content around 14% (Table 4). The apple pruning residues required the previous drying before the pelletizing process.

The two biomass types that have been analysed in this study had low bulk density. The bulk density of fresh biomass ranges from 40-200 kg m^{-3} [32]. For the biomass combustion in boiler systems, the bulk density is a problem because it takes up a lot of space inside the combustion chamber which results in lower energy density.

However, problems related to the low density of the different types of biomass, along with their transportation and storage difficulties, have urged producers to find a solid fuel with higher density and greater hardness, such as pellets and briquettes [15]. These issues are characteristics that make the pelletizing process important for increasing the energy density of biomass fuels.

Results show that, after being ground, both the pine wood particles and the apple pruning residues (Table 4) had bulk densities lower than the one reported by Moon et al. [33]. These authors claim that the bulk density must be at least 200 kg m^{-3} for pelletizing.

The mixtures containing the two biomass types for pellet production also had lower bulk densities than the recommended values from the literature. They ranged from 84 to 138 kg m^{-3} (Table 5). The different mixing proportions influenced the bulk density

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of the treatments. Increasing the proportion of pine wood particles decreased the bulk density of the mixtures before the pelletizing process.

Table 5 - Physical and energetic properties of pellets produced with different mixtures of apple pruning residues and pine wood shavings.

Treatment	BD_{bp} kg m^{-3}	MC_{bp} (%)	MC_{ap} (%)	GCV (MJ kg^{-1})	NCV (MJ kg^{-1})	FC (%)	VM (%)	AC (%)
Ap100	141 a	18.08 a	10.47 a	18.94 a	15.48 a	19.10 a	78.63 a	2.27 a
Ap75P25	138 a	17.40 a	7.62 b	19.06 a	16.16 a	20.53 a	77.83 a	1.64 a
Ap50P50	104 b	17.39 a	9.78 a	19.33 a	15.97 a	19.98 a	78.86 a	1.16 b
Ap25P75	84 c	15.56 b	9.09 a	19.52 a	16.28 a	20.39 a	79.23 a	0.38 b
P100	87 c	13.16 c	9.94 a	19.68 a	16.25 a	22.28 a	76.85 a	0.87 b
CV	5.86	2.93	6.74	3.20	3.70	5.59	1.37	28.15

BD_{bp}: bulk density before pelleting; MC_{bp} = wet basis moisture content before pelleting; MC_{ap}= wet basis moisture content after pelleting; GCV = gross calorific value; NCV = net calorific value; FC= fixed carbon; VM= volatile matter; AC = ash content; CV = coefficient of variation.

Means followed by the same letter IN COLUMN (Lowercase) do not differ statistically between them by the Scott-Knott test ($p > 0.05$).

The proximate analyses presented different results between the two analyzed materials. The pine wood particles had higher fixed carbon and volatile matter and lower ash contents than the apple pruning residues (Table 4). Boschiero et al. [2] obtained an ash content of 4.1% for apple pruning residues, which is slightly higher than the one found

in this study. The pine wood particles have a longer residence time in the furnace and lower ash generation than the apple pruning residues.

The proximate analysis of the pellets showed similar fixed carbon and volatiles content between the treatments with different mixing proportions of the raw materials (Table 5). Therefore, the burning behaviour of the pellets produced with the different mixtures of apple pruning residues and pine wood particles are similar in the boiler.

The highest ash contents were observed in the treatments containing 75% (Ap75P25) and 100% of apple pruning residues (Ap100), which were similar to each other. The ash content of the apple pruning particles before pelletizing (Table 4) was different from the one obtained for pellets produced with 100% apple pruning residues (Table 5). The material analyzed in both cases was obtained from the same sample. However, the observed variation was due to the variability of the species' ash content and not to any different treatment given to the analyzed samples.

The Ap25P75 pellets had lower ash contents than the two residues used in the mixtures (P100 = 0.87% and Ap100 = 2.27%). This phenomenon can be explained by the particle size analysis. The Ap25P75 pellets had the smallest amount of fines (73.6% <3.15 mm) and the largest amount of particles larger than 16 mm. Therefore, the particle size distribution may have contributed to the reduction of mineral waste contamination. Also, the proportion of apple tree bark may have been lower in the mixture, which may have reduced the pellets' ash content.

