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Characterization of hairs and pappi from *Cynara cardunculus* capitula and their suitability for paper production

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ABSTRACT

The capitula of *Cynara cardunculus* contain hairs and pappi representing 7% of the total plant biomass. These low density biomass components could be mechanically separated without apparent losses using a whole-plant processing prototype. Hairs and pappi are filamentous structures made up of longitudinally aligned fibre cells, without intercellular voids or pitting, with the following dimensions regarding length, width and wall thickness: 1.35 mm, 19.8, and 4.8 μm for hairs and 1.78 mm, 10.4, and 2.9 μm for pappi. Chemically hairs and pappi have low content of ash (1.9% and 1.1%, respectively), extractives (5.4% and 6.0%) and lignin (10.6% and 17.8%), and high content of holocellulose (77.5% and 72.8%) and α-cellulose (55.2% and 46.8%).

Pulps could be produced using a conventional kraft process with high yields and low residual lignin, *e.g.* 63% at Kappa 7 for hairs and 48% at Kappa 11 for pappi, low coarseness values (0.04 and 0.03 mg m^{-1}) and adequate pulp properties for paper (40 and 42 N m g^{-1} tensile index; 3.6 and 3.4 kPa m^2 g^{-1} burst index in unrefined pulps of hairs and pappi, respectively). The results also indicated that there is scope for improving pulp quality by optimising pulping conditions to this type of new raw materials. The differences between hairs and pappi may also be further exploited namely the lower lignin content of hairs and the higher slenderness and wall thickness of pappi fibres.

The utilization of hairs and pappi may strengthen the differentiated use of biomass fractions of the *Cynara* plant and its potential as a bioenergy crop.

1. Introduction

The thistle *Cynara cardunculus* L. is one promising perennial crop that can be grown in hot and dry Mediterranean climates with high biomass productivities (Fernández and Manzanares, 1990; Gominho et al., 2001). It is an herbaceous species of the *Asteraceae* family (*Compositae*) that grows as a wild plant in the Mediterranean region (Franco, 1984). In the context of energy crops, it is generally known as *Cynara*. This thistle has been the object of several R&D programs with EU support to evaluate its aptitude for biomass production and use (Fernández, 1990, 1993a, b, 1998). At present the European project ECAS (Energy Crops in the Atlantic Space) studies the large scale cultivation of this

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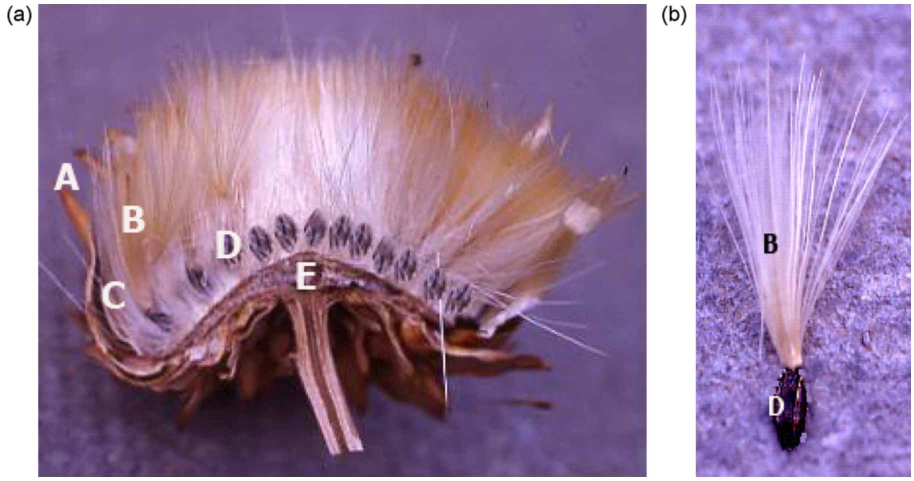

Fig. 1 – Longitudinal cut of the *Cynara cardunculus* L. head at harvest time (a). Macroscopic view of pappus link to achene (b). Legend: (A) bract; (B) pappus; (C) hairs; (D) achene (seed); (E) receptacle.

crop and approximately 400 ha were installed in Portugal (http://www.isa.utl.pt/def/interreg/).

The biomass can be used for multiple purposes *e.g.* energy from biomass combustion (González et al., 2004; Fernández et al., 2006), biodiesel from the oil in the seeds (Benjelloun-Mlayah et al., 1997; Fernández and Curt, 2004; Fernández et al., 2006), forage, enzymatic source for the milk coagulation in traditional cheese making (Pires et al., 1994) or as fibre supply for pulp and paper industries (Villar et al., 1999; Antunes et al., 2000; Gominho and Pereira, 2000, 2006; Gominho et al., 2001).

The average annual production varies from 15 to 20 tons/ha depending on soil and rainfall, with 11–15% moisture content at harvest, and with the following biomass partitioning: 40% stalks, 25% leaves and 35% capitula (Fernández, 1992, 1993a,b; Dalianis et al., 1996). Capitula, commonly known as 'head', are the basic type of inflorescence and rather complex in structure (Fig. 1). Each plant may develop many heads, organized in corymb-like groups. The heads are ovate to globular, 33–75 mm × 32–95 mm in size, and contain numerous tubular flowers ('florets'), about 5 cm long, with a dark or pale lilac or bluish colour. The florets rise from a flattened surface, the 'receptacle', surrounded by bracts. Inside the capitulum, and subtending the florets, there are many bristles (interflower bracts) like stiff white hairs. At maturity, *Cynara* heads contain numerous fruits attached to the receptacle. The fruit is an achene (one-seed dry fruit), the same as in the sunflower, but has a crown of plumose filaments known as 'pappi' (a structure for fruit dispersal) (Fig. 1).

