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Research Article

CHARACTERISATION AND EVALUATION OF PULP AND PAPER FROM SUDANESE WOOD SPECIES FOR PULP AND PAPER MAKING

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ABSTRACT

Chemical composition, fibre dimensions and morphology, elemental analysis and paper characterisation of *Acacia seyal* (*A. seyal*), *Ziziphus spina-christi* (*Z. christi*) and *Tamarindus indica* (*T. indica*) were investigated. Kraft and soda-anthraquinone (so-AQ) pulping as sulfur-free processes were applied. It was found that, the cellulose content of *Z. Christi, A. seyal* and *T. indica* 48.50%, 46.00% and 44.60%, respectively, which is in the range of hardwood. Klason lignin was found to be highest in *T. indica* 22.20% while it was 20.82% and 19.70% in *A.* seyal and *T. indica*, respectively. The solubility with 1% NaOH was 24.40%, 22.00% and 21.40% for *T. indica, A. seyal* and *Z. Christi,* respectively. Moreover, *Z. Christi* showed highest pulp yield (46.60% and 45.30%) with viscosity of (650 ml/g and 590 ml/g) and kappa number of (21.50 and 19.80) for kraft and soda-AQ pulping, respectively. *T. indica* reached the brightness of 75.30% and 71.72% for soda-AQ and kraft pulps, while it was (69.20% and 67.42%) and (75.30% and 71.72%) for soda-AQ and kraft pulps of *A. seyal* and *Z. Christi*, respectively. *Z. christi* showed slightly high average fibre length 0.88 mm compared to 0.77 mm and 0.76 mm of *A.seyal* and *T. indica*, respectively. The studied materials have a potential application in pulp and paper making due to the good mechanical properties (tensile, tear, burst and fold).

INTRODUCTION

The demand for paper and paperboard products in Sudan has grown fast with endless development. Therefore there are many important Sudanese wood species which could be considered for their suitability as raw material for pulp and paper production. The usage of species as raw material for pulp, paper and cellulose based industries are minimizing everyday and the wood imports are exhaust country's foreign currency. In Sudan different wood species most of which could be a good source of pulp and paper production (O. Elzaki, Otuk, & Khider, 2012) however, only few of these materials have been studied as raw material for pulp and paper production such as eucalypts (P Khristova, Kordsachia, Patt, & Dafaalla, 2006), bamboo (Palmina Khristova, Kordaschia, Patt, & Karar, 2006) cajanus cajan (O. T. Elzaki, Khider, & Omer, 2012), albizia lebbeck (O. T. Elzaki, Khider, Omer, & Shomeina, 2012), acacia nilotica (P. Khristova & Karar, 1999) and *typha domingensis* (Khider, Omer, & Taha, 2012).

This work aims to investigate the application of Sudanese wood species, as a source of fibres for pulp and paper manufacturing, namely: *Acacia seyal* (Talha), *Ziziphus spina-christi* (Sidr) and *Tamarindus indica* L. (Aradeib).

A. seyal is blong to the family of Mimosaceae a tree 3-17 m high (Lourenço, Baptista, Gominho, & Pereira, 2008). It is one of the most common trees in the savannah and often occurs as a pure forest over quite large areas of country. (El Amin, 1990; Elbadawi, Osman, Paridah, Nasroun, & Kantiner, 2015). In Sudan, *A. seyal* is known as (Taleh), it is an important multipurpose tree in the savanna zone of Kordofan states. (Fadl, 2012). *A. seyal* is found on dark cracking clays on higher

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inclines of rivers and valleys on the hard clay plains of Central Sudan and on clay of seasonally wet coasts (Mohamed & Röhle, 2011; Mohammed, 2015) *A. seyal* (Taleh) in is the tree number one in Sudan whose promising candidate has never been fully investigate (Mohamed & Röhle, 2011).

Ziziphus spina-christi commonly known as Christ's thorn or Jerusalem-thorn in English and (Sidr, Nabag or Nabak), it is belongs to the genus zizyphs in Rhamnaceae family. It is long-lived massive green tree with strong branches with a height of 20 m,, native to the warm-temperate and subtropical regions (Abu-Raghif, Sahib, & Hanoon, 2015; Alhakmani, Khan, & Ahmad, 2014) *Ziziphus spina-christi* is wild grown in Sudan, it has several physiological and morphological characteristics that assure its ability to adapt to arid environment (Nkafamiya, Shagal, & Haruna, 2013; Osman & Asif Ahmed, 2009).