Prando et al. [6] have found an ash content of 4.3% when analysing the properties of apple pruning pellets. These authors have also compared the characteristics of apple pruning pellets with the European standard for wood pellets (ISO 17225-2). They concluded that the apple pruning pellets are out of the largest limits allowed by the

standard for domestic and commercial uses, in the same way as in this study for the homogeneous apple pruning pellets.

The use of apple pruning pellets in a domestic boiler should consider a technology that can manage a high amount of ashes. A piece of specialized equipment should be implemented to clean the heat exchangers regularly in order to maintain a high heat transfer efficiency. Also, grates should be used to evenly distribute the burning biomass and move the ashes away from the primary combustion zone, preventing the ash from overheating and sticking to burning zone's wall. An alternative could be to add into the mix a raw material with low ash content in order to reduce the ash content of the pellets [6].

Results from the proximate analyses of the pellets obtained in this study prove what was claimed by Prando et al. [6]. They show that there was an ash content reduction with the increase of the proportion of pine wood particles in the mixtures for the pellets production, as presented in Table 5.

Considering the ash content limits of all use categories of the ISO 17225-2 [29], A1 (0.7%), A2 (1.2%), B (2%), I1 (1%), I2 (1.5%), and I3 (3%), the homogeneous pine wood pellets fit only the residential category (A2) and the homogeneous apple pruning pellets fit the industrial one (I3). Pellets containing 25% of apple pruning residues (Ap25P75) could be used in all categories (residential use (A1 and A2), commercial use (B) and industrial use (I1, I2, and I3)) without restrictions. The ones containing 50% of apple pruning residues fit the residential (A2), commercial (B) and industrial (I2 and I3) categories. Pellets with 75% of apple pruning residues fit the commercial (B) and industrial (I3) categories.

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The gross calorific value of the two analysed biomasses was similar, which shows that both materials have the same potential for energy generation in the boiler (Table 4). Boschiero et al. [2] obtained a gross calorific value of 19.03 MJ kg^{-1} when analysing apple pruning residues, a value slightly lower than the one observed in this study.

The net calorific value was different between the two raw materials due to the higher moisture content of the apple pruning residues. San Jose et al. [5], when analysing branches of apple-trees with a moisture content of 25% (in dry basis), obtained a net calorific value of 18.72 MJ kg^{-1} which is higher than the one found in this study. According to Nakomcic-Smaragdakis et al. [7], the apple pruning residue has a net calorific value of 14.15 MJ.kg^{-1} (moisture content of 14-15%).

The analysed mixtures, the homogeneous pine wood, and the apple pruning pellets presented net calorific values below the minimum required (16.5 MJ kg^{-1}) for all pellet applications, according to ISO 17225-2 [29]. The biomass mixtures did not influence the gross calorific value of the analysed treatments. Also, the observed variation of the moisture content of the pellets did not affect the net calorific value of the treatments.

Prando et al. [6] reported net calorific value of 15.9 MJ.kg^{-1} and a gross calorific value of 17.5 MJ. Kg^{-1} when assessing apple pruning pellets. These values are similar to the ones observed in this study, in which the net calorific values of the analyzed treatments were out of the limits of the ISO 17225-2 [29] categories.

The apple pruning residues presented higher content of lignin and extractives, and higher gross calorific value than the pine wood particles. In a similar study, García et al. [34] characterized apple pruning residues as following, 30.60 ± 2.40% of cellulose, 32.24 ± 0.60% of hemicellulose, 17.00 ± 3.41% of lignin, 1.09 ± 0.13% of extractives, and 9.28 ± 0.21% of inorganics (on a dry basis). These results were different from the ones found

in this study. Compositions of lignin, cellulose, and hemicelluloses are crucial factors for the biomass reactivity during combustion [35, 36]. The cellulose decomposes faster between 300 °C and 400 °C while lignin decomposes slower from 250 °C to 500 °C [37]. In addition, lignin is the compound of the lignocellulose biomass with the highest gross calorific value.

