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Integral valorization of tagasaste (*Chamaecytisus proliferus*) under hydrothermal and pulp processing

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ABSTRACT

Tagasaste wood (*Chamaecytisus proliferus* L.F. ssp *palmensis*) was characterized, chemical and energy terms, and assessed its potential as a lignocellulosic raw material, and its integral fractionation by autohydrolysis and delignification with ethanol. The hydrothermal treatment of the raw material at 175–185 °C provided a liquor containing a substantially increased amount of oligomers (between 16.6% and 47.4% as percentages with respect to the content of the raw material in each polymer fraction). A cellulose pulp with autohydrolysis treatment increased yields (53–60%), reduced Kappa number (28.8–34.6) but also viscosity (755–857 mL/g), and decreased paper strength (2.97–5.22 kN m/kg). However, beating ethanol cellulose from tagasaste was found to improve its strength-related properties more markedly than in soda pulp from the same material (tensile index of 44 kN m/kg).

1. Introduction

Lignocellulosic biomass (LB) is a major source of renewable energy and raw materials on the grounds of its substantial weight on the leading world markets and its potential uses, which are as varied as those of petroleum. In fact, LB can be used to obtain virtually any type of product currently extracted from fossil sources (Brehmer et al., 2009). The integral exploitation of LB by biorefining (García et al., 2009; Cherubini and Ulgiati, 2010) is expected to enable the production of fuels, cellulose fibre for papermaking uses, automobile fuels and a wide variety of chemical substances, thereby ensuring economic and environmental competitivity and sustainability (Fatih Demirbas, 2009).

The European Union has for some time promoted the direct exploitation of renewable raw materials by combustion. As a result, LB currently provides 44–65% of the amount of renewable energy used by EU consumers. This amount meets 4% of the overall requirements of the community energy sector and provides additional benefits including diversification of the energy supply in Europe, a substantial reduction (209 million tons) of greenhouse gases, direct employment (250,000–300,000 jobs) and a potential reduction in petroleum prices by effect of a decreased demand (COM, 628 final, 2005).

One of the raw materials, especially interesting is tagasaste (*Chamaecytisus proliferus* L.F. ssp *palmensis*) for biomass production. This is a fast growing bushy legume traditionally used as forage, which can alternatively be cropped for energy production or exploitation of its ligneous residues. Tagasaste is a highly productive species, with typically more than 18 t per hectare per year (González, 2000). In addition, it provides some salient advantages such as sheltering from the wind, control of erosion (Monjardino et al., 2010) and soil salinity (Pannell and Ewing, 2006), soil fertilization by nitrogen fixation and/or nutrient supply (McKenzie et al., 2001), and a high protein content that makes its plants suitable as animal feed.

Lignocellulosic biomass is usually fractionated by hydrolysis and delignification. Autohydrolysis has proved one of the most efficient choices for this purpose inasmuch as it facilitates the dissolution of hemicellulose polymers, which can be used to obtain oligomers, xylose and arabinose for a variety of novel applications in the chemical, pharmaceutical and food industries (Vázquez et al., 2001), and also as fermentation media for the production of substances with a high added value such as ethanol fuel and xylitol (Rivas et al., 2002). The solid fraction from an autohydrolysis treatment can be delignified with sulphur-free chemicals (Muurinen, 2000; Pan et al., 2006). The economic feasibility this procedures sulphur-free relies on the marketing potential of the by-products. In addition to cellulose pulp for manufacturing paper

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and cardboard, LB can provide chemical products such as lignin and furfural, which are useful for various purposes including the production of polymers (Vila et al., 2003).

In this work, was characterized tagasaste (*Chamaecytisus proliferus* L.F. ssp *palmensis*) in chemical and energy terms, and assessed its potential as a lignocellulosic raw material and its integral fractionation by autohydrolysis and delignification with ethanol. The liquor from the autohydrolysis treatment was evaluated as a source of oligomers and monosaccharides, and the solid phase assessed for the production of combustion energy and the manufacturing of cellulose pulp and paper.