Tamarindus indica is know (Aradeib) in Sudan, it belongs to family of *Caesalpiniaceae. Tamarindus indica* is evergreen tree that can reach 24 m high and 120 cm in diameter in favourable ecological condition, it needs dry climate so that the region it is commonly seen extends Africa to Senegal in west, Sudan and Ethiopia in east, Mozambique and Madagascar in south. In Sudan, *T. indica* is located in the central states and extends to the South (El Amin, 1990; Kuru, 2014).

Pulping with kraft and soda anthraquinone (So-AQ) processes of some of the most successfully introduced pulping methods for lignocellulosic material.(P Khristova *et al*., 2006). however, kraft pulping is effective process to transfer the lignocellulosic material into pulp fibres in world. The advantages of the kraft process is the kraft recovery furnace that is high efficient at recovering the pulping chemicals of sodium components. On the other hand, soda-AQ pulping is substitutional process for cooking lignocellulosic material that has the possibility to offer many environmental and economic advantages as compared to the kraft process that is distinguished by high concentrations of hurtful sulfur-containing compounds in the cooking liquor. (Francisco López, Pérez, Zamudio, De Alva, & García, 2012; Nicholson, Leavitt, Stromberg, & Francis, 2017).

To the best of our knowledge, these Sudanese wood species have never been studied for pulp and papermaking. Therefore, the present article reports data about their chemical composition, fibres morphology. Moreover, the kraft and soda-AQ pulping with totally chlorine free bleaching and good physical properties of the hand sheet papers produced from these materials were also evaluated.

Experimental

MATERIALS

A. seyal (Talha), *Z. christi* (Sidr) and *T. indica* (Aradeib) were collected from north kordofan state, west of Sudan (latitudes 12˚ 30 North and longitudes 29˚ 30 East) in January 2016, all the materials with the age in range of 6-8 years old, the species were randomly selected according to TAPPI standard methods. A part of the materials were chipped to 1.5× 1.5 × 2 cm ground to powder with a mesh size of 40-60 using 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 purchased from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China).

METHODS

Chemical compostion

Materials were tested for extractive substances in different liquids according to common TAPPI standards include; cold and hot water T207 cm-99, 1% sodium hydroxide solution T212 om-98 and benzene- ethanol T204 cm-97 (F López *et al*., 2011). The amounts of lignin and ash contents were assessed according to T222cm-99 and T211om-02(Yuan, Kapu, Beatson, Chang, & Martinez, 2016), while, holocellulose contents were determined according to Wise method (Wise, 1946).

The morphological characteristics

For the measurements of fibre's dimensions, samples were macerated in a mixture of 30% hydrogen peroxide and acetic acid (1:1). Fibre length, width and kinked and curled indices 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. The derived values were calculated according the following formula (Albert, Padhiar, & Gandhi, 2011; Pirralho *et al*., 2014)

$$\text{Slenderness ratio} = \text{Fibre length} \div \text{fibre diamete} \quad 1$$

$$\text{flexibility coefficient} = (\text{fiber lumen diameter} \div \text{fiber diameter}) \times 100 \quad 2$$

$$\text{Runkel ratio} = (2 \times \text{fibre cell wall thickness}) \div \text{lumen diameter} \quad 3$$

$$\text{Rigidity coefficient} = (\text{cell wall thickness} \times 100) \div \text{fiber diameter} \quad 4$$

Whereas the fibres morphology and the elemental composition (carbon (C), oxygen (O), aluminium (Al), fluorine (F), silicon (Si), magnesium (Mg), and sodium (Na)) were determined using a scanning electron microscope (SEM-EDS) by (OCTANE 9.88/1114658 AMETEK® (USA)). Before the test, the paper specimens were gold 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 20 nm to 25 nm were chosen as the coating conditions.