Several fractions can therefore be distinguished in the mature head of *Cynara*: receptacle, bracts, pappi, hairs (bristles) and fruits (achenes). Their mass proportion, or head biomass partitioning, varies with the plant development, namely the head size. A mature head may weight from 10 to 120 g, distributed on average as follows: the receptacle represents 18%, the bracts 25%, the fruits 32% and the light material (hairs, pappi, and remains of corolla, stamens and styles) 25% (Fernández and Curt, 2005), of which hairs and pappi represent the main fraction (80%). Similar values were recorded by Piscioneri et al. (2000).

The fruits, or 'seeds' as they are usually called, contain about 25% of oil that can be transesterified with methanol or ethanol to produce biofuels (Benjelloun-Mlayah et al., 1997; Fernández and Curt, 2004). The mechanical separation of seeds from the capitula originates a by-product composed by bracts, hairs and pappi. The hairs and pappi are very light components that can be gravimetrically separated from the other solids. These two fractions are rich in fibres and can be envisaged as a raw material for fibre or pulp products.

The evaluation of the *Cynara* thistle as an energy and industry crop requires assessment of utilization alternatives of all plant components. The objective is to have a full and value-optimized use of the *Cynara* plant with differentiated conversion processes for the various biomass components according to their aptitude. This was the rationale behind our study and we applied it to the fraction of hairs and pappi, which make up about 7% of the whole plant, that have not been characterized so far. We analyzed these components as a potential fibre source, by making their anatomical and chemical evaluation and assessing their potential as a raw material for pulp production.

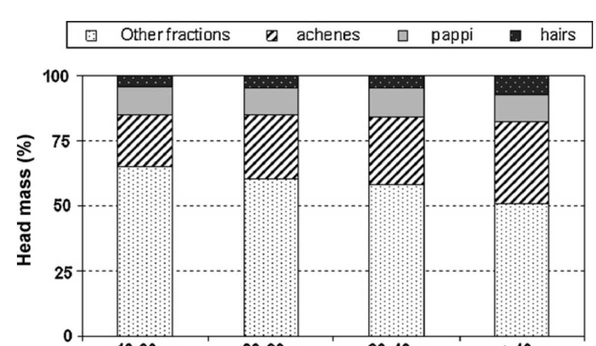

Fig. 2 – Biomass partitioning (%) of the heads of *Cynara cardunculus* L. as a function of the head weight.

2. Material and methods

2.1. Material separation

The plant material used for this work came from *C. cardunculus* L. field trials carried out by the Escuela Técnica Superior de Ingenieros Agrónomos (Universidad Politecnica de Madrid, Spain). The studies were conducted with hairs and pappi from naturally air-dried capitula of *C. cardunculus* previously subjected to mechanical separation in a specially designed prototype as follows. The machine was fed with whole heads which were crushed by a set of counter-rolling cylinders. The achenes were removed by gravimetric separation on vibrating trays endowed with screens and the light material was driven by an air flow to a separation cyclone where hairs and pappi were separated from the other light material. The hairs were separated by sedimentation and pappi were gathered from a screen by a sweeping device. The prototype for separation of hairs and pappi was coupled to existing equipment for the unrolling of whole-plant cylindrical bales and separation of capitula. A mass balance for the mechanical separation process was calculated using the mass of the products obtained in relation to the initial mass of feed material.

The equilibrium moisture of the plant material used for this work was 8% for the hairs fraction and 2% for the pappi. The partitioning of *Cynara* capitula into the fractions of receptacle and bracts, achenes, hairs and pappi was also made by hand in 40 randomly selected heads that were collected in the field at maturity.

2.2. Anatomy and biometry

The structure and anatomy of hairs, pappi and of handsheets produced with their unbleached kraft pulps were studied by electron scanning microscopy (SEM) and optical microscopy.

For the optical observations, hairs and pappi were cut in transverse sections after inclusion in polyethylene glycol (DP 2000) with 0.17 μm thickness with a Reichert sliding microtome, stained with chrysodine and astral blue and mounted in Euparal. The biometry of cells was measured using a semi-automatic system (Leitz-ASM 68K), in dissociated elements obtained by maceration using acetic acid and hydrogen peroxide (1:1) and astral blue staining. Fibre length was measured in 40 unbroken fibres per sample, and total fibre width and lumen width were measured at mid-length. Cell wall thickness was calculated as (fibre width − lumen width)/2. The length of fibre elements in the pulps was measured in 200 fibres. For SEM observations the samples were gold coated and observed using different magnifications.

