# Analysis of Briquettes and Pellets Obtained from Two Types of *Paulownia* (*Paulownia tomentosa* and *Paulownia elongata*) Sawdust

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Sawdust specimens of two *Paulownia* species, namely *Paulownia tomentosa* and *Paulownia elongata*, were evaluated in order to obtain briquettes and pellets. Briquettes and pellets were manufactured from the sawdust, and their physical properties (density), mechanical properties (the resistance of the briquettes to breaking, and the shear resistance of the pellets), and energetic properties (caloric value, black ash content, and calcined ash content) were determined. The densities of the *P. elongata* and *P. tomentosa* briquettes were 790 kg/m$^3$ and 934 kg/m$^3$, respectively, while the pellets had densities of 1268 kg/m$^3$ and 1266 kg/m$^3$, respectively. These values were within the standardized limits, and the ash content had good values. The high calorific value of 16815 kJ/kg and the low calorific value of 16669 kJ/kg was acceptable, since they were greater than other vegetable resources. In conclusion, it was found that the two types of wood biomass are suitable for the production of briquettes and pellets, due to their good physical, mechanical, and energetic properties.

*Keywords: Ash content; Caloric value; Density; Paulownia; Sawdust*

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## INTRODUCTION

*Paulownia* is one of the fastest growing wood species in the world. The genus contains 6 to 17 sub-species (*P. albiphloea*, *P. australis*, *P. catalpifolia*, *P. elongata*, *P. fargesii*, *P. fortunei*, *P. kawakamii*, *P. tomentosa*, *P. australis*, *P. kawakamii*, *P. taiwaniana*, *etc.*) including their hybrids, and is part of the Paulowniaceae family. The tree is originally from China, but is also found in other tropical areas. Its wood is widely used in Japan, China, South Korea, and Australia for surfboards, boats, furniture, pellets, craft items, molded elements, aviation elements, *etc.* In addition, it does not deform, has no drying cracks, has good sound conductivity, is resistant to rot, and is easy to process. Its strength is good compared to its low density (San *et al*. 2016). *Paulownia tomentosa* gets its name in honor of the Queen Consort of the Netherlands, Anna Paulownia (1795 to 1865), daughter of Tsar Paul I of Russia, and is sometimes called Royal Paulownia, Kiri, or Princess Tree. Although it was created as a decorative tree, it finds usage where its low density provides an advantage. Due to its good acoustic properties, in Japan this species is used to build a stringed musical instrument called a Kotos (Japanese harps). Although it is a highly valued species in Asia, in the U.S. it is considered an invasive species (Clapa *et al.* 2014).

From an ecological standpoint, in general terms, when 1 ha of forest comes to vegetative maturity, it absorbs 3.7 tons of $CO_2$ from the atmosphere and returns 2 million tons of oxygen. If it is taken into account that a *Paulownia* plantation reaches maturity in 10 years to 12 years, compared to 80 years to 100 years for other woody species (pine, spruce, beech), the paulownia plantation is 6.6 to 10 times more ecologically efficient. In terms of its microscopic structure, *Paulownia* is a deciduous species with typical annual pores while less often having semi-annual pores, with 3 to 5 rows of large pores in early wood and large to medium pores in late wood and narrow to medium medullary rays visible without a magnifying glass. It has confluent and marginal woody parenchyma. It is a species with sapwood and heartwood; the heartwood has a grey-brown color, sometimes with a reddish hue. The sapwood is white and is not as clearly highlighted as the heartwood. *Paulownia* is categorized as a light, soft, and porous species (Wood Database 2020). The shrinkage amounts of *P. tomentosa* wood are low: volume is 6.4%, radial is 2.4%, tangential is 3.9%, and longitudinal is 0.1%. The parallel compression along the grain is 20.7 MPa, the bending strength (MOR) is 37.8 MPa, the modulus of elasticity of static bending (MOE) is 4.38 GPa, the density is 280 kg/m$^3$ (at a moisture content of 12%), and the Janka hardness is 1330 N/mm$^2$, but it also has good properties in terms of removing nails and screws and shearing cohesion (Akyildiz *et al.* 2010, 2014; Wood database 2020).