Pulping Processing and Testing

Both conventional kraft and soda-AQ pulping processes were carried out in a rotary digester with electrical heating with four individual 2 L vessels, according to (Ramzi Khiari, Mauret, Belgacem, & M'henni, 2010) and (M Sarwar Jahan, Chowdhury, & Ni, 2010), respectively. The material charge was 100 g of oven dried (o.d.). The active alkali Na_2O was constant 20 % on oven dried (o.d.). Sulphidity was 25% (for kraft process) (Yuan *et al*., 2016), while AQ was 0.1 for soda-AQ pulping process(Das, Nakagawa-izumi, & Ohi, 2016). The material in the liquor ratio of 1:5. The cooking was continued for 120 min at the maximum temperature 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 flow of water. Pulp was screened on a 0.15 mm laboratory slot screen vibratory screener yield 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 the Canadian freeness standard (CFS) and pulp viscosity were determined according to T227 om-99 and T 230 om-04 (Feria, García, Díaz, Fernández, & López, 2012), respectively. Moreover, A totally chlorine free bleaching was carried out in two stages at 10% pulp concentration by hydrogen peroxide (H_2O_2) at 4% in sodium hydroxide (NaOH) at 80°C for 2 h of each stage. The pulp was washed properly until neutralization in every stage. The experimental route of the present work is shown in Fig.1.

Papers making and testing

All pulps were beaten to 5000 revolution at 35°SR in a PFI mill T248 sp-00, papers of 60 grammage were made according to the T205sp -95 in a laboratory handsheets machine (PTI laboratory Equipment, Vorchdorf, Austria). The mechanical properties of the samples were determined according to common standards: burst index T 403 om-10, tear index T 414 om- 04, tensile index T 494 om-06 and double fold T 423 cm-98 were analysed. While, the brightness was determined according to T525 om-92.

materials. However, these results are similar to that previous studies of hardwoods (O. Elzaki *et al*., 2012; O. T. Elzaki, T. O. Khider, S. H. Omer, *et al*., 2012; Pirralho *et al*., 2014) and some annual plants such as *Vitis vinifera L* (Prozil, Evtuguin, & Lopes, 2012). On the other hand, *T. indica* wood shown a higher a mount of hemicellulose 22.20%, than that of *A. seyal* 20.82% and *Z. christi* 19.70%. However, this result justifies the higher solubility of *T. indica* in alkali solution (NaOH1%), because the alkali solution is adequate to dissolve the fragile branched components of the cellulosic chain, such as hemicelluloses (Mattos, Lourençon, Gatto, Serrano, & Labidi, 2016). Lignin content was found to be highest in *T. indica* 22.97% while it was 22.32 % and 19.03% in *A. seyal* and *Z. Christi,* respectively. However, these results are comparable with all annual plants and hardwoods (17-26%) and lower than softwoods (25-32%). (Ates, Ni, Akgul, & Tozluoglu, 2008) and similar to some wood materials reported by (Copur & Tozluoglu, 2008).

The importance of ash investigation is to show the absence or presence of some materials such as various organic and inorganic components (Tutuş, Çiçekler, & Küçükbey, 2016).