2.3. Chemical analysis

The chemical analysis was performed according to TAPPI standard methods to determine ash, extractives, lignin and polysaccharides. The inorganic material was determined gravimetrically after total combustion at 500 °C for 6 h in a muffle (T 211 om-02). The extractives content was determined using in succession three solvents with different polarities (dichloromethane, ethanol and water) with an adapted Soxtec extraction system (modified from T 12 os-75). The acid insoluble (Klason) lignin and the acid soluble lignin were determined according to T 222 om-02 and UM T 250, and monosaccharides by GC after derivatisation to alditol-acetates (T 249 cm-00). The carbohydrate complex was also quantified as holocellulose and α-cellulose. Holocellulose content was determined in extractive-free material by the chlorite method with 240 min. reaction time (Browning, 1967) and α-cellulose in extractive-free and lignin-free holocellulose (method described in Rowell, 2005). The hemicelluloses fraction was calculated by difference between holocellulose and α-cellulose content.

2.4. Pulping and pulp properties

Kraft pulps were made with pappi, hairs and a mixture (1:1 in weight) of hairs and pappi, in 100 mL stainless steel autoclaves rotated in an oil bath with controlled temperature. The process variables were: liquor-to-solid ratio 8:1; sulphidity 30%; alkali active (as Na_2O) 15%, 20% and 25%; temperature 170 °C, during 2 h. At the end of pulping, the autoclaves were immersed in ice and the pulps were thoroughly washed with hot water and air-dried.

Total yields were calculated (oven dried until constant weight at 105 °C) and the pulps characterized. Kappa number was measured in accordance with TAPPI 236 os-76 in an automatic titration equipment (TitraLab), and viscosity according to SCAN-CM 15:88. The degree of polymerization

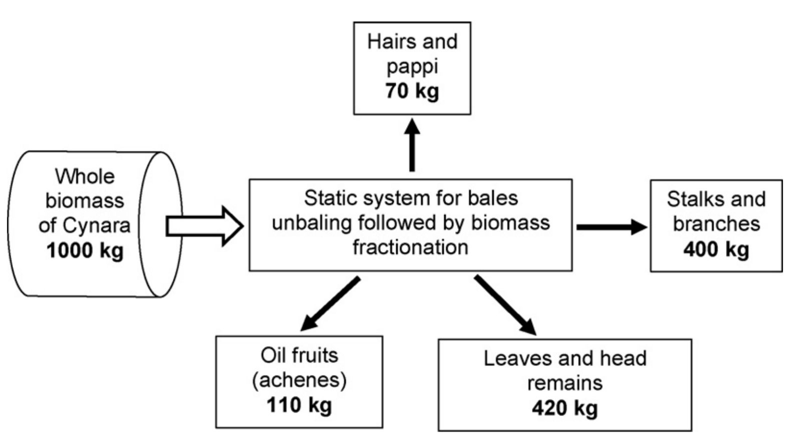

Fig. 3 – Fractionation of *Cynara cardunculus* L. biomass harvested as whole.

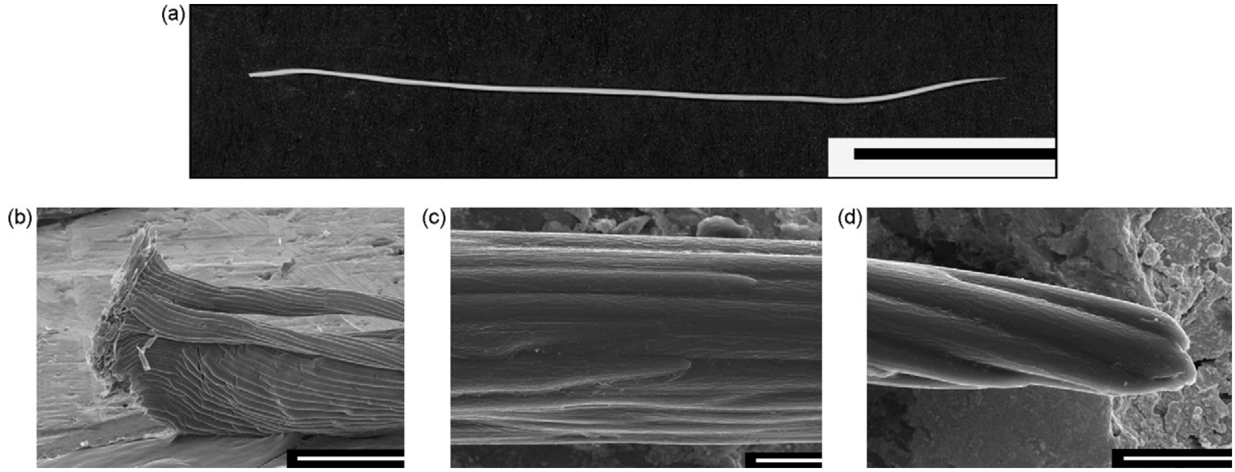

Fig. 4 – General aspect of a hair (a). SEM images showing details of the hair: base (b), middle (c) and top (d). (—) Scale bar; (a) 1 cm; (b) 300 μm; (c and d) 30 μm.

was calculated from viscosity (η) data using $DP^{0.85} = 1.1^*[\eta]$. The content of hexeneuronic acid (HexA) groups was obtained according to Chai et al. (2001): the pulps were hydrolyzed in a chloride-sodium acetate solution and the HexA groups were determined according to the equation: $C_{HexA} = 0.287 \times ((A_{260} - 1.2 \times A_{290}) \times V/w)$, where, A is the absorbance at 260 and 290 nm, V is the volume of the hydrolysis solution (mL); w is the sample weight (g). Handsheets were produced according to Tappi standards (T 205 os-71) and physical-proprieties determined: bulk (T 426 os-46), tensile index, stretch (T 494 om-01) and burst index (T 403 om-91). Paper colour was measured with a Minolta CM-3630 (d/0°) spectrometer using the L^* a^* b^* parameters from the CIE scale, as well as brightness (T 525 om-92). The biometric properties of pulps, i.e. fibre length, width and coarseness were evaluated in a MORFI LB01-TECHPAP equipment.

