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Potencial energético de resíduos madeireiros de uma floresta tropical urbana

Energy potential of wood waste from a tropical urban forest

Potencial energético de los residuos de madera de un bosque tropical urbano

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Resumo

As espécies de florestas tropicais urbanas geram grandes quantidades de resíduos de madeira por meio da poda e remoção de árvores urbanas, que podem ser uma fonte de biomassa acessível para a geração de energia ao invés de ser descartada irregularmente. O objetivo desse estudo foi determinar o potencial de produção de energia com os resíduos de sete espécies mais utilizadas na silvicultura urbana no Estado de São Paulo, Brasil, avaliando as características físicas, químicas e energéticas da madeira. Resíduos madeireiros de 7 espécies comuns do Estado de São Paulo foram coletados na cidade de Piracicaba, caracterizados fisicamente (umidade, densidade básica e densidade à granel), quimicamente (teor de extrativos, materiais voláteis, carbono fixo e teor de cinzas) e energeticamente (poder calorífico superior, inferior, útil, densidade energética e análise termogravimétrica). O maior valor de densidade básica foi encontrado na espécie *Cenostigma pluviosum* (653,76 kg/m³), e todas as espécies apresentaram valores de poder calorífico superior maiores que 19 MJ/kg e a densidade energética das espécies variou entre 4,45 a 10,80 GJ/m³. O uso desses resíduos madeireiros para combustão direta é uma alternativa viável e pode ser considerado como uma solução para substituir a disposição incorreta do material, o que ainda é uma prática comum em muitas cidades de países em desenvolvimento.

Palavras-chave: Biomassa; Bioenergia; Resíduos da arborização urbana; Caracterização da madeira; Sustentabilidade.

Abstract

Urban tropical forest species generate large amounts of wood waste by pruning and removing urban trees, which can be an accessible source of biomass that could be used to generate energy instead of being disposed of irregularly. The objective of this study was to evaluate the potential for energy production of the wood residue of seven species most used in urban forestry in the State of São Paulo, Brazil, by determining the physical, chemical and energetic characteristics. Wood waste of 7 common urban forests species in the State of São Paulo were collected in the city of Piracicaba, characterized (humidity, basic density and bulk density), chemically (extract content, volatile materials, fixed carbon and ash content) and energetically (higher, lower, useful calorific power, density energy and thermogravimetric analysis). The highest value of basic density was found in the species *Cenostigma pluviosum* (653.76 kg/m³), all species had higher calorific values greater than 19 MJ/kg and the energy density of the species varied between 4.45 to 10,80 GJ/m³. The use of these wood residues for direct combustion is a viable alternative and can be considered as a solution to replace the incorrect disposal, which is still a common practice in many cities in developing countries.

Keywords: Biomass; Bioenergy; Urban forestry wood waste; Wood characterization; Sustainability.

Resumen

Las especies de bosques tropicales urbanos generan grandes cantidades de desechos de madera mediante la poda y eliminación de árboles urbanos, una fuente de biomasa accessible que podría utilizarse para generar energía en lugar de eliminarse de forma irregular. El objetivo de este estudio fue determinar el potencial de producción de energía de siete especies más utilizadas en la silvicultura urbana en el estado de São Paulo, Brasil, al evaluar las características físicas, químicas y energéticas de los residuos de madera para y evaluar la reducción de la huella de carbono de la reutilización. energía de este material. Se recolectaron residuos de madera urbana de 7 especies en la ciudad de Piracicaba, y caracterizados físicamente (humedad, densidad básica y densidad aparente), químicamente (contenido de extracto, materiales volátiles, contenido de carbono fijo y cenizas) y energéticamente (mayor, menor, poder calorífico útil, densidad análisis energético y termogravimétrico). El mayor valor de densidad básica se encontró en la especie *Cenostigma pluviosum* (653,76 kg / m³), todas las especies tenían una poder calorífico superior a 19 MJ / kg y la densidad energética de las especies variaba entre 4,45 a 10,80 GJ / m³. El uso de estos residuos de madera para combustión directa es una alternativa viable y puede considerarse como una solución para reemplazar la incorrecta disposición, que sigue siendo una práctica común en muchas ciudades de países en desarrollo.