2. Experimental

2.1. Chemical and energetic characterization of raw material

Branches and twigs with 0.5–5 cm in diameter were used. These pieces were obtained by trimming tagasaste plants from which leaves and non-wood twigs were removed prior to grinding in a hammer mill. The material was collected from several experimental plots in the municipality of Trigueros (Huelva, Spain).

This raw material used, which was prepared in accordance with Tappi T-257, was analysed for the following parameters: ethanol–benzene extractives (TAPPI-204), ash (TAPPI T-211) and holocellulose (Wise et al., 1946).

In addition, the cellulose and hemicellulose composition of the material, in the form of glucan, xylan, araban and acetyl groups, were determined by high performance liquid chromatography (HPLC). To this end, portions of the homogenized wood lot were subjected to quantitative acid hydrolysis with 72% sulphuric acid (TAPPI T-249-em-85). The solid residue after hydrolysis was recovered by filtration and considered as Klason lignin. The monosaccharides and acetic acid contained in hydrolysates were determined by HPLC in order to estimate (after corrections for stoichiometry and sugar decomposition) the contents of samples in cellulose (as glucan), hemicelluloses (as xylan), and acetyl groups (Díaz et al., 2004). Chromatographic runs were done with an Agilent 1100 HPLC instrument equipped with an Aminex HPX-87H column packed with ion-exchange resin under the following conditions: mobile phase, sulphuric acid at 0.05 mol L^{-1}; flow rate, 0.6 mL min^{-1}; column temperature, 50 °C; injected volume, 20 µL.

Higher Heating Values were determined at a constant volume in accordance with "CEN/TS 14918:2005 (E) solid biofuels – method for the determination of calorific value" and UNE 164001 EX standards, using a Parr 6300 Automatic Isoperibol Calorimeter.

2.2. Pulping and beating procedure and formation of paper sheets

2.2.1. Experimental pulping operations

Cellulosic pulps under two different pulping process (ethanol and soda delignification) were carried out. Both pulps were obtained using a batch digester wrapped an electrically heated jacket with rotary agitation. The control unit included temperature and pressure gauges, as well as appropriate safety devices. The sequence of steps of the soda pulping process was as follows: following cooking, the pulp was filtered and washed with abundant water on a screening tray, defiberized to 1.5% consistency and passed through a Sprout–Waldrom refiner operating at 0.5% pulp consistency and using a disk spacing of 0.1 mm. Uncooked material was removed by passage through a Steiner filter of 0.4 mm mesh size and water by centrifugation. The ethanol process involved the same steps except for washing and disintegration. Thus, ethanol pulp was washed with a solution of ethanol at the same concentration as in the cooking liquor on a grid tray and subsequently disintegrated in an aqueous solution of ethanol also at the same concentration as in the cooking liquor, and finally washed with abundant water.

2.2.2. Experimental pulping conditions

For each pulping process, three pulps were obtained. On basis on previous works from authors (Díaz et al., 2004; López et al., 2004), the pulping conditions selection was done. Extreme and intermediate conditions were selectioned for analyze the pulp response to beating process. Operation conditions are shown in Table 1.

2.2.3. Beating process and formation of paper sheets

The resulting pulps were processed on a Valley beater, according standards TAPPI T-200 sp-96, at different process times in order to obtain various drainage levels. The degree of refining was determined in a Shopper–Riegler refinometer (°SR) according standard TAPPI T-248 CM-85. Paper sheets were obtained by using an ENJO-F-39.71 sheet former according to TAPPI T 205 sp-95.

2.2.4. Pulp and paper characterization

The two types of pulp thus obtained were analysed for yield (TAPPI T-257) and Kappa number (TAPPI T-236), as well as for lignin (TAPPI T-222) and α-cellulose (TAPPI T-203). Pulp samples were previously prepared in accordance with TAPPI standard T-220.

The resulting paper sheets were analysed for Tensile Index (TAPPI T-494 om-96), Burst Index (TAPPI T-403 om-97), Tear Index (TAPPI T-414 om-98), and Gurley index (TAPPI T-460 om-96) following conditioning in accordance with (TAPPI T-220 sp-96).