The uses of these species are consistent with the need for low density and high porosity. The other primary appliances of *Paulownia* wood are plywood, veneers, boxes and packaging, the body of musical instruments, *e.g.*, electric guitars, medicine, and sculptures (He *et al.* 2016). In this regard, Kaygin *et al.* (2009) proposed the use of *Paulownia* wood (*Paulownia elongata*) for making pencils, due to its easily cut nature and its elasticity. Kaygin *et al.* (2009) also made a comparison with the species commonly used in the manufacture of pencils, *i.e.*, poplar (*Populus tremula*) and juniper (*Juniperus excelsa*). The experimental results revealed that although the strength properties of *Paulownia* wood are inferior to poplar and juniper wood, *Paulownia* falls within the minimum values requested by the standards in the field of pencil manufacturing. Clapa *et al.* (2014) submitted a comparison between two different species of *Paulownia* (*P. elongate*, and *P. fortunei*) and a hybrid of the two species (P. *elongata x P. fortune*). Even though it is paper detailing the genetics of the species, the authors' contributions are an attempt to create a species resistant to temperatures below -30 °C, with the aim of acclimatizing it in temperate areas with low temperatures during the winter. Ashori and Nourbakhsh (2009) and Ates *et al.* (2008) analyzed the use of *Paulownia* wood in the pulp and paper field. The superior qualitative indices of the anatomical elements make this species better than other deciduous species, through the superior strength properties of the obtained paper. Thermogravimetric gas analysis (TGA) is a method that characterizes materials, and expresses mass loss as temperature increases using 2 to 50 g samples and an inert gas. During the treatment at high temperatures, the volatile substances are released first, then in order hemicelluloses, celluloses, and lignin. Lawson (2010) and Nelis *et al.* (2018) obtained boards made from combinations of *Paulownia* and pine stands, highlighting the superior characteristics of these wood species within the composite boards.

Fan *et al.* (2015) analyzed a disease that affected *Paulownia* wood. Apart from this, it was stated that the wood of this species is used in the construction of houses, solid biofuel, furniture, cellulose pulp, medicine, and pharmacy products. Cáceres-Hidalgo (2016) analyzed the physical properties and found that the density was 0.227 g/cm$^3$ in the anhydrous state, 0.248 g/cm$^3$ at a moisture content of 12%, and 0.209 g/cm$^3$ for the conventional density, 0.43% for the longitudinal shrinkage, 3.81% for the radial shrinkage, 7.33% for the tangential shrinkage, and 8.73% for the volumetric shrinkage. Furthermore, the average value of the modulus of elasticity (MOE) was 3100 MPa and the average values of the modulus of rupture (MOR) of 28.5 MPa were found, according to EN 408 standard (2011). Owfi (2017) and Icka *et al.* (2016) concluded that although *Paulownia tomentosa* was created as a decorative plant, its physical and mechanical properties achieved in a short period of time made it suitable for cultivation in large areas for the purpose of industrial use. In addition, it was found that it had a calorific value of 15 to 18 MJ/kg.

Khanjanzadeh *et al.* (2012) studied the use of *Paulownia* fortune wood in certain chipboard composites, along with other wood species. One of the conclusions of the study was that the increase in the percentage of *Paulownia* will result in an increased modulus of strength and elasticity of the boards, to the detriment of some established species in this field, *e.g.*, pine. Kalaycioglu *et al.* (2005) analyzed the use of *Paulownia tomentosa* wood waste in the creation of chipboards with a density of 650 kg/m$^3$. The boards fulfilled the minimum conditions required by the European standards in this field. Shtereva *et al.* (2014) studied many types of *Paulownia* genotypes in order to find additional species resistant to the action of environmental factors.

Gao (2019) found some solutions to eliminate the oxidation and blackening effect of wood immediately after cutting. Candan *et al*. (2013) found that the heat treatment of *Paulownia* chip composite plates had a positive effect on the MOR and MOE but had a negative effect on the absorption of water and swelling thickness. Pasztory *et al.* (2020) and Kaygin *et al.* (2015) improved the properties of solid *Paulownia* wood.

Popescu and Sabău (2016) and Tang *et al.* (1980) made general considerations about *Paulownia*, stating that it is originally from China, but that it is widely spread in Vietnam, Laos, Japan, Korea, *i.e.*, generally found in Asia, but is also cultivated in Australia and America. The primary uses include as fuel wood, high quality furniture, plywood, musical instruments (guitars, *etc.*), and wood for planes and ships (because the wood can be easily carved). In addition, it can be utilized in intercropping in agriculture, as it is able to develop a suitable climate for agricultural crops therefore increasing yields, as an organic fertilizer, because the leaves are rich in nitrogen, which can also be used as animal fodder. It can also be used as fuel pellets for heating, landscape architecture in the urban and rural areas, for protecting rods, farms, houses, *etc.*, against wind and snowstorms, for the reclamation of the areas affected by mining, for the afforestation of various areas where forests were cut or are insufficient, and the flowers and leaves have medicinal properties, *etc.*

As a result of the bibliographic survey on the study and uses of *Paulownia* wood, it was noted that although these species have many uses and plantations are located all over the world, there are no consistent studies in the field detailing the usage of its biomass for briquettes and pellets. Therefore, the present paper aims to find the optimal conditions for the achievement of good quality briquettes and pellets manufactured from the large sawdust deposits from *Paulownia* timber sawmills. On the other hand, by comparing the two species with other biomass species, it will be obtained how these species differ from other woods and how it is expected that such differences may affect the properties of compressed wood products.

