Physical and chemical evaluation of furniture waste briquettes.

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Highlights

- Chemical characterization of furniture wood and polyurethane foam waste and comparison with other lignocellulosic wastes.
- Study of the parameters affecting quality of waste wood briquettes.
- Study of co-densification of furniture wood waste and polyurethane foam waste.

Keywords: Furniture waste; Briquettes; Durability; Physical characterisation; Chemical composition.

Abstract

Furniture waste is mainly composed of wood and upholstery foam (mostly polyurethane foam). Both of these have a high calorific value, therefore, energy recovery would be an appropriate process to manage these wastes. Nevertheless, the drawback is that the energy content of these wastes is limited due to their low density mainly that of upholstery foam. Densification of separate foam presents difficulties due to its elastic character. The significance of this work lies in obtaining densified material by co-densification of furniture wood waste and polyurethane foam waste.

Densification of furniture wood and the co-densification of furniture wood waste with polyurethane foam have been studied. On the one hand, the parameters that have an effect on the quality of the furniture waste briquettes have been analysed, i.e., moisture content, compaction pressure, presence of lignin...The maximum weight percentage of polyurethane foam that can be added with furniture wood waste to obtain durable briquettes and the optimal moisture were determined. On the other hand, some parameters were analysed in order to evaluate the possible effect on the combustion. The chemical composition of waste wood was compared with untreated wood biomass;

the higher nitrogen content and the concentration of some metals were the most important differences, with a significant difference of Ti content.

1. Introduction

At the end of its life, furniture is often disposed of in municipal solid wood treatment plants. Furniture waste is mainly composed of different types of treated wood (plywood, engineered wood, melamine fibreboard, painted wood...) and upholstery foams (mainly polyurethane foam). Recycling of this waste would be nearly impossible, due to the oils, glues, paints and varnishes used in the fabrication of the furniture (Khalfi et al., 2000). Nevertheless, energy recovery is a possible way to manage this waste, and its use would improve the management of environmental resources and waste.

The use of lignocellulosic waste is becoming increasingly important in power plants. These plants can make direct combustion of biomass or co-firing biomass with coal. However one inconvenience of some types of waste is that their energy content is limited due to their low density. A possible solution to this is the densification of these biomass feedstocks into pellets or briquettes in order to produce a homogeneous fuel with a high energy density. Some existing coal-fired power plants have been transformed to co-fire biomass and coal, but the difference in density between biomass and coal also causes difficulties in feeding the fuel into the boiler. Good densification of the material has proven to solve these problems (Li and Liu, 2000).

This study focuses on the main materials that compose furniture waste, furniture wood waste and polyurethane foam waste. This foam also has a high calorific value; however its low density ($10\text{-}80\text{ kg/m}^3$) is a great disadvantage for its energy recovery. Given the physical characteristics of this material, densification of separate foam is very difficult;

however, a solution would be co-densification with furniture wood waste. In addition, densification reduces the costs of transportation, handling, and storage. Uniform shape and sizes of the densified waste is also an advantage for designing the burning appliances.

Biomass briquettes can undergo fragmentation and abrasion during handling, transportation, and storage. Durability (DU) is the most important parameter for evaluating the quality of densified biomass (CEN, 2003). Low DU causes problems in transportation and storage, biomass losses, and can cause dust emissions during combustion. Frequently, another parameter to evaluate the briquette quality is briquette density (particle density) (Križan, 2009). Nevertheless, Temmerman et al. (2006) found no relation between DU and particle density in pellets and briquettes, nor did Obemberger and Thek (2004) find this relation in pellets. The particle density influences combustion behaviour, because denser materials have a longer burnout time (Oberberger and Thek, 2004).

Some factors that can influence the quality of the densified products are: compaction pressure, material moisture, fraction particle of the initial material, pressing temperature, etc (Ishii and Furuichi, 2014; Kaliyan and Vance Morey, 2009; Križan, 2009; Lee et al., 2013; Stelte et al., 2011).