During the pelletizing process, the high lignin and extractives contents of the homogeneous apple pruning pellets may explain why the apple pruning residues were harder to compact. Lignin and extractive contents together exceeded 46.9%, but they are fundamental for the internal bonding and packing of particles [38, 39, 40] and their contents should be below the threshold level of 34% in wood samples [40].

Another factor that may have influenced the homogeneous apple pruning residues' pelletizing process was the higher amount of particles smaller than 3.15 mm (fines) in their composition (94.3%), which made this material harder to compact than the other treatments (Table 6).

Table 6 – Particle-size distribution of in natura residues and mixtures used for pelleting.

Sieves (mm)	Treatments				
	Ap100	Ap75P25	Ap50P50	Ap25P75	P100
≥31,5	0.0 C	0.0 C	0.0 C	0.9 A	0.3 B
≥16	0.0 A	0.7 A	0.7 A	0.5 A	0.5 A
≥8	0.1 C	2.2 C	4.3 B	2.1 C	6.6 A
≥3,15	4.4 B	8.1 B	14.8 B	23.3 A	11.3 B
Base	94.3 A	89.0 A	80.3 B	73.6 C	81.4 B

Means followed by the same letter IN LINE (Capital letter) do not differ statistically between them by the Scott-Knott test ($p > 0.05$).

The mixtures modified the particle-size distribution in all treatments. Only the particles with sizes between 16 to 31.4 mm showed statistically similar percentages between the treatments. The increase in the amount of pine wood particles in the mixtures decreased the percentage of particles smaller than 3.15 mm (fines) and increased the percentage of particles with sizes between 3.15 to 7.99 mm. The pellets composed of 50% of apple pruning residues (Ap50P50) were the closest to the homogeneous pine wood pellets (P100). The Ap50P50 treatment had the best particle distribution.

Jacinto et al. [41] pointed out that the ideal particle-size distribution for pelleting lignocellulose biomasses is 80% of particles equal or smaller than 3.15 mm, and at least 5% of particles above 3.15 mm, considering a pelletizer machine with a flat-matrix press (the same used in this study). This particle size distribution was ideal for all mixtures containing the raw materials used by Jacinto et al. [41], which worked with the same mixing proportions as in this study but using pine wood particles and *Araucaria angustifolia* empty-seeds.

Similarly, the results showed that the treatments with higher particle-size distribution were better compacted during the pelletizing process of pellets containing different biomass mixtures. In the pelletizer, the treatments with broader particle-size variation made the pelletizing process faster and resulted in longer and entire pellets, which did not break down after leaving the cooling duct.

The pine wood particles required low moisture content in the pelletizing process (MC_{bp}) (Table 5) to obtain quality pellets. It can be said that the greater the amount of apple pruning residues in the mixtures, the greater the amount of water required. The

moisture content influenced the functioning of the pelleting press, which made it harder to obtain pellets with the desired quality. Mixtures containing 50%, 75%, and 100% of apple pruning residues required moisture contents between 17 and 18% for a good pelleting and high pellet quality.

However, the results obtained in this study contradict the maximum moisture content values mentioned by Niedziółka et al. [42] and Monteiro et al. [43]. These authors state that raw materials with moisture contents higher than 15% are difficult to pelletize and they may break or suffer biological degradation during transport and storage. They also state that the moisture content is the main cause of reduction of the pellets' quality and calorific value. Jacinto et al. [41] found that raw materials with higher lignin contents also required higher moisture content for pelletizing, reaching 23% of moisture content for raw materials with approximately 42% of lignin content.

The moisture content of the biomass can affect the densification in three ways: (a) by decreasing the glass transition temperature [44]; (b) by promoting the formation of solid bridges [44, 45], and (c) through the increase of the particles' contact are by Van der Waals forces [32]. The impact of the moisture content depends on the type of biomass to be densified [44], and beyond that, an excessively dry lignocellulose material acts as a thermal insulation that prevents the transmission of heat, a key element of the compaction process [45].