Each value in the experimental results is an average of five (chemical pulp properties) or 12 (paper sheets characterization) samples. The deviations for these parameters from their respective means were all less than 5%.

2.3. Hydrothermal treatment

An hydrothermal treatment was carried out in order to obtain a liquid phase with hemicellulosic sugars and a solid phase. The solid phase was delignified with ethanol. The ethanol process was assayed for various authors (Pan et al., 2005, 2006) and it's an appropriate method of delignification according to the purpose of comprehensive use of the material in view of the results obtained

Table 1
Operation conditions in pulping process.

Pulp number	Soda process	Pulp number	Ethanol process
N° S-1	Temperature (°C): 170 °C Liquid/solid ratio: 4/1 Process time (min): 30 min Soda concentration (%): 12	N° E-1	Temperature (°C): 170 °C Process time (min): 45 min Ethanol concentration (% v/v): 40
N° S-2	Temperature (°C): 180 °C Liquid/solid ratio: 6/1 Process time (min): 60 min Soda concentration (%): 16	N° E-2	Temperature (°C): 185 °C Process time (min): 90 min Ethanol concentration (% v/v): 60
N° S-3	Temperature (°C): 190 °C Liquid/solid ratio: 8/1 Process time (min): 90 min Soda concentration (%): 20	N° E-3	Temperature (°C): 200 °C Process time (min): 135 min Ethanol concentration (% v/v): 80

in the pulping and refining in previous processes. Furthermore, ethanol delignification preserves the cellulose properties, obtaining good yields and cellulose pulps refined and easily bleachable (Oliet et al., 2005).

The autohydrolysis treatment was conducted in a 2-L high-pressure batch reactor from Parr equipped with stirring, controlled heating and an inner thermocouple connected to a module displaying the temperature within the digester. The operating conditions were chosen from previously reported data for the autohydrolysis of eucalyptus wood and other materials (Garrote et al., 2003). The temperatures studied were 165, 175, 185 and 195 °C, and the liquid/solid ratio 6.5/1. Following autohydrolysis, the solid phase was stored refrigerated in air-tight bags until pulping (Alfaro et al., 2009).

The solid phase was delignified with ethanol under the optimum operating conditions established in preliminary tests, namely: an ethanol concentration of 60%, a time of 90 min and a temperature of 175 °C – instead of 185 °C in order to exploit the destructuring action of the autohydrolysis treatment in the previous step. Using a slightly lower temperature additionally reduced degradation of carbohydrates, formation of lignin condensation products and other unwanted reactions (Alriols et al., 2010). The delignification treatment was performed in the same reactor as the autohydrolysis step.

Monosaccharides and oligosaccharides were determined in liquid phase from autohydrolysis by HPLC. Cellulosic pulps were analyzed in yield, Kappa number, viscosity and strength properties of paper sheets. The results were compared with those of a cellulose pulp produced in the same way but without hydrothermal treatment.

3. Results and discussion

3.1. Chemical and energetic characteristics of raw materials

In Table 2, results of chemical and energetic characterization of tagasaste and other lignocelullosic materials were compared. Herbaceous species like *Arundo donax* and sunflower stalks, and tree wood like paulownia and eucalyptus were included. Eucalyptus is the more used wood specie in Spain for pulp and papermaking. These raw materials are currently researched for use as alternative wood in pulp industry, chemical industry and power sources (Garrote et al., 2003; Caparrós et al., 2006, 2008).

Holocellulose content is higher in tagasaste in relation to other lignocellulosic materials in Table 2. Between 20.0% and 41.1% higher than eucalyptus and paulownia, respectively, though the analytical method for holocellulose content in eucalyptus and paulownia was not the same (holocellulose contents expressed as addition of glucan and hemicellulose contents). In the other hand, the lignin content in tagasaste is the lowest of the materials compared which would indicate an easier delignification. The rest of raw materials shown higher percentages in lignin contents, between 15.7% more for eucalyptus and 37.4% more in the paulownia than tagasaste.