Palabras clave: Biomasa; Bioenergía; Residuos de madera de la silvicultura urbana; Caracterización de la madera; Sustentabilidad.

1. Introduction

The tropical urban forest in Brazilian Southeastern cities provides many benefits; however, trees require regular pruning and occasionally removal when diseased, producing a large amount of waste (Shi et al., 2013). This problem is aggravated by the inappropriate choice of sites or species in urban forestry, increasing the effort to sort and dispose of the material (Meira, 2010; Meisel & Thiele, 2014). According to the Brazilian urban sanitation information system (SNIS) latest report, 1,668 Southeastern cities voluntarily declared to have generated 10,488.30 t of waste from pruning and tree branches in 2018 (MDR, 2019). In the tropical urban Brazilian forest context, there is often incorrect disposal of the wood waste, such as dumping in irregular areas and landfills or open-air burning (Araújo et al., 2018; Fetene et al., 2018; Palharini et al., 2018). The higher carbon footprint scenario results of landfill disposal generating almost twice the amount of carbon dioxide than simple incineration and four times compared to reutilization of the tropical urban forest waste wood in processed bioenergy products (Araújo et al., 2018).

The discussion over reduction of greenhouse gas emissions and cleaner development mechanisms have led to proposals to mitigate climate change. In this respect, the implementation of urban solid waste management plans and policies has gained more importance because of the constant population growth and consequent waste generation, leading to new alternatives to use this raw material (Gouveia, 2012). Replacing a share of fossil fuels, the use of urban forestry wood waste as a source of bioenergy could reduce greenhouse gas emissions compared to open air burning and mitigate environmental impacts of carbon dioxide in climate change (Timilsina et al., 2014; Wolf et al., 2016) and that can present 80% reduction in the carbon footprint (Araújo et al., 2018). Wood waste of tropical urban forests has great potential for the production of higher added value products and bioenergy generation is one of the most compatible alternatives due to constant supply of biomass since maintenance of urban forestry is a routine activity and conversion facility at low costs (Dias Júnior et al., 2017; Joshi et al., 2015; Timilsina et al., 2014).

There are several reasons why the wood of common tropical urban forestry species are not the first option for bioenergy, or not as valued as others in the market, such as the lack of knowledge about their quality, heterogeneity and lack of utilization plans by municipal governments (Faraca et al., 2019; Meira, 2010; Pérez-Arévalo & Velázquez-Martí, 2018). In this context, the characterization of the tropical urban forest wood waste is necessary to attest their quality as an alternative bioenergy source since the biomass properties influences their conversion process (Boumanchar et al., 2019; Duarte da Silva et al., 2013; Fetene et al., 2018).

The objective of this study was to evaluate the potential for energy generation of the branches of seven species commonly used in urban forestry in the state of São Paulo (Brazil) in order to indicate a solution to the urban environmental managers. The specific objective was to determine the physical, chemical and energetic characteristics of the wood residues of pruning from the city of Piracicaba, São Paulo.

2. Material and Methods

2.1. Material characteristics and sampling

The research was conducted in Piracicaba, São Paulo State, with humid subtropical climate (Cwa in Köppen climate classification), average annual precipitation of 1,273.3 mm, area of 1,378 km², human population of 404,142 inhabitants and density of 264.5 inhab/km² (IBGE, 2020; Alvares et al., 2013).

In the Southeast region of Brazil, where the state of São Paulo is located, 1,668 cities declared to have generated about 10,488.3 tons in total of pruning waste from urban forests management in 2018 and in Brazil 5,570 cities declared to produce about 97,703.8 tons, a significant amount for indicating a better applicability than the common discarding actions of the country (MDR, 2019). São Paulo's State current energy sources are petroleum by-products (32%), biomass (28%), electricity (20%), ethanol (10%), natural gas (8%) and others (2%), indicating the possibility for growth in the supply of biomass to the State's energy mix (São Paulo, 2019).