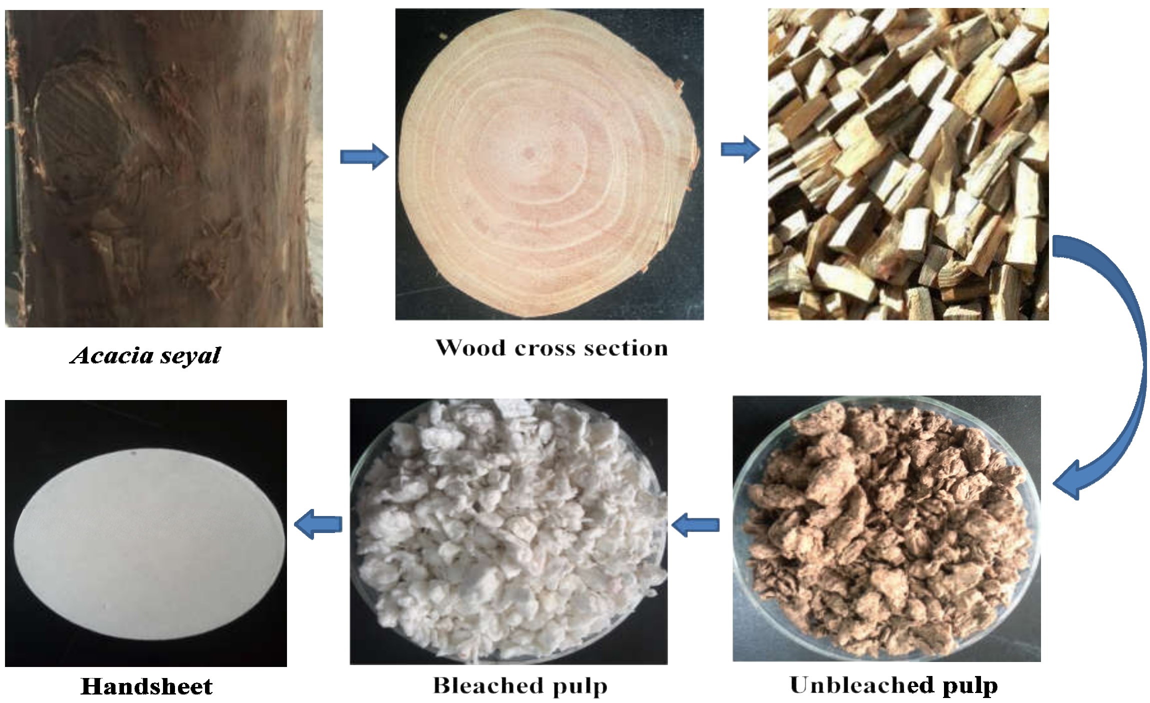

Fig 1 Experimental design used in the present work.

RESULTS AND DISCUSSION

Chemical composition of the hardwood species

A. seyal, *Z. christi* and *T. indica* have been characterized in term of chemical constituents and the results are shown in Table 1. Carbohydrates content of the studied samples, which is directly proportional to pulp yield is varied significantly among the studied wood materials. However, *Z. Christi* shown the highest cellulose contents 48.50% compared to 46.00% and 44.60% of *A. seyal* and *T. indica* respectively. So the pulp yield of *Z. Christi* is expected to be higher than the others two

However, the low ash content demonstrates high pulp yield from pulping process (Daud, Hatta, Kassim, Awang, & Aripin, 2013). The ash contents of studied materials is in the range of (1.00-1.50%) were is the range (1-3%) for hardwoods. However, high ash content is undesirable, as trace elements interfere with bleaching chemicals and alkali earth metals pass in the pulp will cause problems in the chemical recovery line at the pulp mill. Moreover, high ash content may led to damage effect in wood during processing (Dutt, Upadhyay, Singh, & Tyagi, 2009; Francisco López *et al*., 2012)

The highest amount of solubility in cold and hot water was found to be around 17.20% for *T. indica*, while it was 12.90 % and 10.90% for *A. seyal* and *Z. Christi*, respectively. However, these results is similar to that of *H. cannabinus* and *H. sabdariffa* (Dutt *et al.*, 2009) and low than that of vine stems (Mansouri *et al.*, 2012) and *Posidonia oceanica (R. Khiari, Mhenni, Belgacem, & Mauret, 2010)*. The extractives in 1% NaOH were 24.40%, 22.00% and 22.40% for *T. indica, A. seyal.* and *Z. Christi*, respectively. While extractives in benzene- ethanol were 5.60%, 4.40% and 3.80% for *T. indica, A. seyal*. and *Z. Christi*, respectively. However, these results are similar to those of wood sources such as *Prunus amygdalus* and *Tamarisk sp* (Mechi, Khiari, Elaloui, & Belgacem, 2016) but are lower than those of annual plants such as *Isatis tinctoria and Isatis buschiana* (Comlekcioglu, Tutus, Cicekler, Canak, & Zengin, 2016). High solubility will be indicator of low pulp yield as well as higher chemical consumptions both in pulping and bleaching.(Ates *et al.*, 2008; P Khristova *et al.*, 2006)

Table 1 Chemical composition of *A. seyal*, *Z. christi* and *T. Indica*

Chemical Composition (%)	*Z. christi*	*A. seyal*	*T. indica*
Cellulose	48.50	46.00	44.60
Hemicellulose	19.70	20.82	22.20
Klason lignin	19.03	22.32	22.97
Ash (%)	1.00	1.50	1.40
Hot water extractives	7.80	9.70	11.20
Cold water extractives	3.10	3.20	6.00
Alcohol-benzene	3.80	4.40	5.60
1% NaOH	22.40	22.00	24.40