In densification processes, the mechanical pressure creates bonds between the particulate matter and moreover the presence of natural binders (such as lignin, proteins, fats, starch, and water soluble carbohydrates) produces solid bridges between the particles. Kaliyan and Morey (2009; 2010) focused on explaining the significance of natural binders to obtain strong and durable bonding during densification processes. Just as densification of separate polyurethane foam presents significant difficulties, these authors also found difficulties to densify switchgrass. They therefore studied some

strategies to obtain strong bonding between particles: a) find the optimum moisture and temperature to activate the natural binders such as lignin, protein and starch in the biomass, b) adding chemical binders, and c) mixing switchgrass with other biomass-based binders. They concluded that one important factor was preheating at 100 °C to activate the binders before applying pressure. The mixing of 80 % of switchgrass with 20% of corn stover (biomass-based binder) also showed a significant increase in the quality of the briquettes, without the additional cost that the addition of chemical binders would assume. In addition, they also studied the particle bonds in briquettes and pellets of corn stover and switchgrass by micro-structural analysis (SEM technique and Ultraviolet auto-fluorescence microscopy). They were able to conclude that natural binders (mainly lignin and protein) formed strong bonds between the particles.

In the same way, almond shells show elastic recovery after compression, but good quality briquettes were obtained at 70-80 °C or at 180 °C (Font, 2004).

The present work, on one hand, shows a chemical characterisation of furniture wood waste and polyurethane and their values have been compared with those of another three kinds of lignocellulosic waste in order to analyse the effect of the chemical content in the combustion behaviour of these wastes.

On the other hand, furniture wood waste has been subjected to a compaction process at different moisture content, compaction pressures and in the presence of polyurethane foam in different proportions, in order to evaluate the possibility of using this material as a mixed fuel.

2. Materials and methods

2.1. Chemical characterisation

The furniture waste was collected from a municipal solid waste treatment plant. Furniture waste is mainly composed of wood and upholstery foam (mostly polyurethane

foam). Representative samples of both types of waste (furniture wood waste and polyurethane foam) were dried at 105 °C and grounded to carry out a chemical characterisation (Tables 1 and 2).

Table 1 shows the elementary properties (calorific value and ash content) and the main chemical composition of furniture wood waste and polyurethane foam analysed previously (Garrido and Font, 2015; Moreno and Font, 2015). Table 2 shows the major and minor elements of different types of waste and wood. These wastes are compared with other three wastes: a clean waste such as solid wood (Moreno and Font, 2015), treated wood such as engineered wood and a dirty lignocellulosic waste such as vine shoots.

Table 1. Characteristics of the different types of waste and wood studied.

Table 2. Major and minor elements of the different types of waste.

2.1.1. Determination of the total content of carbon, hydrogen and nitrogen

The total content of carbon, hydrogen and nitrogen in biomass was measured following the CEN-TS 15104:2011 Standard. The determination was performed in a Leco Micro TruSpec Elemental Analyzer.

2.1.2. Determination of the net calorific values

The determination of the net calorific values was performed in an AC-350 calorimetric bomb (Leco Corporation, Michigan, USA).

2.1.3. Determination of the ash content

The ash content is calculated by the inorganic matter that remains after combustion under controlled conditions at 550 °C according to CEN-TS 14775:2009. The difference should be remembered between the temperature to determine ash content in solid mineral fuels (815 °C according to Standard ISO 1171:2010) and in biomass fuels (550

°C). The reason is that biomass ash, in practice, contains several volatile inorganic compounds.

2.1.4. Determination of the total content of sulphur, chlorine and bromine

The European Standard to determinate the content of sulphur and chlorine in solid biofuels is the CEN-TS 15289:2011. This method consists in the oxidation of the sample by combustion in a bomb containing oxygen under pressure and the liberated inorganic anions were absorbed in water or in an alkali solution, e.g. sodium carbonate/sodium bicarbonate solution, if the content of chlorine or sulphur is high. The bomb combustate solution was analysed by Ion Chromatography. In addition, the bromide was also analysed from the combustate solution (EPA, 1994); the determination of bromine in these types of waste wood is also important, because they can contain Brominated Flame Retardants (BFRs). The determinations were carried out with a Dionex DX 500 ion chromatograph.