According to Meira (2010), the municipality of Piracicaba generated an average of 181.35 t of pruning waste per month in 2008, most of which was generated by the company that provides services to the city government (73%) and the rest pruned by the energy company (27%). Regardless of the species, there was a greater predominance of thin branches (up to 15 cm of diameter) and fewer proportions over 15 cm, and the species with the highest volume generation of waste were also the largest, such as *Schinus molle*, *Cenostigma pluviosum*, *Terminalia catappa*, *Ficus benjamina* and *Tabebuia sp* (Meira, 2010).

The species collected were *Cenostigma pluviosum* (DC.) E. Gagnon & G.P. Lewis., *Delonix regia* (Bojer ex Hook.) Raf., *Ficus benjamina* L., *Licania tomentosa* (Benth.) Fritsch, *Nectandra megapotamica* (Spreng.) Mez, *Terminalia catappa* L. and *Tipuana tipu* (Benth.) Kuntze, due to the availability of material and its frequency in the urban forestry of Piracicaba and São Paulo State (Klingenberg et al., 2018; Meira, 2010; Silva Filho, 2009). Quantitative techniques were applied for this study (Pereira et al., 2018).

Random samples obtained from three branches each of the 7 different species in the city of Piracicaba from the process of pruning and removal were used to perform all tests. The wood waste was collected without any previous processing. As a very irregular material, the collected branches had minimum diameter of 10 cm and length of 70 cm to facilitate testing.

2.2. Evaluation of physical properties

The moisture content was determined according to ASTM D4442-16 (ASTM, 2016) with the values of wet and dry mass, and the basic density (dry mass by wet volume) was determined in accordance with ASTM D2395-17 (ASTM, 2017). The sawdust bulk density was performed according to ASTM D6683 (ASTM, 2019).

2.3. Evaluation of chemical and energetic properties

The total extractives were determined according to NBR 14853 (ABNT, 2010), where the samples were extracted with ethanol and toluene (2:1), or just ethanol and hot water. The immediate analysis was performed according to the procedure described in standard D1762-84 (ASTM, 1984), adapted from charcoal for application to wood, resulting in volatile materials and ash content. The difference between volatile materials and ash content resulted on the samples fixed carbon.

The calorific value tests were performed in an IKA-WERNE C5000 adiabatic calorimeter pump, applying the conditions described in ASTM E870 – 82 (2019), where three briquettes per branch were produced with the sawdust in a hand press, with approximately 1-2 cm height and 1.5 cm diameter; and placed in a decomposition flask to establish their higher calorific value (HCV). From that, it was possible to determine the lower calorific value (LCV), gross calorific value (GCV). The energy density (ED) was calculated by the product of the GCV and the basic density (BSD).

The thermogravimetric analysis (TGA) was accomplished with 15 ± 4 mg of sawdust (200–270 mesh) at a constant flow rate of 50 ml/min under nitrogen gas atmosphere with a Shimadzu TGA-60 analyzer and at a heating rate of 10°C/min from 25 to 850°C, also according to ASTM E870 – 82 (2019).

2.4. Data analysis

For all tests, 3 branches were selected from each of the seven species of the study and at least three repetitions were made per branch. In the case of the physical tests, 16 samples per branch were used, totaling 48 samples per species. For the chemical and energetic analyzes, the amount of sawdust required by technical standards was used and the tests done in triplicate for each branch.

The data were statistically analyzed with the R software (Team, 2020) and when significant differences were found, the Tukey test was applied to compare the means with 95% probability. Pearson's correlation analysis was applied to the relevant study variables.