3. Results and discussion

3.1. *Head partitioning into hairs and pappi*

The biomass partitioning of the *Cynara* heads into hairs and pappi was determined by randomized head sampling followed by hand fractionation. The weight of *Cynara* heads sampled at harvest time ranged from 13.1 to 110.0 g showing variability in the range already reported by Fernández and Curt (2005). Partitioning is given in Fig. 2 as a function of head size. In medium sized heads (30–40 g), hairs and pappi represented, respectively, 4.8% and 11.2% of the head total weight. The mass proportion of pappi was relatively constant while the proportion of achenes and hairs increased with head weight and the fraction made up by the receptacle and bracts decreased.

3.2. *Mechanical separation*

Tests carried out with the biomass fractionating prototype allowed the development of a whole-biomass processing line for the separation of the different fractions of *Cynara* biomass at operating scale. The system elements were the following: (i) unit for the unrolling of round bales of *Cynara* whole biomass; (ii) head crushing unit; (iii) separation unit of stalks and branches; (iv) unit for aspiration and sedimentation of hairs and pappi; and (v) threshing unit to separate the achenes from other plant material (leaves, head remains). The system worked without problems and the fractions were recovered apparently with adequate homogeneity and without major losses. A diagram of this separation system, with indication

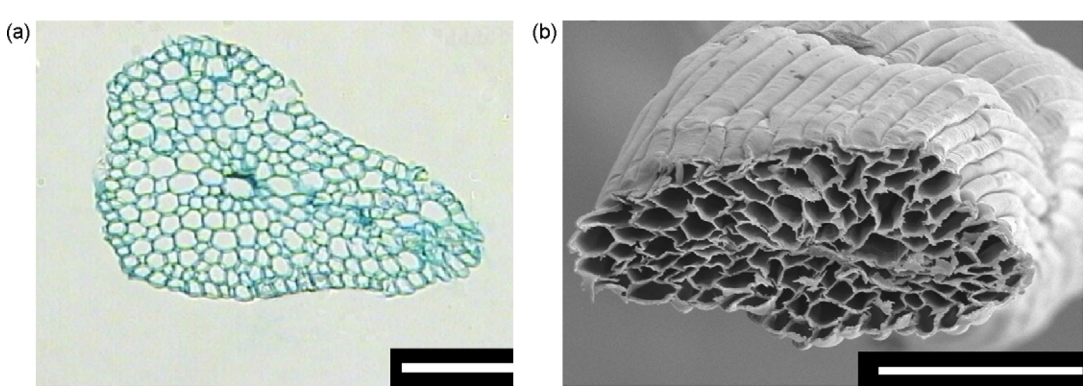

Fig. 5 – Transverse sections of a *C. cardunculus* L. hair observed in optical microscopy with 125× magnification (a) and in scanning electron microscopy (SEM) (b). (—) Scale bar, (a and b) 100 μm.

Table 1 – Length and cross-sectional dimensions for the cells present in hairs and pappi from the capitula of *Cynara cardunculus* L.

	Length (mm)	Width (μm)	Lumen width (μm)	Wall thickness (μm)
Hairs				
Mean	1.35	19.8	10.5	4.8
Standard deviation	0.42	3.6	3.4	1.3
Maximum	2.80	31.9	16.7	8.0
Minimum	0.81	11.4	4.8	2.5
Pappi				
Mean	1.78	10.4	4.6	2.9
Standard deviation	1.13	1.4	1.5	0.6
Maximum	5.40	13.1	7.7	4.8
Minimum	0.66	7.9	1.8	2.1

of the obtained average proportion of each biomass fraction, is shown in Fig. 3. The fraction of hairs and pappi represented 7% of the whole biomass feed, a value that fits well with the obtained biomass partitioning of the capitula and the average head proportion in the plant (Fernández, 1992, 1993a,b; Dalianis et al., 1996).

The collection of these fractions is very advantageous for the *Cynara* raw material handling, namely during shredding and transport, and it is a requirement when separating seeds for oil extraction, because their very low bulk density and tendency to fly away may cause processing and environmental difficulties and be a source of biomass losses.

It is thus feasible to envisage a commercial separation of this light material of the *Cynara* plant and to process it independently, either in a composite sample or fractionated into hairs and pappi.

3.3. *Anatomy and biometry*

The hairs (interflower bracts) of *C. cardunculus* are linked to the receptacle (Fig. 1a). One hair has a filamentous structure (Fig. 4) with an average 40 mm length and an approximate circular cross-section with a mean diameter of about 0.1–0.2 mm (Fig. 5). It is constituted by several fibre cells that are oriented longitudinally along the hair with a tightly parallel arrangement (Fig. 4b and c). The cells show no communication structures, i.e. pits, and they end with a smooth pin-like form (Fig. 4d). In transverse sections it can be observed that the cells are arranged regularly around a central shaft without intercellular voids (Fig. 5a and b). The average dimensions of dissociated cells are 1.35 mm in length, 19.8 μm in width and 4.8 μm in wall thickness (Table 1).