## EXPERIMENTAL

### Methods and Materials

Two types of sawdust were used, *Paulownia tomentosa* sawdust and *Paulownia elongate* sawdust (the latter being slightly coarser than the former). The sawdust was dried to a moisture content of 10% in a laboratory oven at a temperature of 105 °C for 30 minutes. The moisture content was checked periodically using an electrical appliance. Initially, the geometric and granulometric characteristics of the raw materials were determined using sorting sites, with the following dimensions: 3 mm x 3 mm, 2.5 mm x 2.5 mm, 1.25 mm x 1.25 mm, 0.8 mm x 0.8 mm, and 0.4 mm x 0.4 mm. The raw materials were used to form 10 samples that each equated to 100 g of sawdust. The fraction with the smallest dimensions, *i.e.*, the one that passed through the last sieve with the dimensions of 0.4 mm x 0.4 mm, was given the label Rest. After that, the bulk density of the sawdust was determined, which depended on its dimensions. A graduated cylindrical vessel was used to determine the bulk density, in which a precise amount of sawdust (100 g) was introduced. For obtaining the precise height of the sawdust layer in the cylinder, *i.e.*, the volume of the graduated cylinder, the test vessel was kept for 3 min on a horizontal vibration device. The bulk density of the sawdust was made considering the mass of the sample, the diameter of the cylinder on the inside (50 mm), and the height at which the level of sawdust in the cylinder stabilized. This relationship is shown in Eq. 1,

$$\rho = \frac{4 \cdot (m_{cs} - m_{ec})}{\pi \cdot d^2 \cdot H} \cdot 10^6 \; [\frac{kg}{m^3}] \tag{1}$$

where $m_{cs}$ is the mass (g) of the cylinder including the sample, $m_{ec}$ is the mass (g) of the empty cylinder, $d$ is the diameter (mm) of the inside of the cylinder, and $H$ is the height (mm) of the sawdust layer inside the cylinder after being vibrated.

From every category of sawdust, the briquettes and pellets were achieved using a Gold Mark type briquetting press (Brasov, Romania) and a Sarras type pelletizing press (Brasov, Romania). These products were conditioned at a temperature of 20 °C and a relative humidity of 55%, in order to obtain a moisture content of 10%. During the determination period, the briquettes and pellets were kept in watertight-polyethylene foils in order to keep the moisture content unchanged.

The density of the briquettes and pellets (20 briquette samples and 30 pellet samples) was determined considering their cylindrical shape, using the relationship defined by Eq. 2,

$$\rho = \frac{4 \cdot M}{\pi \cdot D^2 \cdot L} \cdot 10^6 \; [\frac{kg}{m^3}] \tag{2}$$

where $M$ is the mass (g) of the pellet or briquette sample, $D$ is the diameter (mm) of the pellet or briquette, and $L$ is the length (mm) of the pellet or briquette.

As with any fuel, the calorific value of *Paulownia* sawdust is the primary characteristic, which was determined using an XRY-1C oxygen bomb calorimeter (Shanghai Geological, Shanghai, China). The initial calibration of the installation was carried out using a 1 g benzoic acid tablet, with a known calorific value of 26454 kJ/kg. In order to ignite the sample, an 8 cm cotton thread as well as a resistive nickel thread with a diameter of 0.1 mm and a length of 10 cm, spiraled to a diameter of 4 mm, were used. For each wood species, 10 valid tests were used with compact samples that were approximately 0.8 g, obtaining both a higher calorific value (HCV) and a lower calorific value (LCV). The method used was the Regnault-Phaundler method, and the primary relationship used by the calorimeter software to achieve superior calorific value is shown in Eq. 3,

$$HCV = \frac{C \cdot (T - T)}{m} - \sum_{i=1}^{n} Q_i \; \left[{}^{kJ}/_{kg}\right] \tag{3}$$

where $C$ is the calorimetric coefficient (kJ· ºC$^{-1}$), $T_f$ is the final temperature (°C) of the calorimeter, $T_i$ is the initial temperature (°C), m is the mass (kg) of the samples, and $\sum_{i=1}^{n} Q_i$ is the heat (kJ·kg$^{-1}$) obtained by burning the nickel wire, cotton yarn, and other additives (if any).

The ash content was determined according to ASTM standard D1102-2001 (2013) and determined the rate of ash discharge and the collection from the fuel combustion furnace. In order to create the 10 test samples of approximately 2 g, the sawdust was sorted with a 0.4 mm x 0.4 mm sieve and dried at a temperature of 105 °C for 1 h. Then, the samples were calcined at a temperature of 600 °C until complete calcination was reached, *via* means of high temperature resistant metal crucibles, in an STS Protherm calcination oven (Ploiesti, Romania). For the protection of the oven, the fine material was first burned on a butane gas flame until the material no longer smoked. Since this form of surface carbonized material had a dark black color, it was called black ash. The black ash and calcined ash contents were determined using Eqs. 4 and 5, respectively,

$$BA = \frac{m_{ba}}{m_s} \cdot 100\ [\%] \quad (4)$$

$$CA = \frac{m_{ca}}{m_s} \cdot 100\ [\%] \quad (5)$$

where $BA$ is the black ash content (%), $CA$ is the calcinated ash content (%), $m_{ba}$ is the mass (g) of black ash, $m_s$ is the mass (g) of the oven-dried sample, and $m_{ca}$ is the mass (g) of the calcinated ash.

The breaking strength of the briquettes (as shown in Fig. 1a) is one of the primary mechanical properties.