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3. Results and Discussion

The humidity values determined for each species were 13.01% for *Cenostigma pluviosum*, 37.75% for *Delonix regia*, 33.09% for *Ficus benjamina*, 17.53% for *Licania tomentosa*, 12.33% for *Nectandra megapotamica*, 18.31% for *Terminalia catappa* and 18.26% for *Tipuana tipu*. Basic and bulk density (Klingenberg et al., 2018), higher and lower calorific value (Klingenberg & Nolasco, 2017) and the chemical properties analyses results of the species studied can be seen in Table 1, with results of basic density (BSD), bulk density (BD), total extractives (TE), volatile materials (VM), ash content (AC), fixed carbon (FC), higher calorific value (HCV), lower calorific value (LCV), gross calorific value (GCV) and energy density (ED).

Table 1. Statistical analysis of the chemical properties of the 7 most commonly used species in the tropical urban forestry in the state of São Paulo (Brazil).

Species	BSD* (kg/m³)	BD* (kg/m³)	TE (%)	VM (%)	AC (%)	FC (%)	HCV** (MJ/kg)	LCV** (MJ/kg)	GCV (MJ/kg)	ED (GJ/m³)
Cenostigma pluviosum (moderated hardwood)	653.76a (48)	172.70ab (9)	8.83a (0.92)	87.56a (0.28)	1.44b (0.24)	11.00c (0.26)	19.36a (0.14)	18.80a (0.03)	15.14a (0.12)	10.80a (0.35)
Delonix regia (light softwood)	447.34c (47)	130.03ab (15)	7.18b (9.10)	85.82b (0.12)	0.48c (0.01)	13.71b (0.13)	19.56a (1.13)	18.30a (0.45)	10.44b (1.54)	4.72d (1.04)
Ficus benjamina (light softwood)	396.86c (46)	126.73b (4)	3.95d (4.79)	82.44c (0.69)	1.59b (0.17)	15.97a (0.60)	19.29a (1.79)	18.02a (0.70)	11.21b (0.64)	4.45d (0.45)
Licania tomentosa (softwood)	649.02a (37)	182.70a (24)	3.38d (2.27)	77.52d (0.30)	5.29a (0.18)	17.19a (0.41)	19.58a (0.42)	18.32a (0.16)	14.67a (0.27)	9.51ab (0.24)
Nectandra megapotamica (softwood)	544.97b (47)	171.53ab (5)	5.51c (0.42)	82.49c (0.48)	0.89c (0.08)	16.62a (0.56)	19.31a (1.76)	18.05a (0.69)	15.51a (0.61)	8.46abc (0.48)
Terminalia catappa (light softwood)	459.84c (59)	119.20b (23)	4.71cd (0.38)	83.09c (0.15)	0.60c (0.11)	16.31a (0.06)	19.88a (0.75)	18.62a (0.29)	14.75a (0.31)	6.77c (0.24)
Tipuana tipu (softwood)	521.99b (23)	156.77ab (22)	5.56c (4.78)	81.94c (0.79)	1.45b (0.15)	16.61a (0.79)	19.67a (0.43)	18.40a (0.14)	14.71a (0.31)	8.02bc (0.46)

Equal letters in columns do not differ by the Tukey test at 95% probability ($p < 0.05$); standard deviation = values between parentheses; *(Klingenberg et al., 2018); **(Klingenberg & Nolasco, 2017).
Source: The authors.

The basic density ranged from 396.86 to 653.76 kg/m³, which demonstrated the variability among species in this study (Klingenberg et al., 2018), due to the different species, ages, shapes and management of each tree in the urban areas. The values found for sawdust bulk density ranged from 126.73 to 182.70 kg/m³, slightly higher than the range of 100 to 120 kg/m³ found by Tenorio and Moya (2013) for ten fast-growing Costa Rican species. The species were classified as light softwoods, softwoods and moderate hardwood (Carvalho, 1996). The basic density of wood is directly related to energy production; denser species have greater energy stored per cubic meter (Castro et al., 2013), but other important factors also can influence the energy use of wood, such as moisture content, total extractives content and other chemical and physical characteristics (Tenorio & Moya, 2013).