2.1.5. Determination of the major and minor elements

A multi-step pressurised digestion was carried out following the CEN-TS 15290:2011 Standard for the determination of the major elements (Al, Ca, Mg, P, K, Si, Na and Ti) and following the CEN-TS 15297:2011 Standard for the minor elements (As, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, V and Zn). Subsequently, the detection of the major elements was carried out by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) following the CEN-ISO 11885:2007 Standard; the detection of the minor elements was carried out by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) following the CEN-ISO 1729-2:2003 Standard.

2.2. Study of the parameters affecting the quality of waste wood briquettes

In this study, a hydraulic piston press briquette machine (Mega KCK-50) has been employed to compare the physical characteristics of the waste wood briquettes. A 53.0 mm diameter cylindrical mould was used to make the briquettes.

The runs were carried out at room temperature and the parameters studied were: compaction pressure, material moisture and percentage of foam included. Five different compaction pressures were studied: 22, 33, 44, 67 and 88 MPa. Different material moisture was also studied: 6%, 8% and 10%. On the other hand, the material moisture was fixed at 8% (this moisture was demonstrated to be suitable to obtain high quality briquettes) to study the effect of the mixture of the waste wood with different percentages of foam.

The densities of the briquettes were measured immediately after the briquettes were ejected from the mould. After stabilisation for 24 hours, the densities were measured once more. During the stabilisation time, the size and parameters of the briquettes change, due to dilatation, as stated in literature (Križan, 2009). Mechanical durability was also measured after stabilisation.

Durability (DU) is the most important parameter for evaluating the quality of densified biomass. The briquette is subjected to controlled shock by collision against the walls of a dustproof rotating prototype. Durability is calculated from the mass of the sample remaining after the separation of fine particles eroded and broken. The European Standard CEN-TS 15210-2:2011 indicates the method to determinate the mechanical durability of commercial briquettes of biomass. A modification of the European Standard was carried out to measure the durability of the briquettes obtained, due to the fact that they are smaller (around 40-50 g) than the commercial briquettes indicated by the Standard. The drum used had an internal diameter and depth of 120 mm, and the

speed rotation was 50 rpm. Several weight measurements were taken to observe the development of the weight losses by erosion.

Two or three briquettes were evaluated for each parameter affecting the quality studied. In the Result and Discussion section, densities and DU values obtained are represented with the average value and the upper and lower limits.

As indicated in the Introduction section, natural binders in lignocellulosic materials (such as: lignin, protein, etc.) help to keep the particles bonded after densification. Lignin and protein show auto-fluorescence under UV excitation, therefore a UV microscope (PCE-MM 200 UV; with UV excitation of 365 nm) was used to confirm the plastification of these natural binders in the briquettes.

3. Results and discussion

3.1. Chemical composition of biomass

As Table 1 indicates, the Net Calorific Values ranged between 15.8 and 19.5 MJ/kg (d.b.) for woody materials, which are typical values for biomass feedstock (CEN, 2010a). The highest Net Calorific Value is in the polyurethane foam, with 24.2 MJ/kg (d.b.), therefore briquettes of mixture would improve the Net Calorific Value (16.7 and 17.5 MJ/kg d.b. for a mixture of furniture wood with 10 wt. % and 20 wt. %, respectively).

Table 1 shows that waste from furniture wood manufacturing and furniture waste has a high nitrogen content, which can mainly be due to the urea-formaldehyde and melamine-formaldehyde resins used as adhesives and coatings (Girods et al., 2008). The highest nitrogen content is in the polyurethane foam sample, with 5.95 wt. % of N content. Briquettes of mixture would increase the N content, although the percentage of polyurethane foam added would not be too high (between 10 wt. % and 20 wt. %).