To respect the cellulose content expressed as glucan, tagasaste is the raw material with higher cellulose content (except eucalyptus). Between 2.3% and 13.1% more than leucaena and sunflower stalks, respectively. These data, together with the relatively low ash content (similar to eucalyptus and substantially below the herbal materials) that would limit the problems in the line of recovery of chemical reagents (Finell and Nilsson, 2004), and greater ease of delignification, indicate the possibility of obtaining good yields in quality cellulose pulp.

Sunflower stalks show the higher xylan contents. Paulownia, tagasaste and *Arundo donax* show similar values and lower for eucalyptus.

In terms of energy production, it was determined the heating value of different basic raw materials. Generically, biomass has a Higher Heating Value between 3500 and 4500 kcal. Tagasaste biomass has been estimated to possess a Higher Heating Value (HHV) of 4676 kcal/g would provide useful fuel with a heating power very similar to that of eucalyptus wood and only 1.4% lower than that of paulownia – the alternative raw material with the highest power studied so far. The energy properties of tagasaste facilitate its processing in biomass combustion facilities, especially if one considers some additional advantages of this material including its favourable environmental impact, high productivity and absence of competition with food uses (like starches, cereals...). The estimate

Table 2
Chemical and energetic characterización of tagasaste (*Chamaecytisus proliferus*) and others lignocelulosic materials.

	Chamaecytisus proliferus (tagasaste)	*Eucalyptus globulus* (eucalyptus)[b]	*Leucaena diversifolia* (leucaena)[c]	*Paulownia fortunei* (paulownia)[d]	*Arundo donax* (reed)[e]	*Helianthus annuus* (sunflower stalks)[f]
Ethanol extractives, %[a]	2.3	1.2	1.7		9.1	
Ash, %	0.7	0.6			3.0	9.4
Holocellulose, %	80.3	66.9	65.8	56.9	64.5	74.2
Glucan, %	38.9	46.8	38.0	34.2	34.8	33.8
Klason lignin, %	19.8	22.9	24.8	27.2	23.0	19.9
Xylan, %	19.9	16.6	15.8	18.3	19.4	23.9
Araban, %	0.6	0.5	1.5	1.1	1.5	0.34
Acetyl groups, %	4.4	3.5	3.3	3.3	3.4	4.3
Higher Heating Value (HHV) over dry basis, kcal/kg	4676	4619	4530	4743	4580	4125
HHV of solid phase from autohydrolysis at 180 °C, kcal/kg	4649	4628	4612	4735	4580	4552
HHV of solid phase from autohydrolysis at 200 °C, kcal/kg	4757	4716	4746	4897	4628	4553
Inferior heating value (IHV), kcal/kg	4353	4296	4254	4420	4257	3803
Wet (%)	4.0	7.2	7.0	9.2	8.9	6.7

[a] Composition values in g/100 g raw material, on dry basis.
[b] Garrote and Parajó (2002).
[c] Alfaro et al. (2009).
[d] Caparrós et al. (2006).
[e] Caparrós et al. (2007).
[f] Caparrós et al. (2008).

Table 3
Characteristics of cellulosic pulps/paper sheets.

Pulping procedure	Operation conditions	Characteristics of cellulosic pulps[a]				Characteristics of paper sheets[b]			
		Yield (%)	Kappa number	Lignin (%)	Cellulose (%)	Tear index (N m^2/kg)	Burst index (MPa m^2/kg)	Tensile index (KN m/kg)	Gurley porosity (s/100 cc)
Ethanol	N° E-1	38.3	68.3	12.5	62.7	0.33	0.15	4.8	5.45
	N° E-2	42.8	56.2	7.6	74.4	0.59	0.15	5.37	9.27
	N° E-3	43.9	45.0	5.9	75.0	0.55	0.11	5.26	7.02
Soda	N° S-1	45.7	54.0	13.0	70.8	0.39	0.13	6.08	5.77
	N° S-2	41.2	26.1	5.2	82.1	0.60	0.56	15.82	8.67
	N° S-3	39.3	15.2	3.6	86.4	0.66	0.32	9.18	5.78

[a] Three experiments in each operation conditions The deviations of these parameters from their respective means were all less than 10%.
[b] The deviations of these parameters from their respective means were all less than 5–10%.

production in Canarias and Huelva (Spain) are 15,568 and 18,314 kg/ha, respectively (González, 2000). Eucalyptus, as forestal crop of short rotation, show an average growth between 10 and 15 t ha^{-1} yr^{-1} over dry material (Az-Balteiro et al., 2009).