Fibre Characterization

The basic parameters that affected the physical properties of the paper are fibre's dimensions that include fibre length, fibre width and fibre cell wall thickness (Albert *et al.*, 2011). The fibre dimensions and the derived values of the raw materials are listed in Tables 2. *Z. christi* showed relatively high average fibre length 0.88 mm compared to 0.77 mm and 0.76 mm of *A.seyal* and *T. indica*, respectively. However, fibre length was in the range of hardwoods (0.7-1.5 mm) and considered as short fibre species. (M Sarwar Jahan, Sabina, & Rubaiyat, 2008). These fibres were similar to wood materials studied previously such as *Crateva adansonii* (0.66 mm) (O. Elzaki *et al.*, 2012), *Salix Serissaefolia* (0.78 mm) (Asuncion, Suzuki, Watanabe, & Kamaya, 2009) and better than *Prunus amygdalus* (0.48 mm) and *Tamarisk* sp (0.36 mm) (Mechi *et al.*, 2016). Fibre length usually had significant effect on the tearing strength of paper. However, the higher the fibre length, the better will be the tearing resistance of paper.(Agnihotri, Dutt, & Tyagi, 2010). Therefore, paper made from these wood materials had good mechanical strength and thus be suitable for producing writing and printing papers as well as wrapping and packaging paperboard. (Dutt *et al.*, 2009). However, it was reported that fibres with length less than unity value are suitable for papermaking (P Khristova, Kordsachia, & Khider, 2005). On the other hand, *A. seyal* shown thick fibre with width of 19.20 µm compared to 18.70 µm and 17.40 µm of *T. indica* and *Z. Christi*, respectively. However, the observed results were almost similar to *A. armatus and P. chloranthus* (Ferhi, Das, Elaloui, Moussaoui, & Yanez, 2014). Generally hardwoods fibre had fiber width in the range of (20.0-40.0 µm) (Comlekcioglu *et al.*, 2016). The physical properties of a handsheet are directly affected by morphological properties of fibre. (Ates *et al.*, 2008). Among the studied species, *Z. Christi* shown the smallest fibre width and intermediate fibre coarseness, which predict its high fibre flexibility. Fibre flexibility is a very critical parameter due to its contribution towards the paper physical properties. Flexibility increases bonding abilities, thereby increasing the paper strength properties.(Kamoga, Kirabira, Byaruhanga, Godiyal, & Anupam, 2016). Moreover, it was reported that the more fibre length and less cell wall thickness had noticeable advantages on the physical properties of produced paper. (Tutus, Comlekcioglu, Karaman, & Alma, 2010). The anatomical structure of *A. seyal*, *Z. christi* and *T. indica* were examined on the transverse sections the observations are showed in Fig. 2 (A,B,C). However it was found that the lumen diameter of *A. seyal* (22.80 µm) was found to be higher than that of *Z. Christi* (20.00 µm) and *T. indica* (19.20 µm). However, these results were similar to *Paulownia elongota* (Ates *et al.*, 2008) and *Hibiscus cannabinus* and *Hibiscus sabdariffa* (Dutt *et al.*, 2009).

Z. Christi pulp shown a high value of kinked index 0.35% compared to that 0.16% of *T. indica* and 0.15% of *A. seyal,* while the curled index of the three materials is same 0.03%. The high values of kinked and curled indices are attributed to its long fibres. While the low kinked and curled fibres of pulps indicated stiffer fibres (Kamoga *et al.*, 2016). As depend on the cell-wall thickness, rigidity coefficient is one of the important parameter. Rigidity coefficient was calculated as (31.64) for *Z. Christi* which is lower than that of *A. seyal* (37.50) and *T. indica* (36.78). However, higher rigidity ratio reduces paper physical properties (Ates *et al.*, 2008). Generally, the studied spices fibres have very good derived values flexibility coefficient, slenderness ratio and runkel ratio compared to those of some hardwoods (Ouadou, Aliouche, Thevenon, & Djillali, 2017; Pirralho *et al.*, 2014) and softwoods (Agnihotri *et al.*, 2010). Fibres showing Runkel ratio < 1 are considered better candidate for pulp and paper manufacturing because they collapse and allowed enough surface area for bonding, while Runkel ratio > 1 is considered poor for pulp and paper making as the fibres are stiffer, less flexible and form bulkier paper of less bonded surface (Pirralho *et al.*, 2014). Therefore, handsheets made from these materials are expected to have increased mechanical strength and thus be suitable for writing, printing, wrapping, and packaging purposes.