After the pelletizing process, the moisture content of the pellets was close to 10%, meeting the specifications of the ISO 17225-2 [29] for all categories of use, except the homogeneous apple pruning pellets. Prando et al. [6] found a wet basis moisture content in apple pruning pellets of 8.3%, on average.

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Regarding the length of the pellets, the homogeneous apple pruning pellets were the largest (Table 7) ones, and statistically different from all the other treatments. The inclusion of pine wood particles in the mixtures contributed to the reduction of the pellet's length. Both the length and the diameter of the pellets of all the analyzed treatments met the specifications of the ISO 17225-2 [29] for all categories of use.

Table 7 - Physical and mechanical properties of pellets produced with different mixtures of apple pruning residues and pine wood particles.

Treatment	L (mm)	D (mm)	UD (kg m^{-3})	DU (%)	F (%)	BD (kg m^{-3})
Ap100	30.00 a	6.09 b	1,060 b	98.57 a	1.45 c	506 c
Ap75P25	22.32 b	6.14 a	980 c	98.60 a	1.42 c	558 b
Ap50P50	20.36 c	6.08 b	1,160 a	97.82 b	2.23 b	552 b
Ap25P75	23.08 b	6.13 a	1,020 b	95.32 c	4.91 a	554 b
P100	14.99 d	6.16 a	1,150 a	98.75 a	1.27 c	654 a
CV	2.02	0.47	2.41	0.26	12.36	1.69

UD = unit density. ISO 17225-2: D = diameter; L = length; BD = bulk density; F = fines; DU = mechanical durability.

Means followed by the same letter IN COLUMN (Lowercase) do not differ statistically between them by the Scott-Knott test ($p > 0.05$).

Both the length and the diameter of the pellets are important during the burning in boiler systems as they are designed for pre-defined diameters and lengths. Increasing the length and the diameter of the pellets can affect the furnace's feed system by clogging the

entry site of pellets into the burner, locking the system and requiring maintenance or shutdown [41].

The mechanical durability of the treatments containing 75% of apple pruning residues and the homogeneous apple pruning and pine wood pellets were higher and statistically similar. Only the treatment with 25% of apple pruning residues did not fit into any of the use categories of the ISO 17225-2 [29]. All the other treatments can be used for domestic, commercial and industrial purposes.

Prando et al. [6] identified mechanical durability of 94.4% in apple pruning pellets, lower durability than the ones obtained in this study. The production of apple pruning pellets in Brazil, whether or not made with mixtures containing *Pinus* particles, does not require binding additives to improve the mechanical durability, as Prando et al. [6] recommended. Regarding the fines content, all the analysed pellets into the industrial use according to the ISO 17225-2 [29] quality categories. Figure 4 shows the direct influence of the bulk density on the energy density of the fresh biomass (Table 4) and the pellets produced with different mixtures of pine shavings and apple pruning residues (Table 7).