3.2. Pulp and paper properties without hydrothermal pretreatment

Table 3 gives the mean values for yield, Kappa number, as well as the α-cellulose and lignin contents in the tagasaste wood pulps provided by the ethanol and soda processes. Also the strength properties of paper sheets are shown: tear index, burst index, tensile index and Gurley porosity.

Overall, before the beating, the soda process was the most efficient in tagasaste delignification. Thus, yields were 2.6–4.1% higher, and α-cellulose contents 12.9–15.2% greater, than those obtained with ethanol. Also, delignification with ethanol left more residual lignin in the material. Based on the lignin/yield ratio, however, ethanol was as efficient as soda. With ethanol, maximizing yields entailed using the strongest operating conditions (N° E-3 in Table 1) in order to avoid the increased proportion of uncooked material obtained with milder conditions.

One of the advantages of using ethanol instead of soda here is that the former is more selective and causes less marked cellulose and hemicellulose degradation. In fact, ethanol may act as a cellulose protector during delignification (Pan et al., 2006). Although the Kappa number for ethanol pulp was much greater than that for soda pulp, one should bear in mind that organosolv pulp is usually easier to bleach despite this disadvantage, which can make it more competitive than conventionally produced pulp (Shatalov and Pereira, 2005).

As regards physical properties, the soda paper sheets were stronger than the ethanol sheets. It was especially so for burst index and tensile index, which were 1.2–5 and 1.3–3 times, respectively, higher for soda paper. This is usually the case with non-wood raw materials (particularly grasses and straw). The highest tensile index values are typically obtained in alkaline media (López et al., 2004). The tear index was relative low with both reagents; this was a result of this index being closely related to fibre length – in addition to other potential factors such as chemical composition and other fibre properties including the length/thickness ratio (García and García, 2005). Tagasaste fibres are short: 0.8 mm (Díaz et al., 2004).

Finally, Gurley porosity in the paper sheets was similar with both soda and ethanol. This suggests that soda and ethanol pulp are similarly amenable to refining and that ethanol can provide paper with substantially improved strength-related properties. Figs. 1–3 show the refining curves obtained and the variation of such properties in paper produced by beating to a Shopper–Riegler index of 48 °SR in Pila Valley.

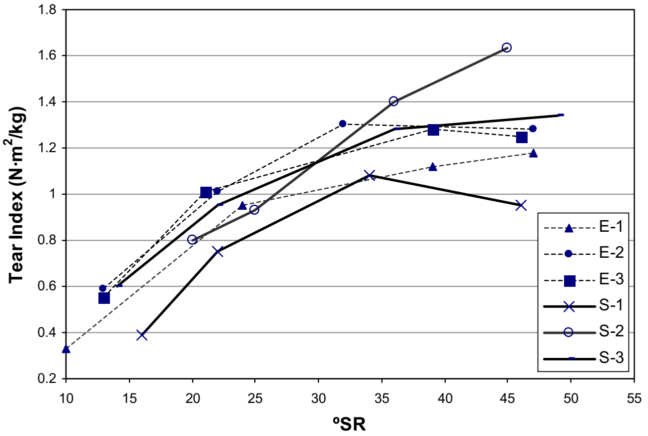

Fig. 1. Tear index variation vs. Shopper–Riegler degree. Ethanol and soda process.

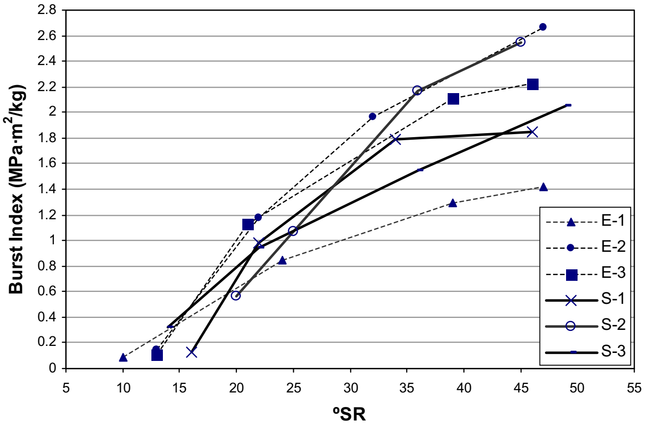

Fig. 2. Burst index variation vs. Shopper–Riegler degree. Ethanol and soda process.