Total extractives content presented wide variation among the different species, ranging from 3.38 to 8.83%. Similar results were observed for the waste wood of temperate forests species presenting values from 2.90 to 8.60% (Mecca et al., 2019), indicating that the content of extractives varies greatly among wood species in temperate and tropical forest species. Extractives are nonstructural phytochemicals and affect many wood properties and their variety and quantities can differ among softwoods and hardwoods (Jankowska et al., 2017; Quinteiro et al., 2019; Wan & Frazier, 2019). The content and composition of wood extractives is a relevant factor for in energy production since it influences volatile materials and compounds emitted to atmosphere during burning (Moulin et al., 2017; Wan & Frazier, 2019).

The results obtained in the proximate analysis showed that among the species there was variation in volatile matter and ash content, which directly influenced the quantity of fixed carbon in the wood species. The values ranged from 77.52 to 87.56% of volatile materials and the ash content from 0.48 to 5.29%. Since the volatile material content influences the rate at which fuel becomes gas, woods with higher VM content can generate more steam, promoted by the devolatilization reactions (Vassilev et al., 2015; Vega et al., 2019). Fixed carbon tests resulted in a range of 11.00 to 17.19%, also reported in the literature for other wood biomasses, between 12 to 26% (Vega et al., 2019). Species like *Cenostigma pluviosum* are highly reactive biomass in consequence of high VM and low FC content that results in quicker burning (Jahirul et al., 2012; Vassilev et al., 2015; Vega et al., 2019).

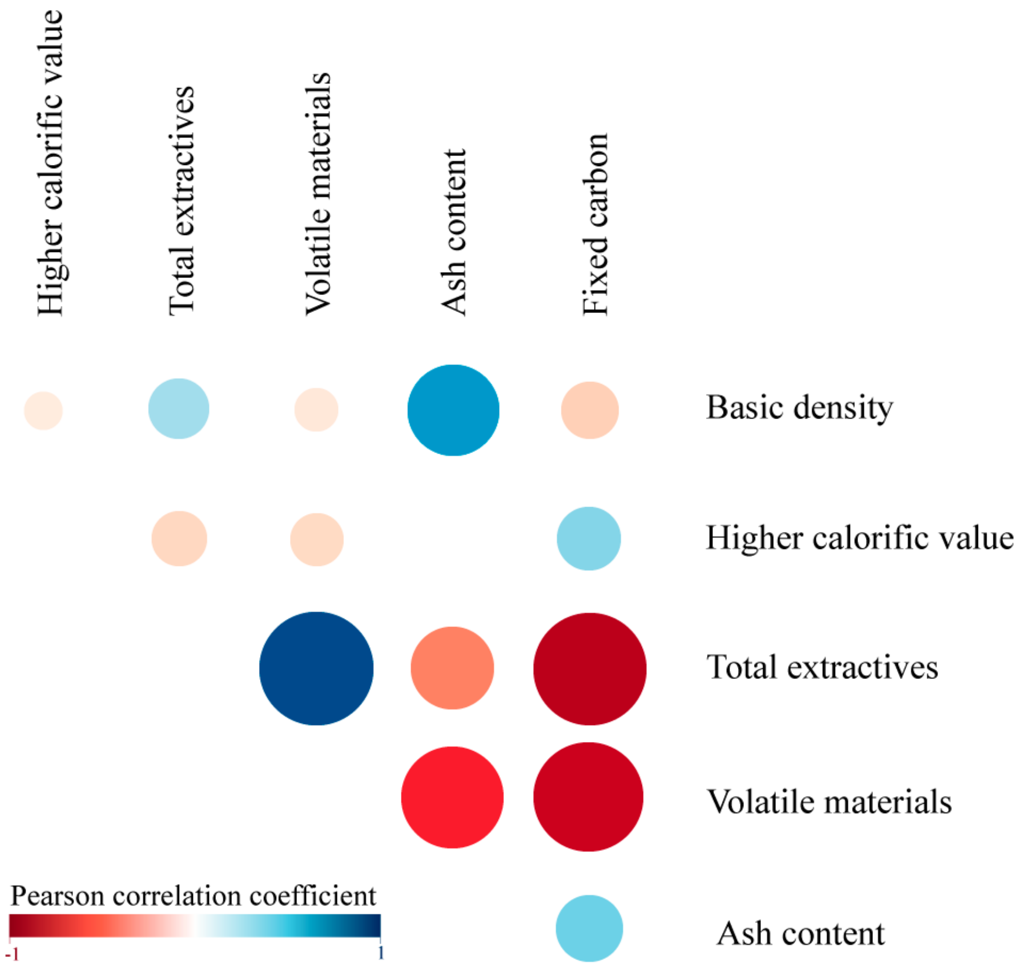
No statistical difference was observed for higher and lower calorific values, a fact also observed in literature for tropical and temperate forests (Antwi-Boasiako & Acheampong, 2016; Kofman, 2009). All seven tropical urban forestry species presented higher calorific values above 19 MJ/kg, in comparison to ranges of 16 to 53 MJ/kg and 19 to 22 MJ/kg for tropical and temperate forests, respectively, found in literature. This energy property is a determining factor of the burning efficiency of the material and for its use to generate energy (Everard et al., 2012; Ping et al., 2016). The small variations in the higher calorific values among the species may be related to the functional groups present in their chemical compositions, which can promote differences in the heat released from burning (Tahir et al., 2019). The calorific potential of wood is directly correlated by water content: the greater the moisture, the more energy is spent to dry the material and the less net energy is generated from burning the material, so species with low water content and higher bulk density are more desirable for energy generation (Jiang et al., 2018; Ping et al., 2016; Wu et al., 2011).