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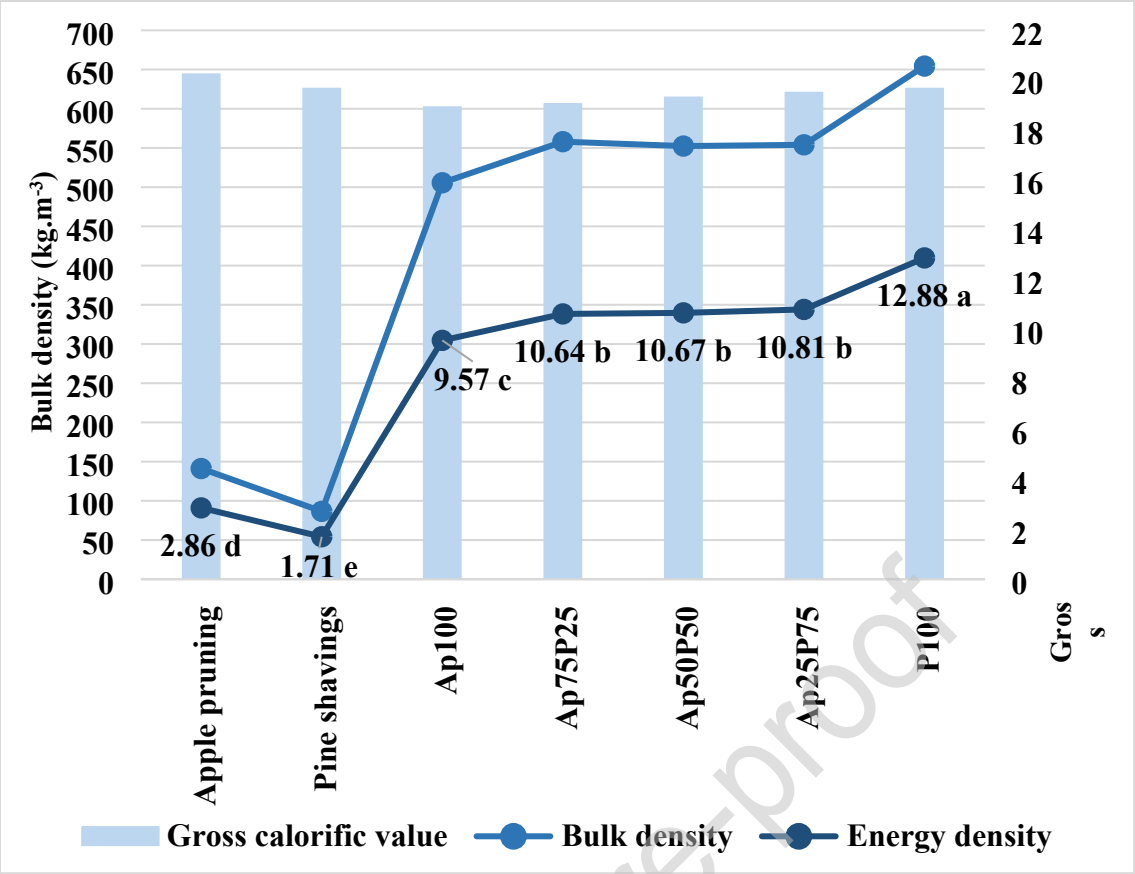

Figure 4 - Relationship between energy density,bulk density, and gross calorific value of the fresh biomass, the apple pruning and pine shavings pellets.

Means followed by the same letter do not differ statistically between them by the Scott-Knott test ($p > 0.05$).

The Pearson's correlation coefficient indicated that the bulk density (R^2= 0.99) of the pellets and the fresh biomass influenced the energy density more than the gross calorific value (R^2= -0.31), being the lowest and most negative correlation. The same was reported by Brand et al. [46], who evaluated the influence of bulk density and gross calorific value on the energy density of bamboo briquettes.

Pine shavings, which presented the lowest bulk density, resulted in the highest energy density pellets (P100). When comparing the energy efficiency of the pine shavings before and after pelletizing, the energy density increased by 7.53 times (P100). Also, the

energy density increased by 3.35 times when apple pruning particles were converted to pellets (Ap100).

De Paula Protásio et al. [28] reported an energy density value similar to the one found in this study for pine shavings pellets (12.56 GJ m^{-3}). Moreover, Arranz et al. [47] obtained energy densities from 14.29 to 15.72 GJ m^{-3} when studying pellets made with pine forest residues and 14.51 GJ m^{-3} for pellets made with fruit tree pruning and pallet wastes. These higher values can be attributed to the higher bulk density of the pellets (713 to 750 kg m^{-3} for pellets made with pine forest residues and 729 kg m-3 for pellets made with fruit tree pruning and pallet wastes).