As can be seen, the paper sheets obtained by delignification with ethanol were those exhibiting the greatest improvement in strength upon beating. Also, the burst index was the individual strength-related property undergoing the greatest changes, followed by the tensile index and irrespective of the particular cooking conditions.

As can be seen from Fig. 1, maximizing the tear index of both soda and ethanol paper required using the intermediate operating conditions. At 32 °SR, which resulted in the highest tear index for ethanol paper, the index was similar to that for soda paper. As can be seen from Fig. 2, the burst index increased more markedly in ethanol paper than in soda paper. Such an index was very similar with the two reagents or slightly higher with ethanol (up to 4% under the intermediate operating conditions). Finally, the tensile in-

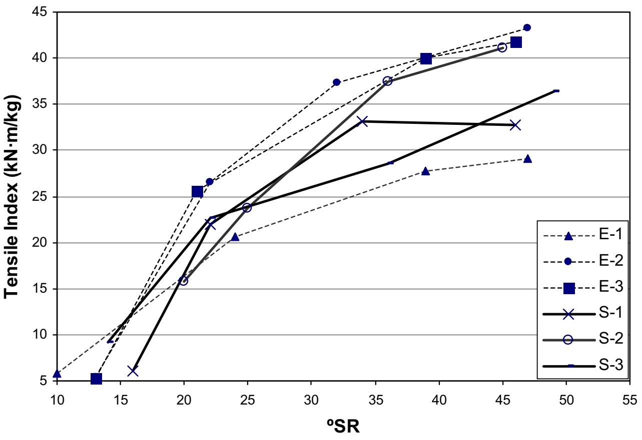

Fig. 3. Tensile index variation vs. Shopper–Riegler degree. Ethanol and soda process.

Table 5
Physical and chemical properties of cellulose pulp samples obtained with and without a hydrothermal treatment at a various temperatures.

Hydrothermal temperature	With hydrothermal treatment				Without hydrothermal treatment
	165 °C	175 °C	185 °C	195 °C	
Hydrothermal yield (%)	93.6	93.8	84.5	74.2	–
Pulping yield (%)	64.3	62.2	68.8	71.3	–
Total yield (%)	60.2	58.4	58.2	53.0	42.61
Kappa number	34.6	34.6	31.0	28.8	66.0
Viscosity (mL/g)	857	762	770	755	1056
Tensile Index (kN m/kg)	4.99	5.22	4.45	2.97	5.76
Burst index (MPa m^2/kg)	0.12	0.07	0.06	0.06	0.18
Tear index (N m^2/kg)	0.92	0.77	0.63	0.52	0.70

dex was the strength-related property exhibiting the greatest improvement by delignification with ethanol relative to soda. Thus, the index was more than 15% higher with the former on identical degree of beating (e.g. 30 °SR).

The pulp best responding to beating was that obtained by delignification with ethanol. In fact, beating it increased its tear, burst and tensile index 2.2, 17.7 and 6.9 times, respectively. Although soda delignification process gave pulp and paper sheets with better properties, the advantages of organosolv processes and the ability to substantially improve the properties of the paper sheets they provide – to levels even higher than those of soda paper – confirm the high potential of ethanol delignification for the integral and fractional exploitation of tagasaste.

3.3. Autohydrolysis treatment and pulp and paper making

Table 4 shows monomeric sugars and oligomers concentration in liquid phase from autohydrolysis of tagasaste wood. The concentration was expresed in g/L and extraction percentage to respect the polymer content in dry raw material. Table 5 shows chemical characteristics of pulps and properties of paper sheets obtained with a ethanol-delignification process applied on solid phase posthydrolysis and raw material at same operation conditions.