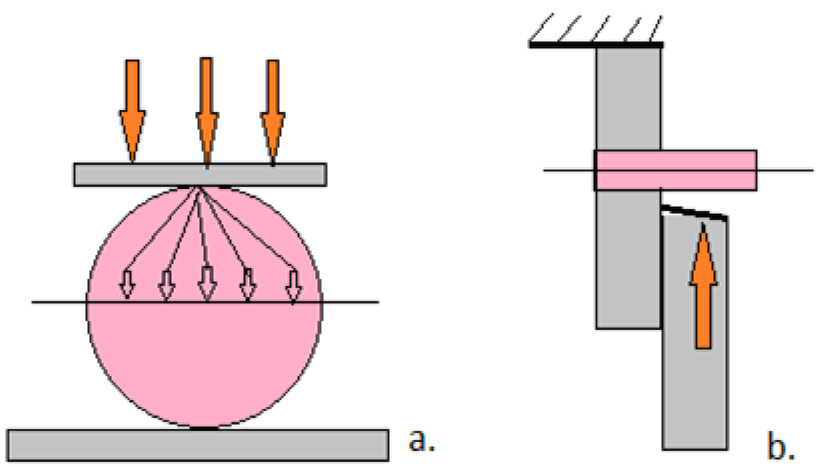



**Fig. 1.** Resistance test principles when breaking the briquettes (a) and shearing the pellets (b)

The breaking strength was determined by the ratio between the maximum breaking force and the corresponding breaking area for 10 vial tests, according to Eq. 6,

$$S_b = \frac{F_{max}}{D \cdot L} \left[\frac{N}{mm^2}\right] \quad (6)$$

where $F_{max}$ is the maximum force (N) achieved when the briquette is broken, $D$ is the diameter (mm) of the briquette, and $L$ is the length (mm) of the briquette.

The shear strength of the pellets (as shown in Fig. 1b) was the major mechanical property determined in this study. However, 5 pellets were simultaneously tested, because the force needed to shear a single pellet was a small value. The sheer force the pellet was subjected to was generated by a universal testing machine (IMAL, San Damaso, Italy), which utilized a special device with two arms, of which one had 5 holes for fixing the pellets, and the other arm represents the knife with a large sharpening angle of approximately 80°. Considering the circular shape of the cross section of the pellets and its multiplication, the shear strength was calculated according to Eq. 7,

$$S_s = \frac{4 \cdot P_{max}}{5 \cdot \pi \cdot D^2} \left[ {}^{N}\!/_{mm^2} \right] \tag{7}$$

where $S_s$ is the shear strength ($N/mm^2$), $P_{max}$ is the maximum breaking force (N) of the pellets, and $D$ is the diameter (mm) of the pellets.

For the statistical processing of the results, the Minitab 18 program (State College Pennsylvania, USA) was used. Microsoft Excel was also used for statistical processing. In both cases, a 95% confidence interval was used.

## RESULTS AND DISCUSSION

Figure 2 shows the granulometry diagrams for the two species of *Paulownia* wood used in this paper. The two curves do not overlap (a small rightward movement of the *P. tomentosa* species); this was found to occur due to the fact that the sawdust of the two species were slightly different, and especially due to the variability of the structure of the two wood species.

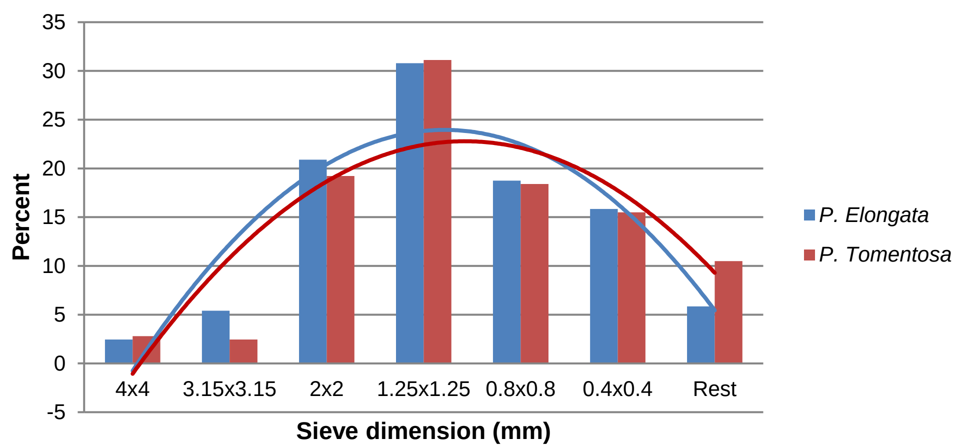



**Fig. 2.** Granulometry of the *P. tomentosa and P. elongata* sawdust

Figure 3 presents a combined histogram for the two *Paulownia* species, in which the average values of the bulk density of the two types of sawdust are shown (126.2 $kg/m^3$ for *P. elongata* and 146.5 $kg/m^3$ for *P. Tomentosa*). A higher variability in the bulk density of *P. elongata* (given by the standard deviation of 2.649 and the spacing of 118 $kg/m^3$ to 134 $kg/m^3$) can be also identified, approximately 50% higher than the bulk density of *P. tomentosa*, which further demonstrates that the two species are different in structure.