The gross calorific value ranged from 10.44 to 15.51 MJ/kg, similar to pine wood particles and apple pruning residues, with 19.69 and 20.27 MJ/kg, respectively (Brand & Jacinto, 2020). The energy density ranged from 4.45 GJ/m³ to 10.80 GJ/m³. Other authors have observed energy density of 13 GJ/m³ in 7.5-year-old *Eucalyptus* trees (Pereira et al., 2013) and ranging from 1.82 and 3.58 GJ/m³ in several combinations of *Eucalyptus* and coffee production residues (parchment, chaff and husk) (Tan et al., 2020); the first one presented higher and the second one lower in comparison to the results in the present study, due to the variability of the wood species. Recent studies have shown that the main determining factor of the higher heating value of biomass is the ash content (Xing et al., 2019), which was not observed in our study, where the highest ash content values were not necessarily associated with the highest calorific values of the species.

The results obtained from Pearson's correlation presented notable negative and positive correlations between the physical and chemical characteristics (Figure 1). Regarding the combination of fixed carbon with total extractives (-0.86) and volatile materials (-0.87), wood with higher quantity of extractives and volatile material tended to present lower percentages of fixed carbon. This was also observed in studies involving the energy characterization of *Eucalyptus sp.*, which found that these variables were inversely proportional (Brun et al., 2018; Moulin et al., 2017; Protásio et al., 2014).

The negative correlation between ash content and volatile materials (-0.74) confirms the organic character of these compounds. What is released during the burning process (volatile materials) does not appear in the inorganic fraction of biomass (ash content) afterward (Lu et al., 2019). Also, the combination between ash content and total extractives presented a negative correlation (-0.49). The volatile material and total extractives correlation presented a high and positive value (0.86), indicating that extractives are more volatile compounds, which are more easily released during burning.

Figure 1. Correlation among urban wood waste's physical and chemical characteristics.



Source: The authors.

Basic density and ash content also presented a positive and significant correlation (0.56), suggesting that wood species with higher basic density contain more inorganic compounds, which can generate higher ash content after burning. The combination of basic density and the calorific value (-0.08), volatile materials (-0.14) and fixed carbon (-0.22) were weakly negatively correlated, as was the calorific value with total extractives content (-0.04) and volatile materials (-0.07), because most of volatile materials are composed of gases that have low calorific value (Özyuguran & Yaman, 2017).