The pappus group numerous plumose filaments (Fig. 6a and b) with 25–40 mm of length that are linked individually to a crown on the top of one achene (Fig. 1b). In cross-section each pappus shows a flattened form with cross-dimensions of about 0.1–0.3 and 0.05–0.1 mm and with an approximate straight and a more convex surface (Fig. 7). The pappus is constituted by parallel aligned cells that are oriented longitudinally without intercellular voids. The cells are fibrous, without pits, and in cross-section have a rather regular arrangement in layers parallel to the surface. The plumes are individual cells that partially separate at the surface of the pappus (Fig. 6d and e). The pappus cells have an average length of 1.78 mm, and the cross-sectional dimensions of dissociated cells are 10.4, 4.6 and 2.9 μm, respectively, for width, wall thickness and lumen width (Table 1).

There are no references in literature regarding the anatomy and the cell biometry in *Cynara* capitula or in other species. The majority of biometric studies made with *Cynara* were related to cells from stalks where the fibres varied in length between 0.9 and 1.3 mm, in total width, 15.0–21.0 and 3.2–9.1 μm in lumen width (Quilhó et al., 2004; Gominho et al., 2001).

Regarding their pulping aptitude, the cells of pappi and hairs from *Cynara* are long and thin walled with an adequate biometry as paper fibres. They compare to other non-wood fibres used in the pulp industry, i.e. in length (kenaf fibres 1.3 mm, reed 1.2 mm, switchgrass 1.1 mm, miscanthus 1.0 mm, cotton stalks 0.8 mm and wheat straw 0.7 mm) and in wall thickness (4.1–5.0 μm for the various crops) (Shatalov et al., 2001; Ververis et al., 2004; Deniz et al., 2004). They are shorter than bamboo (2.8 mm), cotton or hemp (2.0 mm) (Karlsson, 2006). Hairs and pappi fibres also compare favourably with *E. globulus* wood, a valued source of sort-fibres

Table 2 – Chemical composition (% of oven dry mass) of hairs and pappi biomass from capitula of *Cynara cardunculus* L.

	Hairs	Pappi
Ash	1.9	1.1
Extractives	5.4	6.0
Dichloromethane	0.5	0.8
Ethanol	2.8	3.9
Water	2.1	1.2
Lignin	10.6	17.8
Klason	6.9	14.0
Soluble	3.7	3.7
Carbohydrates	76.0	74.5
Rhamnose	–	0.7
Arabinose	0.9	1.7
Xylose	24.4	29.2
Mannose	1.0	1.0
Galactose	0.8	1.4
Glucose	48.9	40.5
Holocellulose	77.5	72.8
α-Cellulose	55.2	46.8

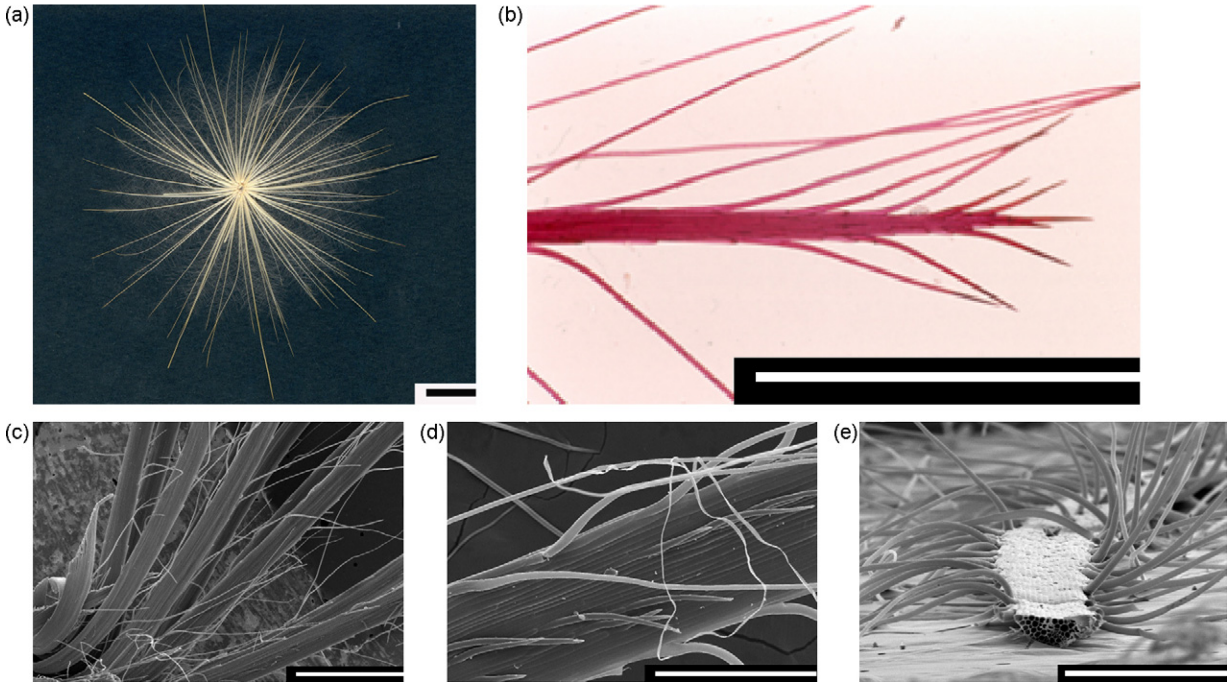

Fig. 6 – General aspect from one pappus (a). Photo obtained in an optical microscope from the top of one row of pappus with plumose filaments (250× magnification) (b). SEM images showing details of pappus: base with several rows (c), middle of one row, showing several plumose filaments (d) and transverse section of a brooked row, also with plumose filaments (e). (—) Scale bar in (a) 1 cm, (b and c) 1 mm, and (d and e) 300 μm.

for paper, which show a fibre length of 0.9–1.0 mm and 6.1 μm wall thickness (Miranda et al., 2001, 2003; Quilhó et al., 2006).