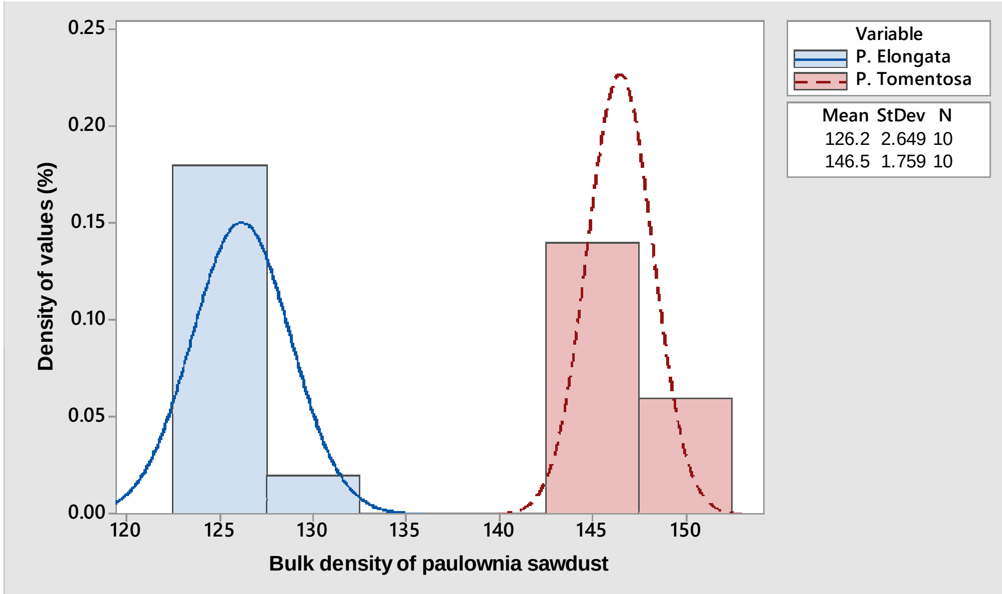
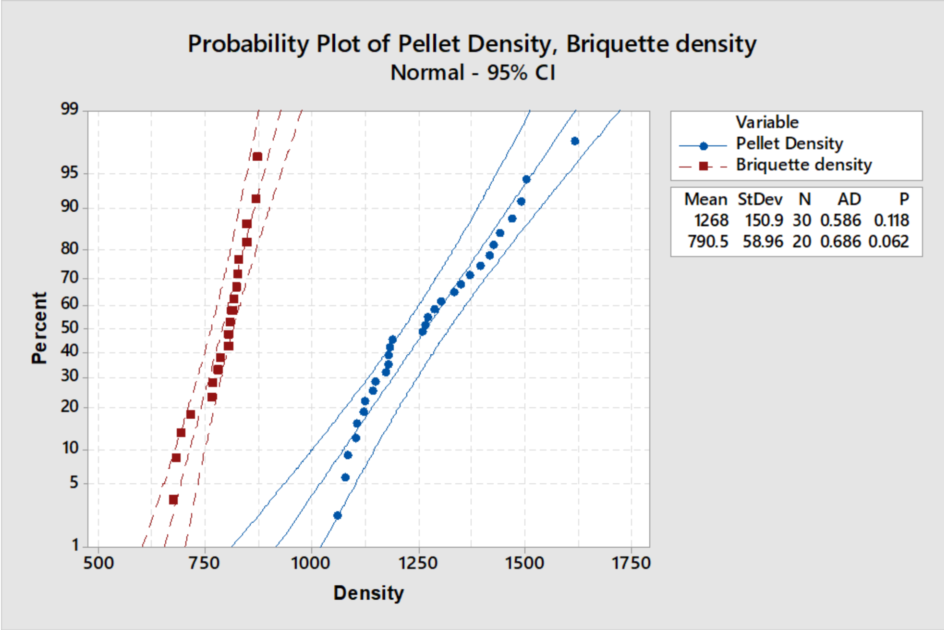