Table 2 Fibres properties of *A. seyal*, *Z. christi* and *T. Indica*

Material	*Z. christi*	*A. seyal*	*T.* indica
Average fibre length (mm)	0.88	0.77	0.76
Average fibre diameter (µm)	17.40	19.20	18.70
Average lumen diameter (µm)	20.00	22.80	19.40
Average cell wall thickness (µm)	5.60	7.20	6.40
Kinked index (%)	0.35	0.15	0.16
Curl index (%)	0.03	0.03	0.03
Rigidity coefficient	31.64	37.50	36.78
Slenderness ratio	44.77	40.00	43.73
Flexibility coefficient	101.52	118.75	111.49
Runkel ratio	0.56	0.63	0.45

Pulp characterization

The physical properties of the pulps obtained from the studied materials are summarised in Table 3. The results reveal that there were a little differences in pulps properties among the different wood materials obtained by the two pulping methods.

seyal compared with the other two wood species. (P Khristova, Kordsachia, & Daffalla, 2004; Lourenço *et al*., 2008).

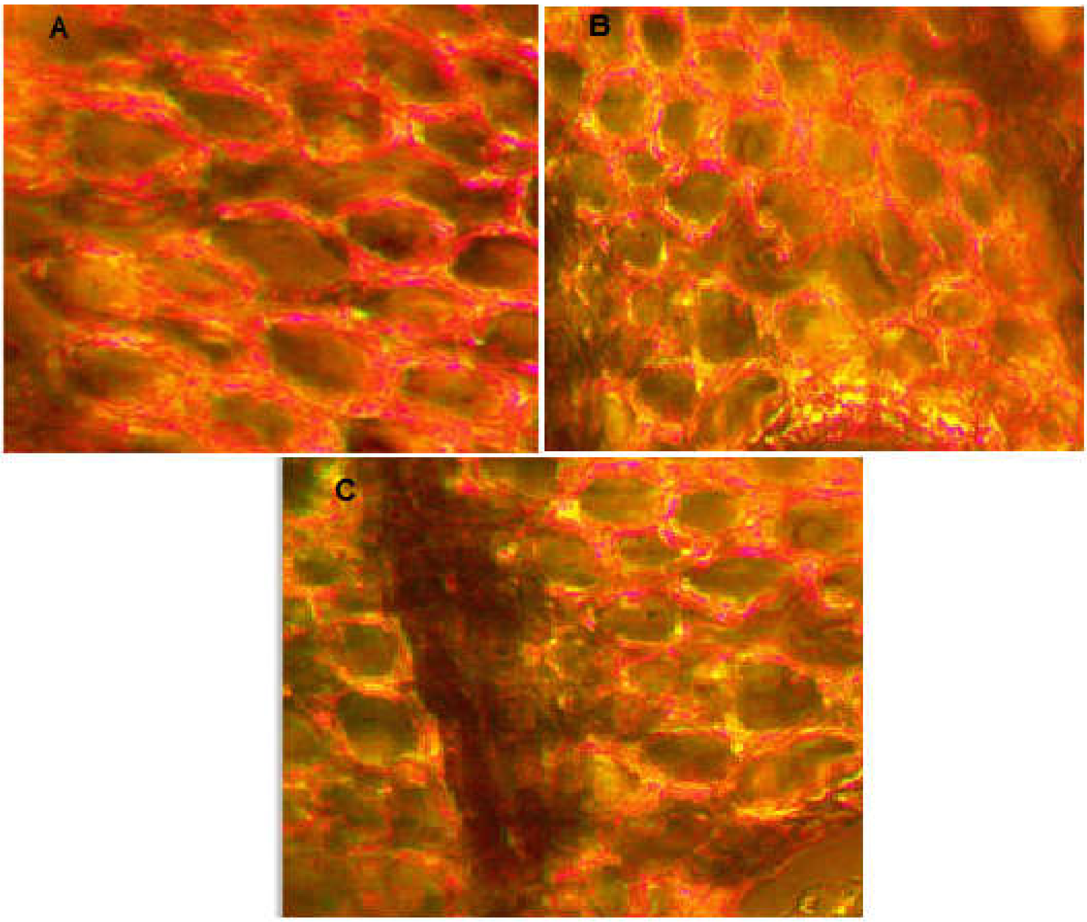

Fig 2 Anatomical structural of *A. seyal* (A), *T. indica* (B) and *Z. Christi* (C) at 400× magnifications.