Although the treatments Ap75P25, Ap50P50, and Ap75P25 presented statistically similar energy densities (Figure 4) and bulk densities (Table 7), the inclusion of pine particles contributed to a progressive increase in energy density of the pellets produced with the biomass mixtures. Thus, the bulk density can be considered the main quality index for the energy use of biomass fuels because it directly influences their energy densities. Also, it is desirable to obtain higher bulk densities because factors such as transportation costs and energy density are essential in the economic viability of biomasses for energy generation, as it allows to transport more energy per unit volume [48].

The homogeneous pine wood pellets presented the highest bulk density and, therefore, they were the ones that met the specifications of the ISO 17225-2 [29] for all categories of use. The other treatments showed bulk densities lower than the minimum value of 600 kg m^{-3} required by the standard.

According to the quality categories of the ISO 17223-2 (Table 8), the apple pruning pellets, both homogeneous and containing pine wood particles in their composition, may have industrial application. The properties that showed values that did

not reach the limit values of the standard are susceptible to adjustments in the industrial process.

Table 8 - Classification of pellets according to the quality categories of ISO 17225-2 for residential (A1, A2) commercial (B), and industrial applications (I1, I2 and I3).

Treatment	D (mm)	L (mm)	M (%)	A (%)	DU (%)	F (%)	Q (MJ kg^{-1})	BD (kg m^{-3})	General Classification
Ap100	A1	A1	-	I3	A1	I1	-	-	I3
Ap75P25	A1	A1	A1	B	A1	I1	-	-	I1
Ap50P50	A1	A1	A1	A2	A1	I1	-	-	I1
Ap25P75	A1	A1	A1	A1	-	I2	-	-	I2
P100	A1	A1	A1	A2	A1	I1	-	A1	I1

ISO 17225-2: D = Diameter; L = Length; M = Moisture; A = Ash; BD = Bulk density; Q = Net calorific value; F = Fines; DU = Mechanical durability; (-) = did not meet the parameters of any of the categories of use of the standard.

The final moisture content of the pellets can be adjusted by reducing the moisture content of the raw material entering the pelletizer to the minimum moisture content required for pelleting. The net calorific value can be increased by reducing the final moisture content of the pellets and controlling the gross calorific value of the raw material entering the pelletizing process. Moreover, the bulk density of the pellets can be increased by reducing the number of raw material particles smaller than 3.15 mm (fines) and using raw materials with lower bulk densities.

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These adjustments in the pelletizing process will further contribute to the reduction of the fines content of the pellets, and they can change the values to fit the limits of commercial and residential applications, according to ISO 17225-2 [29]. Only the high ash content of the homogeneous apple pruning pellets limits their commercial and residential uses.

CONCLUSION

The aim of this study was to determine the potential use of apple pruning residues for energy generation as process steam or power energy. In order to do so, the energetic quality of apple pruning residues was compared to the pine wood particles. Also, pellets produced with both apple pruning residues and pine wood particles, and with different mixtures of them were compared to the ISO 17225-2 standards.

The apple pruning residues have a higher amount of biomass per unit volume for energy generation than the pine wood particles. They also have less residence time in the burning systems and they generate more ashes after burning. Therefore, the apple pruning residues have energy potential for burning in boilers, for the production of process steam and power energy in South Brazil.

The homogeneous apple pruning pellets least fit the use categories of the ISO 17225-2 and can only be applied in industrial uses (I3). The mixing of pine wood particles with apple pruning residues reduce the ash content and increase the bulk density and energy density, improving the quality of the pellets.

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Author Contribution Statement

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The author contributed to the following activities in the research project and manuscript:

- *Conceptualization*
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- *Validation*
- *Formal analysis*
- *Investigation*
- *Resources*
- *Writing - Original Draft*
- *Writing - Review & Editing*
- *Visualization*
- *Supervision*
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- *Resources*
- *Writing - Original Draft*
- *Writing - Review & Editing*
- *Visualization*

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Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Highlights

- Tree pruning generate a substantial amount of residues that can generate energy.
- Management of apple cultivation can be an important source of biomass for energy.
- Mixing different types of biomass improves pellet quality.
- Apple pruning is an energy suitable for industrial use in boiler and as pellet.
- Adjustment of the process can improve the quality of apple pruning pellets.

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