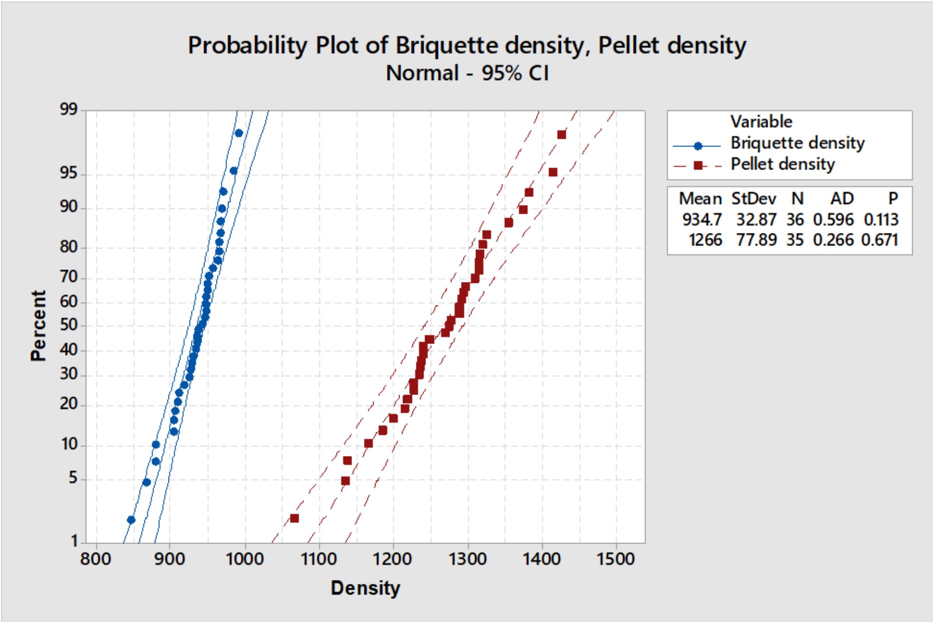

**Fig. 3.** Combined histogram of the bulk densities (expressed in kg/m$^3$) of *P. tomentosa and P. elongata*

The density of the pellets (1268 kg/m$^3$) was higher than the density of the briquettes (790 kg/m$^3$) in the case of *P. elongata* (as shown in Fig. 4) and for the density of the pellets and the briquettes in the case of *P. tomentosa* (1266 kg/m$^3$ and 934 kg/m$^3$, respectively). This was determined according to the method used to obtain the densities, *i.e.*, hydraulic in the case of the briquettes and mechanical extrusion in the case of the pellets. Moreover, the Austrian standard for pellets ÖNORM M 7135 (2000) provided limiting values for the unit density of pellets of at least 1.12 g/cm$^3$, and the German standard DIN 51731 (1996) provided a minimum value of 600 kg/m$^3$ for the bulk density of pellets. This differentiation of the values was shown by the fact that the diameters of the pellets were variable (within the limits of 4 mm to 20 mm, according to ÖNORM standard M 7135 (2000)), and their density strongly depended on this diameter.

The calorific value did not depend on the type of compressed product, *i.e.*, briquette or pellet, or on the type of the species analyzed, *i.e.*, *Paulownia elongata* or *Paulownia tomentosa*; the values achieved were within the confidence interval. As expected, the high calorific values (HCV) and low calorific values (LCV) were obtained, as noted in Fig. 5. It was observed that the calorific values were lower than the values of other wood species used for making briquettes and pellets; these values depended on the chemical compounds in the paulownia wood, *i.e.*, the lignin, cellulose, hemicellulose, and ash content, or the elementary chemical composition, *i.e.*, the carbon, oxygen, and hydrogen content, as well as the extractable substances and minerals). In this regard, Icka *et al.* (2016) found a calorific value of 15 kJ/kg to 18 kJ/kg.




a.




b.

**Fig. 4.** Density of the briquettes and pellets expressed in kg/m$^3$ for *Paulownia elongata* (a) and *P. tomentosa* (b)

The black and calcined ash content was significantly different in the two *Paulownia* species considered, with both the black and calcined ash content being higher in *Paulownia elongata* than in *Paulownia tomentosa*. These differences are attributed to the different structures of the two species (Clapa *et al*. 2014). A 14.5% increase in the black ash content (as shown in Fig. 6a) and a 72.6% increase in the calcined ash content (as shown in Fig. 6b) were identified. In this regard, it is worth noting the values of 2% to 5% for bark (Lunguleasa and Spîrchez 2017; Dumitrascu *et al.* 2018; Majlingova *et al.* 2019; Müller *et al*. 2020) and 6% to 16% for cereal straw (Lunguleasa and Spîrchez 2015).