Table 3 Properties of pulp from *A. seyal*, *Z. christi* and *T. Indica*

Material	Pulp yield(%)		Kappa number		Viscosity (ml/g)		CSF (ml)	
	Kraft	So-AQ	Kraft	So-AQ	Kraft	So-AQ	Kraft	So-AQ
Z. christi	46.60	45.30	21.50	19.80	650	590	330	340
A.seyal	44.50	44.10	20.10	19.10	630	585	310	300
T.indica	44.30	43.55	22.80	21.60	595	560	330	320

For all the studied materials the pulp yields in the kraft pulping process were estimated to be significantly higher than that of soda-AQ pulping process Fig. 3 these results are in agree with data reported by (Asuncion *et al*., 2009; Das *et al*., 2016; P Khristova *et al*., 2006). Among the studied materials, *Z. christi* shown the highest yield regardless of the pulping method. However ,the obtained pulp yield from *Z. christi* (46.60% and 45.30%) from both kraft and soda-AQ pulping methods were significantly higher than those from *A. seyal* (44.50% and 44.10%) and *T. indica* (44.30% and 43.55%), which are expected because of the higher cellulose content (Table 2). However, the obtained pulp yield is better that that of the annual plants and agricultural crops (30-35%) (Ferhi *et al*., 2014). However, the differences in the amounts of yields of pulp may be due to the differences in lignin content as well as the type of lignin present in these wood species.(Ndukwe, Jenmi, Okiei, & Alo, 2009). *T. indica* pulp shown the highest kappa numbers of 22.80 and 21.60 for kraft and soda-AQ pulps, respectively, while *A. seyal* shown the lowest kappa numbers 19.10 and 20.10 for soda-AQ and kraft pulps, respectively. This is attributed to the low lignin content of *A.*

However, these results are in agree with the previous reports (Asuncion *et al*., 2009; M Sharwar Jahan, Chowdhury, & Islam, 2007). The values of the Canadian standard freeness (CSF) of all kraft and soda-AQ pulps are in the range of 350-300 ml at PFI beating degree at 35° around 5000 revolutions. Among the studied materials *Z. Christi* shown highest CSF this shows high interactions of pulp fibres with water molecules (Kamoga *et al*., 2016). Generally, the viscosities of the soda-AQ pulps were lower than those of the kraft pulps for the studied materials. This may be due to the loss of the cellulose's sub-chains during the soda-AQ pulping, which is not the case with kraft pulping. (Das *et al*., 2016; Kamoga *et al*., 2016). However, *Z. Christi* had highest viscosity values 650 ml/g and 590 ml/g for kraft and soda-AQ pulp, respectively, while it was (630 and 585 ml/g), (595 and 560 ml/g) for kraft and soda-AQ pulp of *A. seyal* and *T. indica*, respectively. However, these observations are similar to that of eucalypts (P Khristova *et al*., 2006).

Paper Properties

The physical properties of handmade paper sheets produced from kraft and soda-AQ pulps of the studied species are listed in Table 4. The paper sheets produced from the wood species had good formation with basis weight ranging between 60.30 to 62.50 g/m^2 with thickness of 130-1250 µm, regardless the pulping methods.

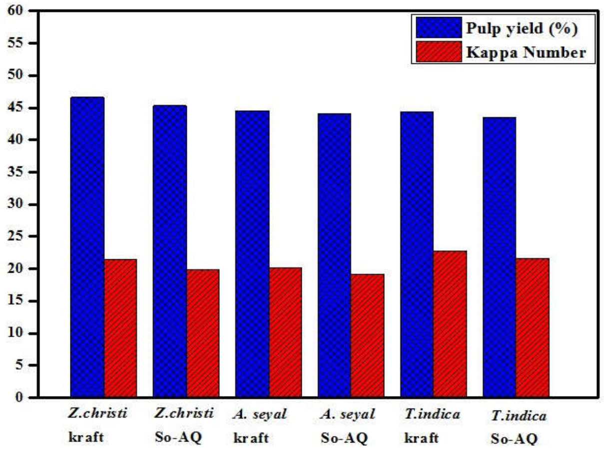

Fig 3 Pulp yield and kappa number of the studied species by both kraft and soda-AQ methods