The correlations between the basic density and the total extractives (0.25) and between the fixed carbon and ash content (0.32) and calorific value (0.13) were positive. Regarding the higher calorific value and fixed carbon combination, the wood samples with higher fixed carbon content had higher calorific values, because of their greater energy potential, but also had higher ash content, as confirmed by literature (Brun et al., 2018). In literature, wood species with lower ash content have greater calorific values since mineral materials mass is accounted but do not participate in the combustion process (Brand, 2010; Kenney et al., 2013; Nunes et al., 2016).

The combination between ash content and higher calorific value presented low negative correlation (-0.001) for the species of this particular tropical urban forest. As these individuals are planted in an urban area, it is possible to assume that many other factors can affect the chemical characteristics of the wood. Although not a very common result, these factors may have influenced the calorific value and ash content of the studied species.

In the thermogravimetric analysis, the DTG curve (which represents the first derivative of the TGA curve) had two mass loss peaks (Figure 2). The first peak is related moisture release (Xin et al., 2018) and varied between 100 and 109°C, where *Licania tomentosa* presented the highest peak, probably due to its density; greater energy expenditure is necessary to remove free water from the material, since the mass loss peak occurred at a higher temperature.

The second DTG curve peak is influenced by the degradation of holocellulose and lignin present in the wood (Gan et al., 2019; Varma & Mondal, 2018; Xin et al., 2018). Between 230 and 330°C occurs hemicellulose degradation; followed by cellulose between 305 and 380°C; and lignin starts to decompose between temperatures of 400 and 500°C (Arias et al., 2008; Gaitán-Álvarez et al., 2018). The second peak temperature varied between 364 and 373 °C, where *Tipuana tipu* wood presented the lowest one. All species studied showed adequate thermal stability properties for energy generation purposes.

The residual mass found in the materials varied between 15.04% for *Tipuana tipu* and 26.65% for *Cenostigma pluviosum*. The high value of the residual mass is due to the fact that the atmosphere used in the analysis was inert, indicating that the residual material is a solid fraction with high fixed carbon content. This would not occur in an oxygen atmosphere, where oxidation occurs. In these conditions, the residue would be composed only of ashes.