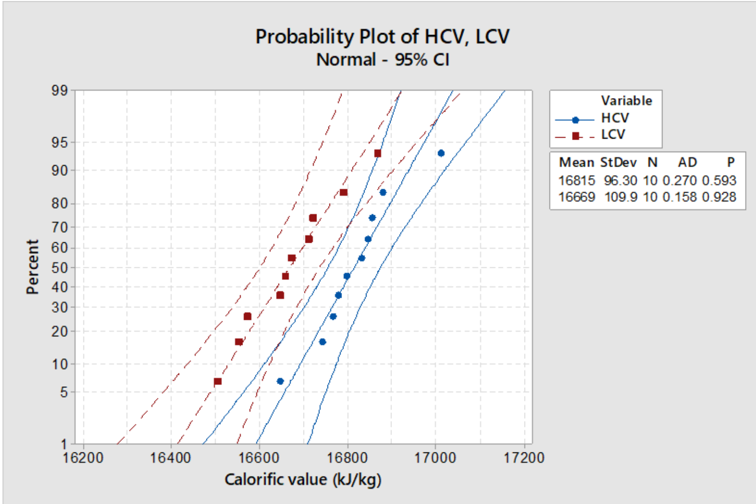



**Fig. 5.** The calorific values (HCV and LCV) of the *Paulownia* briquettes and pellets

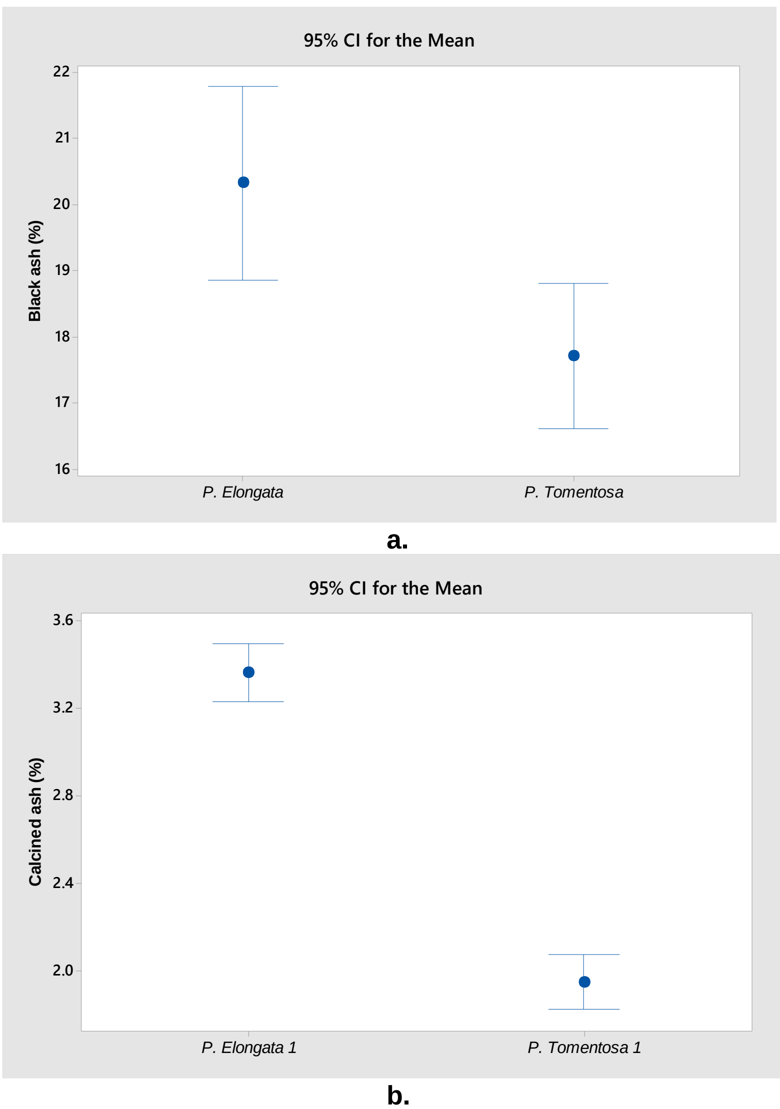



**Fig. 6.** Interval plot of the *Paulownia elongata* and *Paulownia tomentosa* black ash content (a) and calcined ash content (b)

The average compressive breaking strength of the *P. elongata* briquettes was 0.5 N/mm$^2$, while the average compressive breaking strength of *P. tomentosa* was 1.7 N/mm$^2$ (as shown in Fig. 7). The differences in the breaking resistance were particularly related to the density of these briquettes, since the *P. tomentosa* briquettes had a density of 934 kg/m$^3$, which was 18.2% greater than the density of the *P. elongata* briquettes, as well as the differences in bulk density of the sawdust.

