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Sudanese Dicots as Alternative Fiber Sources for Pulp and Papermaking

Sudanske dvosupnice kao alternativni izvor vlakana za proizvodnju celuloze i papira

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ABSTRACT • *The suitability of the stems from two Sudanese dicotyledonous annual plants, namely castor bean (Ricinus communis) and Leptadenia pyrotechnica (L. pyrotechnica) were investigated for pulp and papermaking. Chemical compositions, elemental analysis, fiber dimensions, paper physical properties and morphology revealed a relatively high α-cellulose content (46.2 and 44.3 %) and low lignin (19.7 and 21.7 %) in the stems of castor bean and L. pyrotechnica, respectively. The average fiber length of castor bean and L. pyrotechnica is 0.80 and 0.70 mm with fiber width of 16.30 μm and 18.20 μm, respectively, which makes them acceptable candidates. Soda-AQ pulping of castor bean stem led to a higher pulp yield of 43.2 % at kappa number 18.2 compared to 40.3 % at kappa 20.3 for L. pyrotechnica. This yield is less than that obtained for wood plants and similar to that observed for annual plants. Paper handsheets produced from castor bean showed better mechanical properties than L. pyrotechnica. SEM images indicated that the produced papers were quite homogeneous, compact, closely packed, and well assembled.*

Key words: *Sudanese annual plants, castor bean, Leptadenia pyrotechnica, pulp and paper*

SAŽETAK • *U radu je opisano istraživanje prikladnosti stabljika dviju sudanskih jednogodišnjih biljaka dvosupnica, ricinusa (Ricinus communis) i Leptadenia pirotechnica za dobivanje celulozu i proizvodnju papira. Kemijski sastav, elementarna analiza, dimenzije vlakana, fizikalna svojstva papira i morfologija pokazali su da je u stabljikama ricinusa i L. pyrotechnica relativno visok sadržaj α-celuloze (46,2 i 44,3 %) i nizak sadržaj lignina (19,7 i 21,7 %). Prosječna duljina vlakana ricinusa i L. pirotechnice iznosi 0,80 i 0,70 mm, a širina vlakana im je od 16,30 μm i 18,20 μm, što ih čini prihvatljivima za proizvodnju celuloze i papira. Sulfatnim je postupkom od stabljika ricinusa dobiven veći prinos celuloze (43,2 %) pri kappa broju 18,2 u usporedbi s prinosom celuloze (40,3 %) pri kappa broju 20,3, koji je dobiven pri proizvodnji celuloze od stabljika L. pyrotechnice. Dobiveni prinos manji je od prinosa koji se postiže proizvodnjom celuloze od drvenastih biljaka i jednak je prinosu koji se ostvaruje proizvodnjom celuloze od jednogodišnjih biljaka. Listovi papira proizvedeni od ricinusa pokazali su bolja mehanička svojstva od papira proizvedenoga od stabljika L. pyrotechnice. Slike dobivene skenirajućim elektronskim mikroskopom (SEM) pokazuju da su proizvedeni papiri bili posve homogeni, kompaktni, zbijeni i dobro sastavljeni.*

Ključne riječi: *sudanske jednogodišnje biljke, ricinus, Leptadenia pirotechnica, celuloza i papir*

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1 INTRODUCTION
1. UVOD

The annual world consumption of paper and paperboard is growing 2.1 % and it will reach an estimated 490 million tonnes by 2020 (Dutt *et al.*, 2008). However, ~ 4 billion trees are cut across the globe for pulp and paper manufacturing often raising ecological and climatic issues (Kamoga *et al.*, 2016) and leading to a demand for alternative pulp and papermaking raw materials. In some countries, pulp and paper industries have been facing some challenges due to the shortages of forest resources (Ferhi *et al.*, 2014b). However, non-wood species or annual plants and agriculture residues are likely the best candidates as alternative sources of cellulosic fibers (Kamoga *et al.*, 2016). Furthermore, as these cellulosic fiber materials have identical properties, they could be used as wood fibers for pulp and papermaking (Mechi *et al.*, 2016), textile, boards, and green composite materials (Mansouri *et al.*, 2012).