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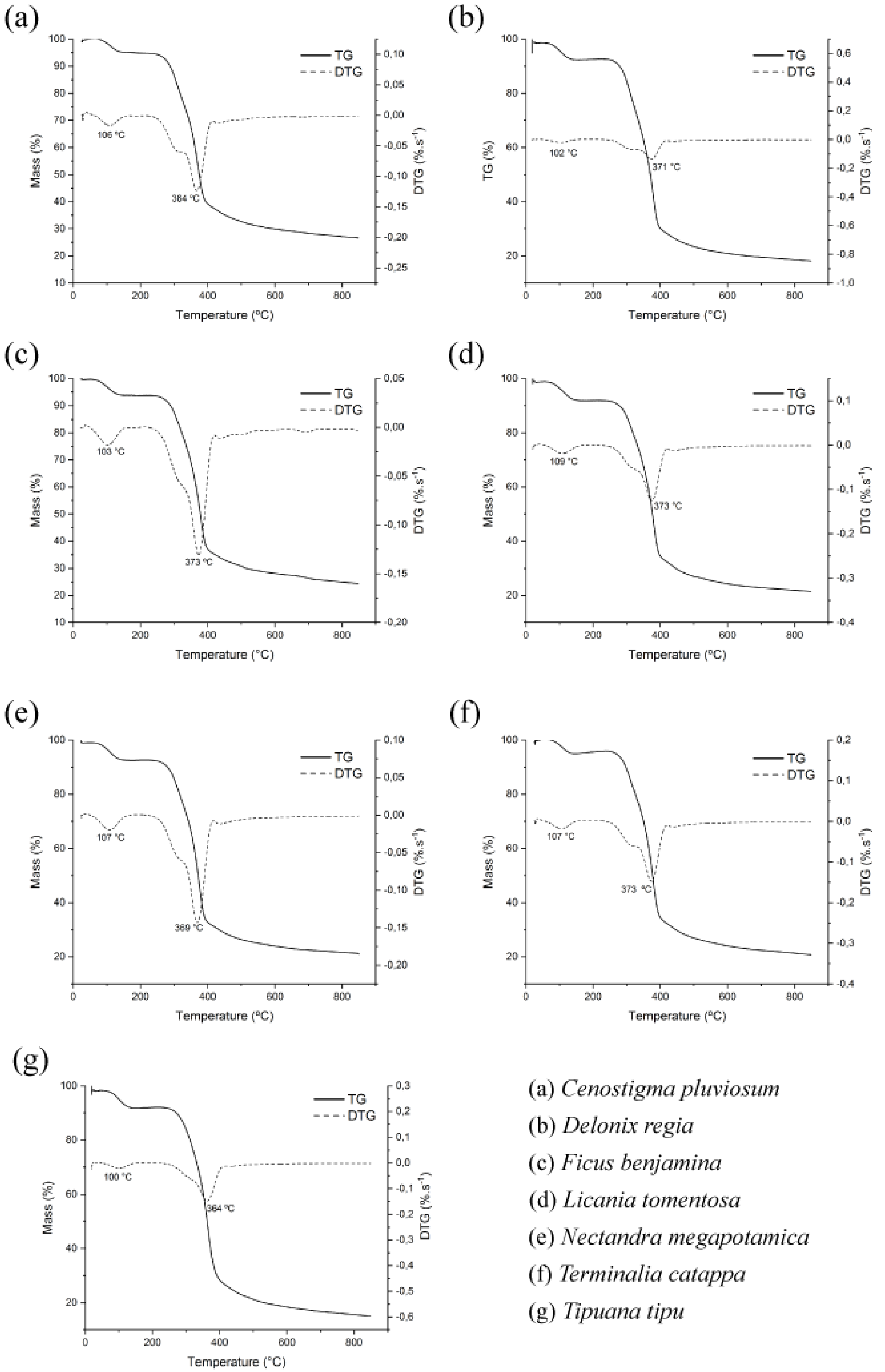
Figure 2. Thermogravimetric analysis results of the urban forestry species.



(a) *Cenostigma pluviosum*
(b) *Delonix regia*
(c) *Ficus benjamina*
(d) *Licania tomentosa*
(e) *Nectandra megapotamica*
(f) *Terminalia catappa*
(g) *Tipuana tipu*

Source: The authors.

The chemical and physical characteristics observed in these species allows their use for energy production, concluding that the wood residues from pruning and removal of trees present similarities to other wood commonly used for this purpose. In controlled combustion chambers the carbon previously stored in the wood waste presents better efficiency in carbon neutrality than open-air burning or landfill disposal (Araújo et al., 2018; Cereceda-Balic et al., 2017).

The study presented that the wood species analyzed are suited for energy production and that using this biomass waste as an energy source is a more environmentally-friendly scenario than the common practices chosen by municipalities in Brazil, as society demands more sustainable alternatives and urban environmental managers have to adequate their current end-of-life scenarios to the National Policy on Solid Waste (Brasil, 2010).

Despite the energy efficiency attested in this research, it is important to conduct studies regarding the economic viability of using wood waste of urban forestry as an energy source. It is also important to investigate other uses and applications for wood from the management of urban forestry, that generates large amounts of waste around the world.

4. Conclusion

The wood waste of seven most common urban forestry species of the State of São Paulo presented similar characteristics for energy generation than other wood species currently used for the same purposes. Also, this would be a more environmentally friendly end-of-life scenario for this biomass than irregular disposal, a common practice in developing countries. These results support decision making of urban environmental managers that face with new sustainable policies to adequate their current waste management and disposal.

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