Consequently, the N content in the mixture would be 3.17 wt. % and 3.48 wt. % for the addition of 10 wt. % and 20 wt. % of polyurethane foam, respectively. These values would be even lower than the N content of engineered wood (3.96 wt. %). For non-industrial use of wood briquettes, the European Standard regarding fuel specifications and classes (CEN, 2010b) indicates that the maximum content of nitrogen allowed is 1.0 wt % (d.b.). However, woods with a higher content of nitrogen can be combusted in industrial boilers, which have been technologically improved to reduce NO_x emissions (air staging: primary and secondary combustion zones) or/and flue gas cleaning technologies (SCNR and SCR processes).

Furniture wood waste has the highest sulphur content. This can cause SO_x gaseous emissions, although the presence of earth-alkali metals (mainly Ca) in the fuel produces a sulphur retention in the ash and emission problems are expected above 2000 mg/kg of sulphur (Oberberger et al., 2006), but its content in samples is less.

Regarding the Cl content, it is observed that solid wood and vine shoots have a low content of Cl; these values are acceptable by the European Committee for Standardization for the domestic use of heating (CEN, 2010a). Waste wood from furniture manufacturing and furniture waste contains non-wood materials with chlorine content, such as adhesives, paints, preservatives and fire protection agents. Polyurethane foams can also have a high content of Cl, which could be due to the retention of inorganic chlorines from atmospheric particles in the upholstery foams and also to the additives used, but all of which are within the European limits proposed for non-industrial briquettes (less than 1000 mg/kg of Cl (CEN, 2010b)).

Furniture wood waste and polyurethane foams have a high ash content due to their chemical treatment, and moreover to soil contamination.

Analysis of the inorganic content

The combustion process is affected by the inorganic elements, due to the deposit formation, the fly ash emissions and their influence in the ash melting behaviour. In addition, this content also affects the possibility of ash disposal (Oberberger et al., 1997).

It must be pointed out that the inorganic elements in foam can vary, due to its retention capacity. In fact, this material has been used to carried out atmospheric analysis (Kavouras and Koutrakis, 2001; Moreno et al., 2003).

K, Na, Si and Al, but especially the alkaline ones, decrease the ash melting point, which means that the inorganic vapours condense on the surface of the heat exchanger tubes causing fouling problems (Miles, 1996; Oberberger et al., 1997). Ca and Mg however, raise the ash melting point (Oberberger et al., 1997); in fact, a possibility to increase the ash melting point is the addition of some additives, such as lime or kaolin (Jandacka et al., 2015). From Table 2, it can be concluded that Ca, Si and Ti are the most abundant inorganic compounds in furniture wood waste, and Ca (with a great contribution) and Si are the most abundant in polyurethane foam waste. The presence of Ca is beneficial for combustion because it raise the ash melting point. However, the presence of Si decreases the ash melting point and this fact causes fouling problems in combustion equipment. Table 3 summarises the total content of alkali in the samples studied and it shows that the highest content of alkali belongs to the vine shoots. Wood wastes and polyurethane foam have alow content of alkali. In straws, grasses and herbaceous fuels, the alkali content is higher than in wood from trunks, therefore the high content of alkali in vine shoots was expected. A simple method to reduce the alkali content is leaching the elements from the fuel with water (Davidsson et al., 2002; Jenkins et al., 1996).

Table 3. Alkali content of the different types of waste and wood studied.

3.2. Parameters affecting quality of waste wood briquettes

Furniture wood waste and polyurethane foam were ground to a size less than 19.1 mm for the production of the studied briquettes.

Moisture content:

The moisture effect on the durability of densified material has been widely studied (Križan, 2009; Li and Liu, 2000; Temmerman et al., 2006).

The presence of water is necessary, because it acts as a binding agent. Water exerts Van der Waals forces between the particles holding them together. However, when the moisture content is high, the densified materials have lower durability and easily become eroded and broken. For instance, Li and Liu (2000) determined that the range for producing good quality of the densified material was 5 – 12 % for all the woody materials studied; the optimum moisture content was around 8 %. On the other hand, Križan et al. (2009) found in their study that the optimal moisture was between 10 % and 20 %. Therefore, the study of this parameter is very important to obtain good quality densified materials.