3.4. *Chemical composition*

The results obtained for the chemical analysis of the hairs and pappi are summarized in Table 2. Hairs and pappi are chemically rather similar. Ash content is low and extractives represent on average 5.7% of the material, mainly polar compounds that are soluble in ethanol and water. Lignin content is low, although higher in pappi (17.8% vs. 10.6%) and holocellulose content is high (77.5% and 72.8%). The hemicelluloses are mostly made up of xylan, as shown by the sugar composition after total hydrolysis, with xylose as the main hemicellulosic monosaccharide and only minor amounts of mannose, galactose and arabinose, each representing on average 1% of the material. Pappi contained more hemicelluloses than hairs, *e.g.* xylose amounted to 29.2% and 24.4%, respectively, and less α-cellulose (46.8% vs. 55.2%). Correspondingly the xylose-to-glucose ratios were 0.50 for hairs and 0.72 for pappi.

From a chemical point of view the analysis of the pulping quality of hairs and pappi shows favourable aspects, namely the low ash, extractives and lignin content, and the high holocellulose and α-cellulose contents. The ash content in hairs and pappi is much lower when compared with other aerial biomass fractions from *Cynara*, namely the values ranging 5.4% and 8.0% reported for stalks (Antunes et al., 2000; Gominho et al., 2001). *Cynara* stalks have also substantially more extractives from 14.6% to 31.8% (Pereira et al., 1994; Antunes et al., 2000; Gominho et al., 2001; Ye et al., 2005).

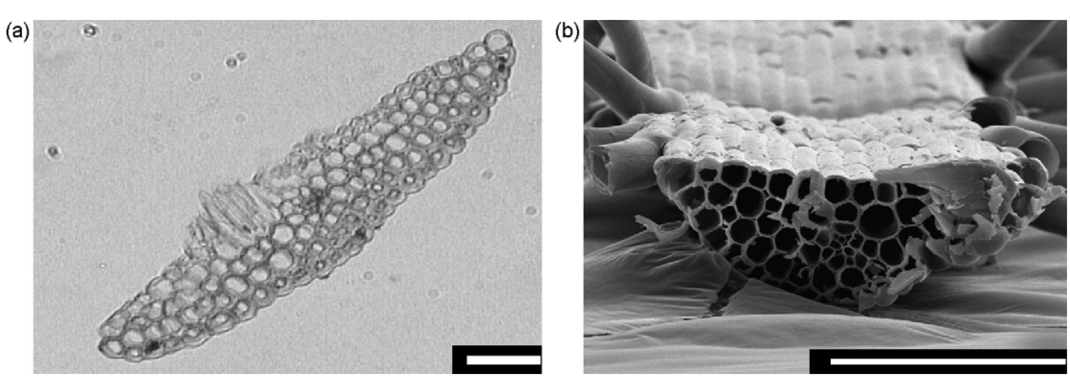

Fig. 7 – Transverse sections of *C. cardunculus* L. pappus row: observed in optical microscopy with 250× magnification (a) and in scanning electron microscopy (SEM) (b). (—) Scale bar in (a) 30 μm and (b) 100 μm.

Table 3 – Characteristics of unbleached kraft pulps made with hairs, pappi and their 1:1 mixture, obtained with different alkali charge

Pulp	Active alkali (% as Na_2O)	Yield (%)	Kappa number	HexA (μmol g^{-1} pulp)	Intrinsic viscosity (mL g^{-1})	$DP^{0.85}$
Hairs	15	63	7	24.1	1069	1176
	20	59	8	62.1	933	1027
	25	57	6	57.0	856	941
Pappi	15	53	38	35.7	942	1036
	20	48	11	46.9	887	976
	25	45	11	31.9	882	971
Mixture	15	59	13	45.9	1102	1212
	20	53	7	43.5	1008	1109
	25	49	7	22.8	808	889

As regards lignin, pappi showed more Klason lignin than hairs (14.0% vs. 6.9%) but both are below the values of 17% reported for Klason lignin in stalks by Pereira et al. (1994) and Gominho et al. (2001). The values compare favourably to other non-wood crops like kenaf (13.2–15.0%), cotton stalks (16.0%), wheat straw (17.0%), reed (19.3%), grass (17.7–24.0%), bamboo (23.0%) and miscanthus (28.0%) (Ververis et al., 2004; Madakadze et al., 1999; Shatalov and Pereira, 2002; Touzinsky, 1987) or eucalypt wood (21%) (Pereira, 1988; Miranda et al., 2003).