Many studies have been carried out to find new alternative lignocellulosic materials. Some of these studies have used tobacco (Shakhes *et al.*, 2011a), rice straw, sugarcane bagasse and cotton stalk (Adel *et al.*, 2016), pineapple (Wutisatwongkul *et al.*, 2016) millet stalks and date palm leaves (Saeed *et al.*, 2017b), *J. procera* (Nasser *et al.*, 2015), sunflower stalk (Barbash *et al.*, 2016) *gracilaria* and *eucheuma* (Machmud *et al.*, 2013), bitter orange (Tutuş *et al.*, 2016), *ipomea carnea* and *cannabis sativa* (Dutt *et al.*, 2008), *c. orientalis* and *c. tataria* (Tutus *et al., 2010),* wheat straws (Espinosa *et al.*, 2016) and broad bean, bell pepper and asparagus (Gonzalo *et al.*, 2017). However, there is no previous study on the application of castor bean (*Ricinus communis*) and *Leptadenia pyrotechnica* (*L. pyrotechnica*) stems for pulp and paper production.

Castor bean (*Ricinus communis*) is a tropical annual and fast-growing plant. It belongs to the Euphorbiaceae family that is grown across the world (de Assis Junior *et al.*, 2011; Udoh and Abu, 2016). Vasconcelos *et al.* (2014) investigated the physical and chemical properties of fibrous residues of castor bean, and they found that castor bean stems consist of 50.46 % of cellulose, 29.64 % of hemicelluloses, 17.34 % of lignin and 1.48 % of ash.

Leptadenia pyrotechnica (*L. pyrotechnica*) is an important multipurpose non-wood species of tropical and sub-tropical arid regions. Mojumder *et al.* (2001) investigated the chemical composition of *L. pyrotechnica,* and determined that it consists of 4.93 % of lignin, 75.26 % of α-cellulose and 2.77 % of ash. However, the results reveal that castor and *L. pyrotechnica* residues are a good alternative for the pulp and paper industries since they are plants of high cellulose content. This work investigated the chemical components and fiber properties of castor bean (*Ricinus communis*) and *L. pyrotechnica* stems after soda-AQ pulping.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

Castor bean (*Ricinus communis*) and *L. pyrotechnica* stems were collected from North Kordofan State, west of Sudan (latitudes 12˚ 30 North and longitudes 29˚ 30 East) in March 2017. Materials were randomly selected according to TAPPI standard methods. A part of the material was chipped to 1.5×1.5×2 cm and ground to powder with a mesh size of 40-60 in a laboratory by using a Wiley mill grinder for determining their chemical components. Hydrogen peroxide (H_2O_2), sodium hydroxide (NaOH), sodium oxide (Na_2O), acetic acid and anthraquinone (AQ) were acquired from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China).

2.2 Methods
2.2. Metode

2.2.1 Chemical composition
2.2.1. Kemijski sastav

Materials were tested for extractive substances in different liquids according to common TAPPI standards: cold and hot water T207 cm-99, 1 % sodium hydroxide solution T212 om-98 and alcohol-toluene T204 cm-97 (López *et al.*, 2011). The amounts of lignin and ash contents were assessed according to T222 cm-99 and T211 om-02 (Yuan *et al.*, 2016), while, holocellulose contents were determined according to Wise method (Wise, 1946).

2.2.2 Morphological characteristics
2.2.2. Morfološka obilježja

For the measurements of fiber dimensions, samples were macerated in a mixture of 30 % hydrogen peroxide and acetic acid (1:1). Fiber length, width and kinked and curled index were measured with FQA device (OpTest, Canada), model LDA-02 according to T271 om-07. Lumen diameter and wall thickness were measured by Leica DMLB (Leica Microsystems GmbH, Wetzlar, Germany) connected to a video camera Leica DFC490 (Leica Microsystems GmbH, Wetzlar, Germany) at 400× magnifications. Fibers morphology and elemental composition (Carbon (C), Oxygen (O), Aluminium (Al), Nitrogen (N), silicon (Si), magnesium (Mg), and Calcium (Ca)) were determined using a scanning electron microscope (SEM-EDS) by (OCTANE 9.88/1114658 AMETEK® (USA)). Before the test, the paper specimens were coated with gold-palladium in a Sputtergerät SCD 005 sputter coater (England). A sputter current of 60 mA, sputter time 90 s, and film thickness of 20 nm to 25 nm were chosen as the coating conditions**.**