In the present study, the moisture effect on the durability of briquettes of wood furniture waste has been studied and the results are shown in Figures 1 and 2.

Fig. 1. Variation of durability of briquettes (average value and upper and lower limits, n=2 or 3) with compaction pressure and with moisture content of the wood furniture waste used.

Fig. 2. Relation between durability (average value and upper and lower limits, n=2 or 3) and particle density for briquettes of wood furniture waste with different moisture content.

It can be observed that briquettes of 6 wt. % and 8 wt. % of moisture have high durabilities above 44 MPa pressure of compaction. Worse results were obtained however, for the briquettes with 10 wt. % of moisture. This could be explained by the equilibrium moisture content of wood. Briquettes of wood with moisture higher than the equilibrium moisture have worse durabilities, because the free moisture prevents the formation of durable bondings. Equilibrium moisture content depends on the ambient relative humidity and is expected to be between 6-9 wt.% within a 30 and 50 % relative humidity range.

Figure 2 shows DU vs. particle density for the different moistures studied. From this Figure, it is clear that durabilities rise when particle density increases. Nevertheless there is no clear relation with the briquettes of 10 wt.% of moisture.

With regard to statistical analysis, the highest relative standard deviations (RSD) are obtained when the smallest compaction pressure (33 MPa) is applied. The maximum RSD obtained for density values was 12.9 % (at 33 MPa of compaction pressure and 6 wt. % of moisture content). The maximum RSD obtained for durability values was 22.0 % (at 33 MPa of compaction pressure and 10 wt. %).

Natural binders:

Kaliyan and Morey (2010) and Forero Núñez (2014) found by UV auto-fluorescence that natural binders such as lignin and proteins are the cause of solid bridges between particles in briquettes or pellets. These authors detected the presence of these components by using an auto-fluorescence effect under UV excitation: green or yellow-green for protein and brilliant blue for lignin.

Table 4 shows the composition of furniture wood waste and this is compared with the values of a woody biomass (Klass, 1998). Lignin is approx. 35 wt. % of the organic

composition of furniture wood waste; this value is in agreement with that obtained for pine wood. Protein content has not been analysed, but according to Klass (1998), the quantity of protein in biomass can be approximated by multiplying the organic nitrogen by 6.25. Consequently, it can be deduced that the protein content in furniture wood waste is negligible, because its nitrogen content is due to the additives and moreover the nitrogen content for untreated wood is negligible (Table 1). Woody biomass has negligible or low protein content, but on the other hand, herbaceous biomass can have high protein content (Klass, 1998).

Table 4. Organic composition of wood.

Therefore, just lignin (as a natural binder) can originate the bonding of the particles in furniture wood waste briquettes used in the present work.

Heating produces the plastification of natural binders (Kaliyan and Morey, 2010). In the present study, the plastification of lignin with compaction pressure without heating was also confirmed. The equipment used to observe the lignin plastification was a UV microscope (PCE-MM 200 UV; with UV excitation of 365 nm). Previously, UV microscopy images were taken for a furniture wood waste briquette (Figure 3) and some blue emissions were observed. Nevertheless, another assay was carried to confirm that blue emissions represent lignin. This consisted of adding a small quantity of kraft lignin (Sigma-Aldrich) on the briquette surface and applying firstly a small compaction pressure (22 MPa) and after that applying a high compaction pressure (88 MPa). Emission of a blue colour was not observed after the application of 22 MPa of compaction pressure (Figure 4a), but with 88 MPa of pressure, a blue colour was observed in the UV microscopy image (Figure 4b). Therefore, when lignin is plastified, a blue colour emission under UV excitation is observed in an extensive area.

Fig. 3. UV microscopy image (magnification at 60x) of furniture wood waste briquette (88 MPa of compaction pressure)

Fig. 4. UV microscopy image (magnification at 60x) of furniture wood waste briquette with a small addition of kraft lignin (a) at 22 MPa of compaction pressure (b) at 88 MPa of compaction pressure.

Co-densification:

In order to study the effect of using a mixture of furniture wood waste and polyurethane foam waste, some assays have been carried out. All the assays have been done with 8 wt.% material moisture.