The cellulose content in hairs and pappi was high with 55.2% and 46.8% of α-cellulose compared to wood with an average 45.4% for hardwood and 43.7% for softwood (Rowell et al., 2005) and to the following non-wood crops: reed (31.1–34.4%), wheat straw (38.2%), miscanthus (41.5%), kenaf (37.4–42.2%) (Ververis et al., 2004; Deniz et al., 2004; Shatalov and Pereira, 2002; Madakadze et al., 1999; Touzinsky, 1987).

The hemicelluloses to cellulose ratio of hairs and pappi is about 1:2 which is similar to other non-wood species used in the pulp industry. This ratio is significant for their pulping aptitude considering the importance of the hemicelluloses in sheet formation during papermaking.

3.5. *Pulping and pulp properties*

Well-delignified pulps could be obtained using hairs and pappi, or their mixture, as raw materials. For instance, with 20% active alkali pulps were obtained with yields of 59% and 48%, and kappa numbers of 8 and 11, respectively, from hairs and pappi (Table 3).

No data was found for the use of hairs and pappi of any species on pulping. For *Cynara*, the aptitude of stalks for pulping has been studied by several researchers using kraft (Gominho et al., 2001; Gominho and Pereira, 2006), soda-anthraquinone (Abrantes et al., 2007; Antunes et al., 2000) and organosolv methods (Ligero et al., 2007). A mixture of stalks and leaves was used by Benjelloun-Mlayah et al. (1997), and the influence of pith in stalks was studied by Gominho et al. (2001), Gominho and Pereira (2006). Overall these studies considered that stalks of *Cynara* could be used as a raw material for pulping. However in comparison to the reported yields of 43.5–51.3%, kappa number of 11–26 and 879 mL g^{-1} of viscosity obtained in stalks pulps (Gominho et al., 2001; Gominho and Pereira, 2006; Benjelloun-Mlayah et al., 1997; Abrantes et al., 2007), hairs and pappi show more favourable yields and delignification (Table 3).

The variation of the alkali charge influenced differently the pulping of hairs and pappi in direct relation to their chemical composition. In the case of hairs, well-delignified pulps were already obtained at the lower alkali charge of 15% (kappa number, 7) with substantially higher yield (63%), higher viscosity and lower HexA content. This shows that less severe pulping conditions can be used for delignification of hairs resulting into a lower cellulose depolymerization and hemicelluloses degradation. Pappi have more lignin than hairs, and therefore they were more difficult to delignify showing a higher kappa number of 38 at 15% alkali charge. The mixture of hairs and pappi had results in between of the individual components.

Table 4 – Biometric properties of unbleached kraft pulps made with hairs and pappi (20% alkali charge)

Average characteristics	Hairs	Pappi
Fibres (million/g)	39.7	60.0
Length (mm)		
Arithmetic mean	0.57	0.45
Length weighted in length	0.73	0.65
Width (μm)	19.3	16.3
Coarseness (mg/m)	0.043	0.033
Curl (%)	4.2	4.9
Broken ends (%)	20.4	15.9
Fine elements (% in length)	25.0	37.7

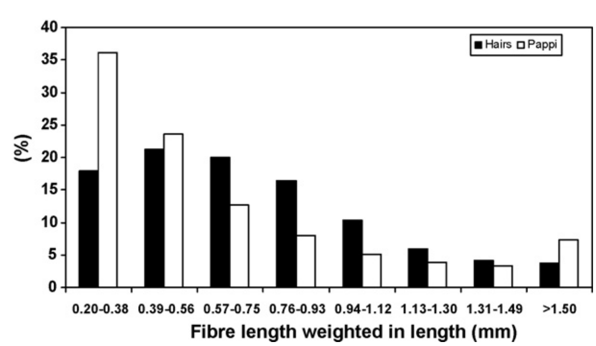

Fig. 8 – Class distribution of fibre length weighted in length for unbleached kraft pulps from hairs and pappi.

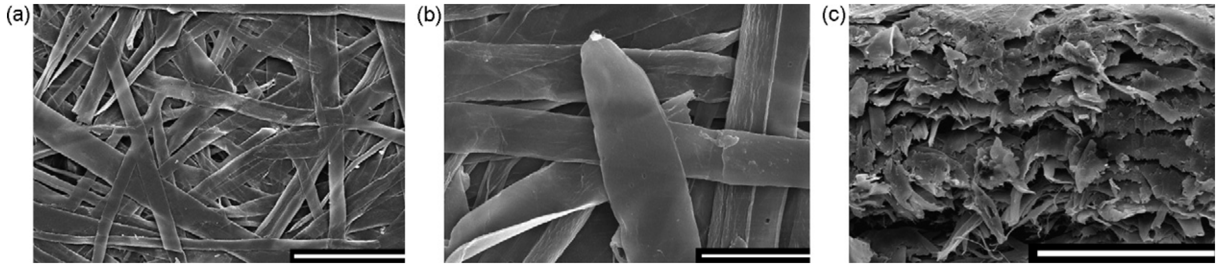

Fig. 9 – Scanning electron micrographs (SEM) of handsheet paper from unbeaten kraft pulp of *C. cardunculus*, from mixture of pappies and hairs. Notice the fibre collapsing and conforming at fibre–fibre intersections (a and b) and in transverse section of handsheet paper the bulk of the paper (c). (—) Scale bar, (a and c) 100 μm, and (b) 30 μm.