2.2.3 Pulping processing and testing
2.2.3. Proizvodnja i ispitivanje celuloze

Soda-AQ pulping was carried out in a rotary digester with electrical heating with four individual 2 L vessels. The charge was 100 g of oven dried (o.d.) material. The active alkali (NaOH) was constant 20 % on oven dried (o.d.), while AQ was 0.1 %. The cooking was continued for 120 min at the maximum temperature of 170 °C. At the end of pulping, pressure was relieved to atmospheric pressure; pulp was taken out from the digester, disintegrated and washed by continuous water flow. Pulp was screened on a 0.15 mm laboratory slot vibratory screener and the yield was determined gravimetrically. Pulp yield was determined as dry matter obtained on the basis of o.d. raw material. The pulp was subjected to mechanical beating using the PFI mill according to T248 sp-00, kappa number was determined according to T 236 cm-85 (Sarker *et al.*, 2017), while pulp viscosity was determined according to T 230 om-04 (Feria *et al.*, 2012). Moreover, a totally chlorine-free bleaching was carried out. According to Moral *et al.* (2016) 10 % pulp concentration is bleached in two stages by 4 % hydrogen peroxide (H_2O_2) in 0.2 % sodium hydroxide (NaOH) at 80 °C for 2 h of each stage. The pulp was washed properly until neutralization in every stage.

2.2.4 Papermaking and testing
2.2.4. Proizvodnja i ispitivanje papira

All pulps were beaten to 5000 revolution at 35°SR in a PFI mill T248 sp-00, and papers of 60 grams were made according to the T205sp -95 in a laboratory handsheet machine (PTI laboratory Equipment, Vorchdorf, Austria). The physical properties of the samples were determined according to common standards: burst index T403 om-10, tear index T414 om- 04 and tensile index T494 om-06 (Rudi *et al.*, 2016). The brightness and opacity were determined according to T525 om-92 and T425 om-96 (Tutuş *et al.*, 2016), respectively.

2.2.5 Calculations
2.2.5. Proračuni

The following parameters were calculated using the following formulas (Albert *et al.*, 2011; Pirralho *et al.*, 2014).

Slenderness ratio = fiber length ÷ fiber diameter (1)

Flexibility coefficient = (fiber lumen diameter ÷ fiber diameter)×100 (2)

Runkel ratio = (2×*fiber cell wall thickness*) ÷ *lumen diameter* (3)

Rigidity coefficient = (*cell wall thickness*×100) ÷ *fiber diameter* (4)

Felting power = fiber length ÷ fiber width (5)

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Chemical composition and extractives of castor bean and *L. pyrotechnica* in comparison with some common representatives of lignocellulosic annual plants are shown in Table 1. Castor bean and *L. pyrotechnica* show a relatively high cellulose content of 46.20 % and 44.30 %, respectively, compared to *prunus amygdalus* (Mechi *et al.*, 2017), *A. armatus* (Ferhi *et al.*, 2014a) vine stems (Mansouri *et al.*, 2012) and bagasse (Saeed *et al.*, 2017a), but lower than that of *I. tinctoria* (Comlekcioglu *et al.*, 2016), *cactus* (Mannai *et al.*, 2017) and similar to that of palm leaves (Saeed *et al.*, 2017b). On the other hand, *L. pyrotechnica* show a higher amount of hemicellulose (22.15 %) compared to castor bean value of 20.50 %. This result may explain the higher solubility of *L. pyrotechnica* in alkali solution (1 % NaOH), because it is adequate to dissolve the fragile branched components of the cellulosic chain, such as hemicelluloses (Mattos *et al.*, 2016). However, these results are not in line with vine stems (Mansouri *et al.*, 2012) and *A. armatus* (Ferhi *et al.*, 2014a). Lignin content was found to be higher in *L. pyrotechnica* (21.70 %), while it was 19.70 % in castor bean. However, these results are comparable with those of the listed annual plants and hardwoods (17-26 %) and lower than those of softwoods (25-32 %) (Ates *et al.*, 2008). Castor bean and *L. pyrotechnica* showed almost the same ash contents, 2.60 and 2.40 %, respectively, which is the range (1-3 %) for hardwoods and less than those of the materials listed in Table 1. However, high ash content is undesirable, as trace elements interfere with bleaching chemicals and alkali earth metals in the pulp will cause problems in chemical recovery. Moreover, high ash content may lead to damage in wood during processing (Dutt *et al.*, 2009, López *et al.*, 2012).