Figure 5 shows a mixture of waste furniture wood waste with 10 wt.% of polyurethane foam waste used to obtain a briquette applying 88 MPa of compaction pressure.

Fig. 5: (a) Mixture of furniture wood waste with 10 wt.% of polyurethane foam waste. (b) Briquette obtained with a mixture of furniture wood waste with 10 wt.% of polyurethane foam waste at 88 MPa of compaction pressure.

The first assay consisted in studying the quality of briquettes obtained with wood mixed with 5 wt% of polyurethane foam at different compaction pressures. Figure 6 shows the durability obtained, DU (%), at the different compaction pressures studied, comparing the results of briquettes of furniture wood waste and briquettes of furniture waste mix (with 5 wt. % of polyurethane foam). As can be observed in Figure 6, higher differences of durability with low compaction pressure have been found, but on the contrary, briquettes manufactured at a compaction pressure higher than 66 MPa had similar durability.

The highest relative standard deviation (RSD) of the durability values for briquettes with 5 wt. % of polyurethane foam are obtained at a compaction pressure of 44 MPa (4.8 % RSD).

Fig. 6. Durability comparison (average value and upper and lower limits, n=2 or 3) between briquettes of furniture wood waste and briquettes of furniture waste mix (with the addition of 5 wt% of polyurethane foam)

Another assay consisted in studying the effect of adding different quantities of foam to the mixture to be densified. This assay was carried out with a fixed compaction pressure (88 MPa) and with the addition of foam from 0 wt % to 35 wt %. Figure 7 shows the results of durability of the briquettes studied. From Figure 7, it can be concluded that the briquette durabilities are similar to a common briquette of furniture wood waste up to a maximum of 15-20 wt % of polyurethane foam.

In this case, the highest relative standard deviations (RSD) of the durability values are obtained with the highest content of polyurethane foam (4.2 % RSD).

Fig. 7. Durability of briquettes (average value and upper and lower limits, n=2 or 3) with different additions of polyurethane foam (at 88 MPa of compaction pressure).

The particle density is also an important parameter as explained in the Introduction section. Figure 8 shows the briquette densities measured immediately after the briquettes were ejected from the mould and after stabilising for 24 hours. From Figure 8 it can be concluded that the limiting factors to add high quantities of polyurethane foam are the briquette densities obtained.

The highest relative standard deviations (RSD) of the density values are obtained with 25 wt. % content of polyurethane foam (9.1 % RSD).

Fig. 8. Briquette densities (average value and upper and lower limits, n=2 or 3) with different additions of polyurethane foam (at 88 MPa of compaction pressure).

Due to the elastic character of polyurethane foam, it is important to follow the evolution of the briquette densities. The densities of three briquettes of furniture wood waste with 10, 15 and 20 wt% of polyurethane foam, respectively, were measured periodically over a long period of time (27 days). As can be observed in Figure 9, the main expansion of the briquettes occurs during the first 24 hours, but their densities tend to stabilise from the third day on.

Fig. 9. Briquette densities vs. time (at 88 MPa of compaction pressure).

It must be commented that the CEN-TS 15210-2:2011 Standard does not consider the stabilisation period of time. The possible dilation of the briquettes after their formation can depend on the relative humidity in air, the small pressure undergone in their packing and/or piles during the storage or transportation.

As a result, according to the assays carried out, the co-densification of furniture wood waste with polyurethane foam (up to a maximum of 20 wt %) is an appropriate process to improve energy recovery of these wastes.

3. Conclusions

Regarding the chemical composition, the main drawback is the nitrogen content. Furniture wood waste has a high nitrogen content (2.86 wt. %) in comparison with untreated wood (< 0.01 wt. %), and polyurethane foam waste has a higher nitrogen content (5.95 wt. %), so briquettes of mixtures increase the nitrogen content. Due to this high nitrogen content, the combustion of furniture waste would not be allowed for domestic use. Although waste with high nitrogen content can be combusted in industrial boilers, which have been technologically improved to reduce NO_x emissions. As far as

the sulphur and chlorine content is concerned, the values in furniture waste are around the values shown in untreated wood and biomass samples. With regard to the inorganic content, the elements Ca, Si and Ti are the most abundant in furniture waste.