The dimensions of the fibre elements in the pulps of hairs and pappi (Table 4) are also related to their biometric characteristics in the original material (Table 1). Coarseness is low although somewhat higher in pulp from hairs than from pappi (0.04 mg m^{-1} vs. 0.03 mg m^{-1}) as a result of their higher wall thickness. It is noteworthy that these are very low values, compared for instance with 0.12 mg m^{-1} in pulp from *Cynara* stalks (Gominho et al., 2001), 0.08 mg m^{-1} in cordgrass pulps (Madakadze et al., 1999) and 0.105 mg m^{-1} for eucalypt pulps (Abrantes et al., 2007). Low fibre coarseness in pulps is an indication of flexible fibres that give good surface sheet formation because of an increased bond area and denser sheets, which are qualities valued for production of printing papers (Ramezani and Nazhad, 2004). Therefore, pulps from hairs and pappi present advantages in paper formation due to their low coarseness values.

The distribution of fibre length in the pulps of hairs and pappi is shown in Fig. 8. Pulps from hairs presented higher values (0.57 mm vs. 0.45 mm) and less fine elements (25.0% vs. 37.7%, Table 4) than pulps from pappi. These results show that pappi cells have higher breakability which may be the result of more brittle cell walls due to the higher lignin content. The comparison of mean fibre length between pulps and the original material shows that in pulps the fibres are 42% and 25% of the intact hairs and pappi, respectively. Although it is typical in the production of pulps to have a shortening of fibres to less than half of the length during raw material preparation and delignification and depending on processing conditions, it is again noticeable that pappi were more extensively broken than hairs.

The results show that there is scope to improve the pulping process of hairs and of pappi by taking into account their chemical composition and anatomical structure. Further studies should test less intensive cooking conditions and diffusion of delignification chemicals should be improved, *e.g.* by steam conditioning. In such cases high yields and well-delignified pulps should be obtained with little cellulose and xylan degradation.

Fig. 9 shows the network formed by a mixture of hairs and pappi fibres after kraft pulping. It can be noticed that there is an effective interfibrilar bonding due to the conformability of the fibres (Fig. 9a and b) and that these have no pits (Fig. 9b).

The physical and optical properties of the pulps are summarised in Table 5. The handsheets made with unrefined pulps from hairs and pappi (20% active alkali) showed promising paper making characteristics: 1.8 $cm^3\,g^{-1}$ bulk, 40 N m g^{-1} tensile and 3.6 kPa $m^2\,g^{-1}$ burst index for hairs and 1.4 $cm^3\,g^{-1}$ bulk, 42 N m g^{-1} tensile and 3.4 kPa $m^2\,g^{-1}$ burst index for pappi. The resistance of these pulps is similar to the values reported for unrefined eucalypt pulps by Wimmer et al. (2002): 57.09 N m g^{-1} for tensile index and 2.83 kPa $m^2\,g^{-1}$ for burst index, although other authors report higher values for eucalypt pulps (Carvalho et al., 2000). However the full potential

Table 5 – Physical and optical properties of unbleached kraft pulps made with hairs, pappi and mixture, obtained with different alkali charge

Pulp	Active alkali (% as Na_2O)	Bulk ($cm^3\,g^{-1}$)	Tensile index (N m g^{-1})	Elongation (%)	Burst index (kPa $m^2\,g^{-1}$)	Brightness R_{457} (%)	CIE$_{Colour}$		
							L^*	a^*	b^*
Hairs	15	2.18	38	1.27	3.46	40	76	3	11
	20	1.80	40	1.14	3.62	40	76	3	11
	25	1.84	32	1.19	2.88	44	78	2	11
Pappi	15	1.87	18	0.56	2.04	24	64	6	14
	20	1.37	42	0.81	3.40	32	70	4	13
	25	1.26	31	0.71	2.79	27	67	5	13
Mixture	15	1.91	36	0.86	3.15	25	64	6	12
	20	2.29	37	0.90	3.01	30	69	4	13
	25	1.74	57	1.10	2.93	36	74	3	11

of pulps in relation to resistance properties should only be assessed after refining.

The lower content of lignin was reflected in the optical properties of the pulps, especially in the pulp obtained with hairs that presented 41.3% for brightness and 77; 3; 11 in $L^* a^* b^*$, CIELAB colour space. The brightness values obtained are comparable to those reported for grasses unbleached kraft pulp (27.9–35–5%) by Madakadze et al. (1999).

4. Conclusions

In this work a detailed characterization of hairs and pappi of *C. cardunculus* capitula was made at cellular and chemical levels, which allows insight into these rather unknown plant materials.

It was also possible to demonstrate the feasibility to separate hairs and pappi as individual fractions from the capitula of *C. cardunculus* during the whole-plant fractionation. Although this fractioning might not be economically justified in most cases, these low density biomass components represent a non-negligible proportion of the whole plant (7% of the total biomass) and their utilization will strengthen the differentiated use of biomass fractions of the *Cynara* plant.

The anatomical and chemical features of hairs and pappi indicated their potential as fibre materials. They are homogeneous in terms of cell type structure, with long and slender fibres, and chemically they have low ash, extractives and lignin contents. Pulps could be produced using a conventional kraft process with high yields, low residual lignin, low coarseness values and adequate pulp properties for paper. The results also indicated that there is scope for improving pulp quality by optimising pulping conditions to this type of new raw materials. The differences between hairs and pappi may also be further exploited namely the lower lignin content of hairs and the higher slenderness and wall thickness of pappi fibres.

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