Table 1 Chemical composition of castor bean, *L. pyrotechnica* and some other annual plants
Tablica 1. Kemijski sastav ricinusa, *L. pyrotechnica* i nekoliko drugih jednogodišnjih biljaka

Annual plants *Jednogodišnje biljke*	**Chemical compositions** *Kemijski sastav*				**Solubility** / *Topljivost*				**Literature** *Literatura*
	Cellulose, % *Celuloza, %*	**Hemicellulose, %** *Hemiceluloza, %*	**Lignin, %** *Lignin, %*	**Ash, %** *Pepeo, %*	**Hot water, %** *Vruća voda, %*	**Cold water, %** *Hladna voda, %*	**Alcohol-toluene, %** *Alkohol-toluen, %*	**%1 NaOH, %**	
Castor bean / *ricinus*	46.2	20.5	19.7	2.6	10.5	9.4	4.8	18.6	Current Study
L. pyrotechnica	44.3	22.1	21.7	2.4	12.1	11.5	5.6	20.9	Current Study
Prunus amygdalus	40.7	20.0	19.2	3.6	12.3	11.3	5.0	28.7	Mechi *et al.* (2016),
I. tinctoria	48.5	18.6	23.9	4.9	17.2	13.6	4.4	43.8	Comlekcioglu *et al.* (2016)
A. armatus	41.5	29.3	19.0	2.8	15.6	12.2	4.0	39.0	Ferhi *et al.* (2014)
Vine stems / *stabljike vinove loze*	35.0	30.4	28.1	3.9	13.9	8.2	11.3	37.8	Mansouri *et al.* (2012)

The extractives also contain extraneous ingredients, such as inorganic compounds, tannins, gums, sugars and coloring in the lignocellulosic plants (Dutt *et al.*, 2009). The amount of extractives of castor bean and *L. pyrotechnica* in hot and cold water is relatively high compared to hardwood (2-8 %) (Ferhi *et al.*, 2014b), but less than that of several annual plants such as *I. Tinctoria* (Comlekcioglu *et al.*, 2016) and *A. armatus* (Mechi *et al.*, 2016). However, it is comparable to other annual plants such as *Prunus amygdalus* (Mechi *et al.*, 2016). The extractives in 1% NaOH are 18.60 % and 20.90 % for castor bean and *L. pyrotechnica*, respectively, lower than those for annual plants listed in Table 1. Castor bean showed similar alcohol-toluene extractives to *I. tinctoria* (Comlekcioglu *et al.*, 2016) and *A. armatus* (Ferhi *et al.*, 2014a). Among the listed data, castor bean showed the least hot and cold water and 1% NaOH extractives. However, the lower solubility resulted in high pulp yield and less chemical consumption in pulping and bleaching processing (Comlekcioglu *et al.*, 2016). The large cellulose contents and lower lignin content enhance the investigation of such annual plants as they have a high potential for use as fibers for pulp and paper production.

The basic parameters that affected the physical properties of the paper are fiber dimensions including fiber length, fiber width and fiber cell wall thickness (Albert *et al.*, 2011). The average fiber length of castor bean and *L. pyrotechnica* are 0.80 and 0.70 mm, respectively. They are less than that of softwood (2.7-4.6 mm) and in the range of hardwood (0.7-1.6 mm) (Comlekcioglu *et al.*, 2016) and they are considered as short fiber species (Jahan *et al.*, 2008). These fibers were similar to *A. armatus* (Ferhi *et al.*, 2014a) and longer than vine stems (Mansouri *et al.*, 2012) and *prunus amygdalus* (Mechi *et al.*, 2017). It is expected that paper handsheets produced from *L. pyrotechnica* pulp with relatively short fibers may give a smoother paper than that of castor bean because short fibers will fill the voids in the paper sheet, while the paper handsheet formed from castor bean pulps would result in higher strength properties and less fine sheet structure (Nasser *et al.*, 2015). Moreover, the higher the fiber length, the better will be the tearing resistance of paper (Agnihotri *et al.*, 2010). Therefore, paper made from these materials showed good mechanical strength and can be suitable for producing writing and printing papers as well as wrapping and packaging paperboard. On the other hand, *L. pyrotechnica* showed a thicker fiber with the width of 18.20 μm compared to the 16.30 μm of castor bean. However, the observed fibers are thinner than those of *A. armatus* (Ferhi *et al.*, 2014a), and those of *Prunus amygdalus* (Mechi *et al.*, 2017) are thicker than those of *I. tinctoria* (Comlekcioglu *et al.*, 2016). Cell wall thickness of castor bean (6.40 μm) is lower compared to that of *L. pyrotechnica* (7.00 μm) and *I. tinctoria* (Comlekcioglu *et al.*, 2016), However, longer fiber with lower cell wall thickness showed significant advantages in physical properties of the produced paper (Tutus *et al.*, 2010).