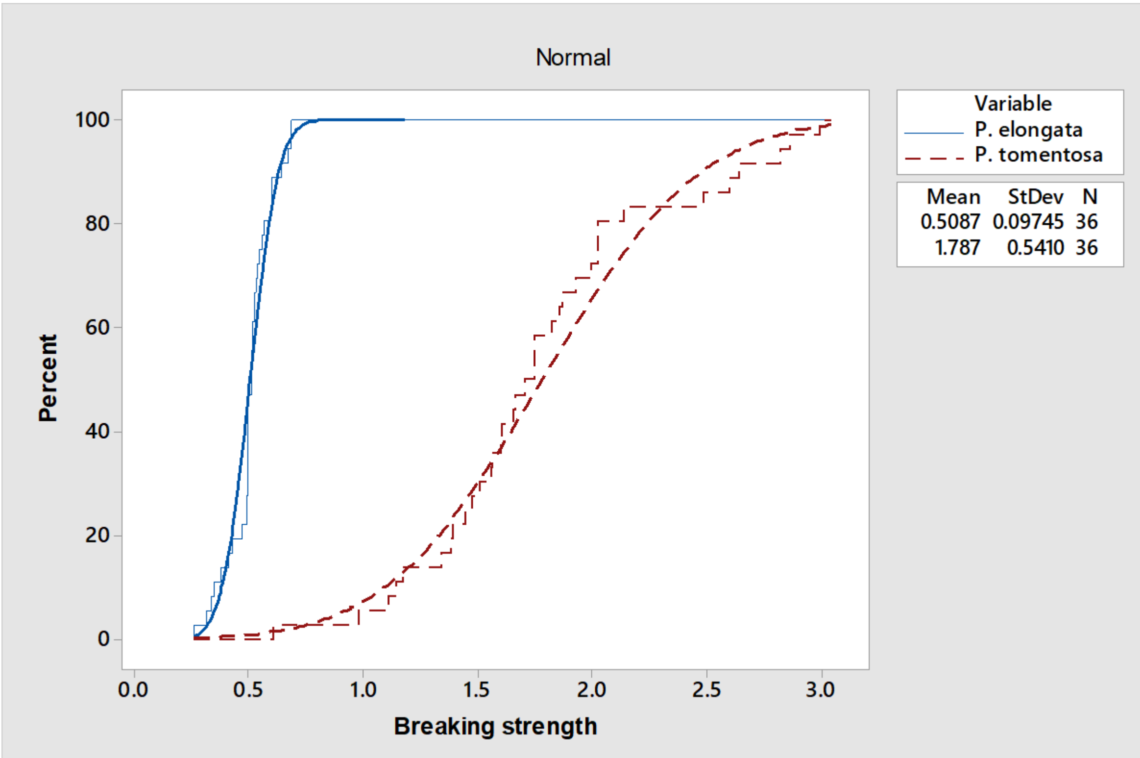



**Fig. 7.** Shape graph of the briquette breaking strength expressed in N/mm$^2$ for *Paulownia elongata* and *Paulownia tomentosa*

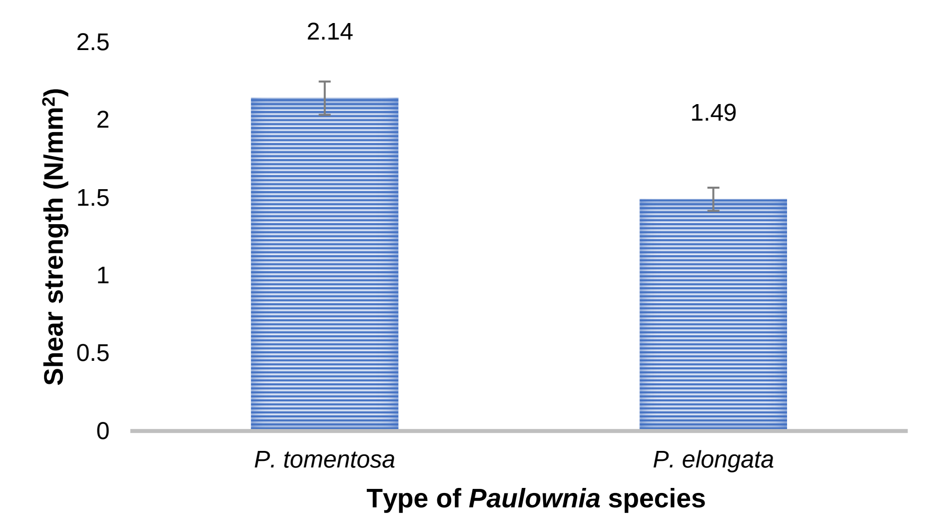



**Fig. 8.** Shear strength of the *Paulownia* pellets

Even though no standard has been established for the shear strength of pellets, the methodology and results are presented in studies by Plistil *et al*. (2005) and Spîrchez and Lunguleasa (2016). The values achieved in this paper are higher in *P. tomentosa* (2.14 N/mm$^2$) than in *P. elongata*, with a total increase of 43% (as shown in Fig 8). As in the case of briquettes, this increase in shear strength is caused by the difference in density of the two types of pellets (an increase of 0.15%). However, the difference in shear strength is especially due to the differences in structure and granulometry (as shown in Fig. 2), as well as the differences in the bulk density of the sawdust (an increase of 16.08%).

Taking into account all the physical and mechanical properties of the two paulownia species analysed, a slight increase was observed for *Paulownia tomentosa* compared to *Paulownia elongata*.

## CONCLUSIONS

1. The two types of studied wood species (*Paulownia tomentosa* and *Paulownia elongata*) are soft, have a rapid growth rate, and their wood biomass (resulting from log processing) can be considered for the production of briquettes or pellets.
2. The values of the briquette densities were 790 and 934 kg/m$^3$ and densities of the pellets were 1268 and 1266 kg/m$^3$ (with respect to *P. elongata* and *P. tomentosa*). These values correspond to the minimal limits of the specialized standards, showing that the *Paulownia* species are easily compressible and compactable.
3. The calorific values of 16820 and 16670 kJ/kg (HVC and LCV, respectively) are acceptable, even if they are slightly below the calorific values of other wood species.
4. While the calcined ash content is slightly higher than other wood species, it was still lower than the calcined ash content of bark or cereal straw.
5. Furthermore, the two resistances tested, *i.e.*, the breaking strength of the briquettes (0.5 and 1.78 N/mm$^2$) and the shearing strength of the pellets (2.14 and 1.49 N/mm$^2$), showed that the manufactured briquettes and pellets were compact and resistant during storage and handling until their combustion.

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