In addition, the co-combustion of furniture wood waste and this foam generates more heat and energy than the combustion of wood waste because the Net Calorific Value of polyurethane foam (24.2 MJ/kg in d.b.) is higher than that of furniture wood waste (15.8 MJ/kg in d.b.).

As far as the physical properties of the briquettes are concerned, the optimal moisture is 8 wt. %, and a compaction pressure of 44 MPa is sufficient to obtain durable briquettes of furniture wood waste. Lignin plastification was observed in the densification process, justifying the durable bonds created between particles of lignocellulosic materials. Furthermore, the effect of the addition of polyurethane foam to the initial material on the quality of briquettes was studied; briquette durabilities were similar to a common briquette of furniture wood waste up to a maximum of 20 wt % of polyurethane foam.

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Highlights

- Chemical characterization of furniture wood and polyurethane foam waste and comparison with other lignocellulosic wastes.
- Study of the parameters affecting quality of waste wood briquettes.
- Study of co-densification of furniture wood waste and polyurethane foam waste.

FIGURES:

Fig. 1. Variation of durability of briquettes (average value and upper and lower limits, n=2 or 3) with compaction pressure and with moisture content of the wood furniture waste used.

Fig. 2. Relation between durability (average value and upper and lower limits, n=2 or 3) and particle density for briquettes of wood furniture waste with different moisture content.

Fig. 3. UV microscopy image (magnification at 60x) of furniture wood waste briquette (88 MPa of compaction pressure)

Fig. 4. UV microscopy image (magnification at 60x) of furniture wood waste briquette with a small addition of kraft lignin (a) at 22 MPa of compaction pressure (b) at 88 MPa of compaction pressure.

Fig. 5: (a) Mixture of furniture wood waste with 10 wt.% of polyurethane foam waste.
 (b) Briquette obtained with a mixture of furniture wood waste with 10 wt.% of polyurethane foam waste at 88 MPa of compaction pressure.

Fig. 6. Durability comparison (average value and upper and lower limits, n=2 or 3) between briquettes of furniture wood waste and briquettes of furniture waste mix (with the addition of 5 wt% of polyurethane foam)

Fig. 7. Durability of briquettes (average value and upper and lower limits, n=2 or 3) with different additions of polyurethane foam (at 88 MPa of compaction pressure).

Fig. 8. Briquette densities (average value and upper and lower limits, n=2 or 3) with different additions of polyurethane foam (at 88 MPa of compaction pressure).

Fig. 9. Briquette densities vs. time (at 88 MPa of compaction pressure).

TABLES:

Table 1. Characteristics of the different types of waste and wood studied.

	Furniture wood waste (Moreno and Font, 2015)	Polyurethane foam (Garrido and Font, 2015)	Solid wood (Moreno and Font, 2015)	Engineered wood	Vine shoots
NCV, MJ/kg (d.b.)	15.8 ± 0.1	24.2	19.5 ± 0.5	18.3 ± 0.1	17.4 ± 0.1
Ash content, wt% (d.b.)	1.8 ± 0.1	5.5	0.3 ± 0.1	1.3 ± 0.4	4.2 ± 0.8
C, wt% (d.b.)	47.9 ± 0.03	57.8	52.7 ± 0.1	49.4 ± 0.1	49.2 ± 0.1
H, wt% (d.b.)	6.0 ± 0.1	7.4	6.2 ± 0.1	6.1 ± 0.03	6.0 ± 0.1
N, wt% (d.b.)	2.86 ± 0.58	5.95	n.d.	3.96 ± 0.31	0.79 ± 0.03
O, wt% (d.b.)	41.4 ± 0.6	23.4	40.8 ± 0.1	39.3 ± 0.4	40.5 ± 0.1
S, mg/kg (d.b.)	540 ± 130	130	70 ± 50	260 ± 40	330 ± 10
Cl, mg/kg (d.b.)	630 ± 70	390	160 ± 80	410 ± 100	250 ± 20
Br, mg/kg (d.b.)	8.8 ± 0.8	n.a.	0.02 ± 0.04	1.8 ± 0.7	2.5 ± 0.1

n.d.: not detected, <0.01 wt%
n.a.: not analysed

Table 2. Major and minor elements of the different types of waste.