Values derived from the fiber dimensions, important for determining the suitability of the material for paper production, are listed in Table 2. Castor bean showed a relatively high felting power of 49 compared to 38.46 for *L. pyrotechnica*. However, these values are similar to those of hardwood (40-55) and lower than those of softwood (60-80) (Comlekcioglu *et al.*, 2016). If the felting power of a fibrous material is lower than 70, it is suitable for the pulp and paper industry (Tutus *et al.*, 2010). The values of the rigidity coefficient negatively influence tensile, tear, burst and double fold resistance of the paper (Anoop *et al.*, 2014). Both castor bean and *L. pyrotechnica* fibers showed higher rigidity coefficients of 38.04 and 38.46, respectively, compared to 30.44 of *cymodocea serrulata* (Syed *et al.*, 2016) and 26.40 of *I. tinctoria* (Comlekcioglu *et al.*, 2016). Moreover, it was reported that, if the slenderness ratio of fibrous material is less than 70 and higher than 33, the lignocellulosic material is considered to be good for pulp and paper production (Shakhes *et al.*, 2011a; Syed *et al.*, 2016). Both castor bean and *L. pyrotechnica* showed slenderness ratios of 49.00 and 38.46, respectively. Castor bean had a relatively high flexibility coefficient of 63.19 compared to 62.64 and 47.2 of *L. pyrotechnica* and *I. tinctoria*, respectively. Previous

Table 2 Fiber properties of castor bean, *L. pyrotechnica* and some annual plants
Tablica 2. Obilježja vlakanaca ricinusa, *L. pyrotechnica* i nekoliko drugih jednogodišnjih biljaka

Material *Materijal*	**Castor Bean** *Ricinus*	***L. pyrotechnica***	***Prunus amygdalus***	***I. tinctoria***	***A. armatus***	**Vine stems** *Stabljike vinove loze*
Fiber length, mm / *Duljina vlakana,* mm	0.80±0.05	0.70±0.06	0.48	0.60	0.81	0.59
Fiber width, μm / Širina *vlakana,* μm	16.30±1.4	18.20±2.2	21.00	15.70	20.60	24.60
Lumen diameter, μm / *Promjer lumena,* μm	10.30±1.5	11.40±1.3	N/A	8.80	N/A	N/A
Cell wall thickness, μm *Debljina stanične stijenke,* μm	6.20±1.1	7.00±2.1	N/A	8.60	N/A	N/A
Felting power / *Snaga filcanja*	49.00	38.46	N/A	39.7	N/A	N/A
Rigidity coefficient / *Koeficijent krutosti*	38.04	38.46	N/A	26.4	N/A	N/A
Slenderness ratio / *Vitkost*	49.00	38.46	N/A	N/A	N/A	N/A
Flexibility coefficient / *Omjer fleksibilnosti*	63.19	62.64	N/A	47.2	N/A	N/A
Runkel ratio / *Runkelov omjer*	1.20	1.23	N/A	1.1	N/A	N/A
Literature / *Literatura*	Current Study	Current Study	1	2	3	4

[1)] Mechi *et al.* (2016), [2)] Comlekcioglu *et al.* (2016), [3)] Ferhi *et al.* (2014), [4)] Mansouri *et al.* (2012), N/A: Not available

Table 3 Properties of pulp from castor bean, *L. pyrotechnica* and some annual plants
Tablica 3. Svojstva celuloze proizvedene od ricinusa, *L. pyrotechnica* i nekoliko drugih jednogodišnjih biljaka

Material *Materijal*	**Total yield** *Ukupni prinos* %	**Screened yield** *Prinos prosijavanja* %	**Kappa number** *Kapa broj*	**Viscosity** *Viskoznost* mPa·s	**Literature** *Literatura*
Castor bean / *ricinus*	43.20	42.10	18.20	6.46	Current study
L. pyrotechnica	40.30	38.80	20.30	5.12	Current study
Prunus amygdalus	45.2	42.94	N/A	5.28	1
I. tinctoria	26.09	25.37	N/A	N/A	2
A. armatus	32.00	N/A	15.20	N/A	3
Vine stems / *stabljike vinove loze*	45.00	N/A	25.50	8.50	4