The greatest increase in oligomer concentration in the autohydrolysis liquor (for a temperature increase of 10 °C) occurred between 175 and 185 °C, and, to a lesser extent, from 185 to 195 °C. The favourable effect of a high temperature on the oligomer extraction efficiency, and the foreseeably increased cellulose degradation obtained, may detract from the strength-related properties of paper sheets obtained from the solid phase remaining after autohydrolysis (Hendriks and Zeeman, 2009). As can be seen from Table 4, however, the highest autohydrolysis temperature studied (195 °C) only dissolved 3.2% of cellulose (as glucose) in the raw material, which suggests that the glucan fraction was scarcely affected. Also, degradation products such as furfural and hydroxymethylfurfural were detected at very low concentrations (<0.2 g/L), and only at the highest operating temperature (195 °C) (Garrote and Parajó, 2002; Zhuang et al., 2009).

Each solid fraction from the autohydrolysis treatment was used to obtain pulp under the above-described conditions. The yields were quite high (53.0–60.2%) if one considers that they were the result of two cooking processes and that the autohydrolysis pretreatment reduced the amount of uncooked material remaining after delignification (Table 5). One other favourable effect of the autohydrolysis treatment was a substantial reduction in Kappa number (47.6–56.4% relative to the absence of treatment), which should facilitate bleaching of the resulting pulp. By contrast, autohydrolysis also reduced pulp viscosity, albeit only slightly.

As can be seen from Table 5, a high autohydrolysis temperature detracted from strength-related properties in the paper (particularly burst index). On the other hand, an intermediate temperature (175 or 185 °C) led to a tear index 10% higher than in the absence of autohydrolysis. The tensile and burst index were both lower by an average 16.0% and 63.8%, respectively, in autohydrolysed pulp.

The solid fractions from the autohydrolysis of tagasaste at 180 and 200 °C were used to determine their Higher Heating Value in order to assess their energy potential. As can be seen from Table 2, raising the temperature by 20 °C increased the heat power of the solid residue by 2.3%. Such an increase exceeds those previously obtained for other reference species (e.g. eucalyptus) and may facilitate the use of an alternative fractionation process including autohydrolysis to obtain hemicellulose sugars and subsequent valorization of the residual mass for energy production.

Table 4
Concentrations of oligomers, monomers and miscellaneous substances in the liquors from the hydrothermal treatments, expressed as concentrations (g/L) and as percentages with respect to the content of the raw material in each polymer fraction.

	Sugars concentration (g/L) Hydrothermal temperature (°C)				Oligomers and monomers percentage (%) with respect to the content of the raw material in each polymer fraction Hydrothermal temperature (°C)			
	165 °C	175 °C	185 °C	195 °C	165 °C	175 °C	185 °C	195 °C
Oligomers[a]	3.3	5.7	16.1	23.4	9.6	16.6	47.4	69.8
Glucose	1.5	1.9	1.8	2.1	2.3	2.8	2.7	3.2
Xylose	1.1	1.3	1.5	2.8	3.2	3.7	4.5	8.3
Arabinose	0.2	0.4	0.7	1.0	23.0	32.9	62.6	97.3
Acetic acid	0.4	0.5	0.8	1.7	3.9	5.0	8.7	18.9
HMF[b]	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.2
Furfural	0.0	0.0	0.0	0.2	0.0	0.1	0.1	0.8

[a] It expressed as xylose equivalents.
[b] HMF: hydroxymethylfurfural.

4. Conclusions

Tagasaste lends itself readily to valorization for energy production purposes, and also for integral, fractional exploitation by autohydrolysis and delignification with ethanol, which can additionally bring environmental benefits to cropping zones.

The hydrothermal treatment of the raw material at 175–185 °C provided a liquor containing a substantially increased amount of oligomers. A cellulose pulp with autohydrolysis treatment increased yields, reduced Kappa number – but also viscosity, and decreased paper strength. However, beating ethanol cellulose from tagasaste was found to improve its strength-related properties more markedly than in soda pulp from the same material.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biortech.2010.04.059.

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