Elements mg/kg (d.b.)	Furniture wood waste (Moreno and Font, 2015)	Polyurethane foam (X-ray fluorescence analysis) (Garrido and Font, 2015)	Solid Wood (Moreno and Font, 2015)	Engineered wood	Vine shoots
Al	480 ± 10	80	30 ± 20	380 ± 10	563 ± 2
Ca	1590 ± 240	> 20000	260 ± 50	730 ± 100	5170 ± 110
Fe	280 ± 30	250	25 ± 4	290 ± 60	240 ± 10
Mg	320 ± 80	100	100 ± 30	220 ± 60	1820 ± 6
P	100 ± 20	20	20 ± 10	83 ± 1	1540 ± 20
K	400 ± 150	n.d.	160 ± 90	280 ± 140	5470 ± 10
Si	2150 ± 140	1050	109 ± 3	1160 ± 180	2430 ± 240
Na	300 ± 120	270	20 ± 10	120 ± 70	80 ± 10
Ti	1600 ± 200	n.d.	2.1 ± 0.8	1530 ± 100	31 ± 1
As	0.4 ± 0.03	n.d.	0.01 ± 0.004	0.5 ± 0.1	0.2 ± 0.02
Cd	1.0 ± 0.1	n.d.	0.1 ± 0.02	0.2 ± 0.06	0.01 ± 0.01
Co	1.1 ± 0.1	n.d.	0.05 ± 0.004	0.3 ± 0.01	0.3 ± 0.01
Cr	6.7 ± 1.4	n.d.	2.0 ± 1.3	9.6 ± 2.1	6.5 ± 2.0
Cu	6.4 ± 0.7	n.d.	1.4 ± 1.4	4.3 ± 0.3	5.7 ± 0.3
Hg	0.03 ± 0.04	n.d.	0.01 ± 0.003	0.01 ± 0.004	< 0.01
Mn	40.0 ± 3.6	n.d.	46.8 ± 7.1	70.8 ± 10.6	20.7 ± 0.03
Mo	0.3 ± 0.03	n.d.	0.02 ± 0.02	0.3 ± 0.04	0.3 ± 0.01
Ni	1.2 ± 0.3	n.d.	0.04 ± 0.07	1.7 ± 0.5	0.6 ± 0.04
Pb	6.3 ± 3.6	n.d.	0.04 ± 0.06	12.3 ± 4.3	0.4 ± 0.1
Sb	2.0 ± 0.4	n.d.	0.01 ± 0.01	1.2 ± 0.1	0.04 ± 0.001
V	0.9 ± 0.04	n.d.	0.1 ± 0.002	0.5 ± 0.003	0.9 ± 0.01
Zn	69.4 ± 2.0	n.d.	7.7 ± 0.9	26.7 ± 1.8	13.9 ± 0.1

n.d. : not detected (< 1 mg/kg)

Table 3. Alkali content of the different types of waste and wood studied.

	Furniture wood wastes	Polyurethane foam	Solid wood	Engineered wood	Vine shoots
wt. % alkali (Na+K) (d.b.)	0.070	0.027	0.018	0.040	0.56

Table 4. Organic composition of wood.

	Furniture wood waste (Moreno and Font, 2015)	Pine wood (Klass, 1998)
Wood Composition		
Hemicellulose (wt. %)	18.0 ± 3.6	24.9
Cellulose (wt. %)	44.7 ± 2.5	40.4
Lignin (wt. %)	33.0 ± 1.1	34.5
Crude protein (wt. %)	n.a.*	0.7

* n.a. = not analysed, but it can be considered negligible or quite low.