[1)] Mechi *et al.* (2016), [2)] Comlekcioglu *et al.* (2016), [3)] Ferhi *et al.* (2014), [4)] Mansouri *et al.* (2012), N/A: Not available

studies stated that higher Runkel ratio fibers are stiffer, less flexible, and form bulkier paper of lower fiber to fiber bond than lower Runkel ratio fibers. High average fiber length and low Runkel ratio result in good pulp strength properties (Shakhes *et al.*, 2011b). Both castor bean and *L. pyrotechnica* showed high Runkel ratio of 1.20 and 1.23 compared to that of 1.1 of *I. tinctoria*.

The physical properties of the pulp obtained from the studied materials are summarized in Table 3. The results reveal that castor bean shows higher total pulp yield of 43.20 % with an acceptable kappa number of 18.20 compared to that of 40.30 % with kappa number of 20.30 of *L. pyrotechnica*. The low pulp yield of *L. pyrotechnica* is attributed to a relatively high content of extractives, especially in hot and cold water compared to that of castor bean (Ferhi *et al.*, 2014a) as well as low cellulose content (Gonzalo *et al.*, 2017). These values are higher than those of *A. armatus* (Ferhi *et al.*, 2014a) and *I. tinctoria* (Comlekcioglu *et al.*, 2016) and lower than those of vine stems (Mansouri *et al.*, 2012) and *A. armatus* (Ferhi *et al.*, 2014a). However, the differences in kappa number could be attributed to differences in lignin content in the materials. The value of viscosity is an indicator of fiber length and degree of polymerization (Kamoga *et al.*, 2016). However, caster bean showed higher viscosity (6.46 mP·s) compared to that of *L. pyrotechnica* (5.12 mP·s) and *prunus amygdalus* (5.28 mP·s) (Mechi *et al.*, 2017) but lower than that of vine stems (8.50 m mP·s) (Mansouri *et al.*, 2012).

3.1 Handsheet physical properties
3.1. Fizikalna svojstva listova papira

The physical and optical properties of handmade paper sheets produced from soda-AQ pulps of the studied annual plants are listed in Table 4. The paper handsheets produced from these species had good formation with basis weights of 63 and 65 g/m^2 and thicknesses of 115 and 117 μm for castor bean and *L. pyrotechnica*, respectively. Hand sheet formed from castor bean showed higher values of tensile, tear and burst index compared to those of paper produced from *L. pyrotechnica* and *Prunus amygdalus* (Mechi *et al.*, 2016). Castor bean and *L. pyrotechnica* papers showed a lower tearing index than that of *A. armatus* (Ferhi *et al.*, 2014a) and vine stems (Mansouri *et al.*, 2012). Remarkably high brightness of 75.20 and 69.20 % was achieved for caster bean and *L. pyrotechnica* with a preliminary bleaching sequence. This high brightness predicts good bleachability of the pulps from these two annual plants, meaning that lower chemical charges are required.

3.2 Morphological analysis of papers obtained from castor bean and *L. pyrotechnica*
3.2. Morfološka analiza papira proizvedenoga od stabljika ricinusa i *L. pyrotechnica*

Paper handsheets were observed by SEM and SEM-EDS analysis, as presented in Fig. 1. Handsheets were magnified at 500 x. SEM images indicated that the produced papers are quite homogeneous, compact,

Table 4 Physical properties of papers from castor bean, *L. pyrotechnica* and several annual plants
Tablica 4. Fizikalna svojstva papira proizvedenoga od ricinusa, *L. pyrotechnica* i nekoliko drugih jednogodišnjih biljaka

Properties *Svojstvo*	**Castor bean** *Ricinus*	***L. pyrotechnica***	***Prunus amygdalus***	***I. tinctoria***	***A. armatus***	**Vine stems** *Stabljike vinove loze*
Thickness, μm / *debljina,* μm	115±4	117±5	110±8	N/A	144	N/A
Basis weight, g/m^2 *osnovna jedinična masa,* g/m^2	63±0.5	65±0.2	64±0.8	N/A	65.20	69.50
Tensile index, N·m/g *vlačni indeks,* N·m/g	4.5±0.15	3.10±0.20	4.08±0.16	3.33	3.37	N/A
Tearing Index, mN·m^2/g *indeks cijepanja,* mN·m^2/g	2.24±0.26	2.01±0.54	2.19±0.27	1.03	3.57	5.74
Bursting Index, kPa·m^2/g *Indeks pucanja, kPa·m^2/g*	1.84±0.03	1.45±0.02	1.38±0.05	2.17	1.62	1.72
Opacity, % / *neprozirnost,* %	99.20±5.2	98.00±15	99.84±8.5	99.65	N/A	
Brightness, % / *sjajnost,* %	75.20±3.1	69.20±2.4	N/A	25.22	N/A	70.00
Literature / *literatura*	Current Study	Current Study	1	2	3	4

[1)] Mechi *et al.* (2016), [2)] Comlekcioglu *et al.* (2016), [3)] Ferhi *et al.* (2014), [4)] Mansouri *et al.* (2012), N/A: Not available

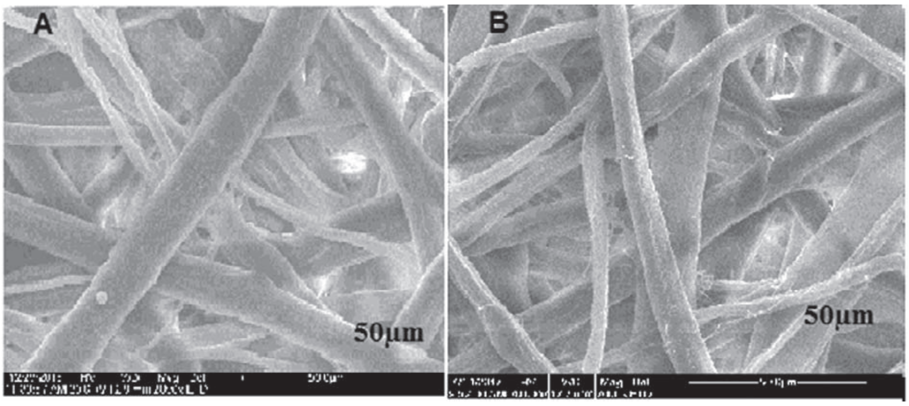

Figure 1 Scanning electron microscopy of (A) *L. pyrotechnica*, (B) castor bean
Slika 1. Slike dobivene skenirajućim elektronskim mikroskopom (A) *L. pyrotechnica*, (B) ricinus

Table 5 Elemental analysis of castor bean and *L. pyrotechnica*
Tablica 5. Elementarna analiza ricinusa i *L. pyrotechnica*

Material / *Materijal*	**C (%)**	**O (%)**	**N (%)**	**Mg (%)**	**Al (%)**	**Si (%)**	**Ca (%)**
Castor bean / *ricinus*	49.49	43.17	0.90	0.02	0.12	0.07	0.13
L. pyrotechnica	49.93	42.24	1.19	0.05	0.04	0.10	0.08

with a closely packed arrangement and good assembling. Well-arranged and compact fibers will lead to smooth surface and good structure of the produced paper, and thus higher mechanical properties could be obtained (Saeed *et al.*, 2017a).

3.3 Elemental analysis of castor bean and *L. pyrotechnica*
3.3. Elementarna analiza ricinusa i *L. pyrotechnica*

The detailed elemental analysis of castor bean and *L. pyrotechnica* is listed in Table 5. It clearly shows that ash is mainly composed of O, C, Mg, N, Al, Ca and Si atoms. Silicon is negligible in both castor bean and *L. pyrotechnica* (0.07 % and 0.10 %). Similar results were observed for *gracilaria* and *eucheuma* (Machmud *et al.*, 2013). High silicon-containing lignocellulosic materials are generally not preferable for pulping because they contribute to system issues in cooking and washing (Ferhi *et al.*, 2014a).

4 CONCLUSIONS
4. ZAKLJUČAK

The chemical composition of castor bean and *L. pyrotechnica* stems revealed a sufficient level of polysaccharides and reduced lignin contents compared to other annual plants, which explains their suitability as new lignocellulosic candidates for pulp and paper making. The pulp and paper of castor bean were identified with acceptable yield, medium viscosity, high bleachability, long and narrow fibers compared to *L. pyrotechnica.* Values derived from fiber dimensions, such as felting power, rigidity coefficient and slenderness ratio, determined the suitability of the material for paper production. SEM images indicated that the produced papers are quite homogeneous, compact, with a closely packed arrangement and good assembling, thus providing good mechanical properties of the produced papers.

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