(2.40 and 2.10 KPa m2/g) for kraft and so-AQ pulps handsheet, respectively, these results are similar to that of hardwood such as *Trema orientalis* (M Sarwar Jahan *et al.*, 2010), *Salix serissaefolia* (Asuncion *et al.*, 2009) and better than that of agriculture resides (Saeed, Liu, Lucia, & Chen, 2017) and annual plant (Ferhi *et al.*, 2014). These results implied that these species can be used in special cases where high burst indices are required, for example in packaging bags.(Kamoga *et al.*, 2016). The best bleachability and highest brightness (75.30% and71.72%) was achieved by *T. indica* for soda-AQ and kraft pulps, respectively, while it was (68.50% and 66.34%) and (67.20% and 69.42%) of kraft and soda-AQ pulps of *Z. Christi* and *A. seyal,* respectively. These results are similar to *dhaincha* (M Sarwar Jahan *et al*., 2009) and *Trema orientalis* (M Sarwar Jahan *et al*., 2010). However, brightness represent the kappa number, which in turn to evaluates the level of delignification. This explains why soda-AQ pulps were brighter than the kraft pulps of the same wood species (Kamoga *et al*., 2016). Moreover, *T. indica* showed the highest opacity of (89.60% and 88.40) of both kraft and soda-AQ pulps, respectively, while it was (88.22% and 85.20%) and (84.88% and 82.50%) of kraft and soda-AQ pulps for *Z. Christi* and *A. seyal,* respectively, these result are similar to that of *Acacia auriculiformis* (M Sarwar Jahan *et al*., 2008).

Table 4 Physical properties of papers from pulps of *A. seyal*, *Z. christi* and *T. Indica*

Properties	*Z. christi*		*A. seyal*		*T. indica*	
	Kraft	So-AQ	Kraft	So-AQ	Kraft	So-AQ
Thickness (µm)	130.00	130.00	125.00	125.00	130.50	130.00
Basis weight (g/m^2)	60.30	61.20	60.50	62.40	62.50	61.80
Tensile Strength (N m/g)	32.42	31.20	30.46	30.00	28.58	27.15
Tearing Index(mNm2/g)	19.13	19.00	18.94	18.30	14.64	13.40
Bursting Index (KPa m2/g)	3.65	3.25	2.40	2.10	3.23	2.80
Density(g/cm^3)	2.80	2.45	3.10	3.25	2.85	2.95
Opacity (%)	88.22	85.20	84.88	82.50	89.60	88.40
Brightness (%)	66.34	68.50	67.42	69.20	71.72	75.30
Double fold (no.)	8	7	6	6	6	5

The paper sheets produced from *Z. Christi,* shown the highest tensile strength (32.42 and 31.20 Nm/g) and tearing index (19.13 and 19.00 mNm2/g) for kraft and soda-AQ pulps, respectively. While the lowest tensile strength (28.58 and 27.15 Nm/g) and tearing index (14.64 and 13.40 mNm2/g) was found in paper sheet from *T. indica*. This may be due to the varying fibre length of the materials because long fibres generally produced paper with higher mechanical properties than paper from short fibre as well as high coarseness of the fibres and hence low flexibility, which does not allow good formation of a bonded network (Fagbemi, Fagbemigun, Mgbachiuzor, Igwe, & Buhari, 2017). The results reveals that physical strengths of paper were increased with increase in fibre length and decrease of cell wall thickness. (Tutus *et al*., 2010). (Gonzalo *et al*., 2017) reported that the properties and strength of the individual fibres, their structure, arrangement, and the extent to which they are bonded to each other are all important parameters which can affect tensile strength of the produced paper. Considering the pulping method, the tensile and tearing indices of the kraft hand sheets were higher than those of the corresponding soda-AQ hand sheet, which is in agree with previous reports.(Kamoga *et al*., 2016). The paper sheets from *Z. Christi* shown higher burst index (3.65 and 3.25 KPa m2/g) than that of *T. indica* (3.23 and 2.80 KPa m2/g) and *A. seyal*

However, opacity is very important for printing and writing papers, while for tracing paper, lampshades, and some packing papers, brightness is considered very important. (Saeed *et al*., 2017; Tajik *et al*., 2016). Considering kappa number and pulp yield of the kraft and soda-AQ pulping, *Z. Christi* was the most suitable lignocelluloses material for pulp production among the three studied species. The mechanical properties of all studied materials are not varied, with high acceptable level for pulp and paper making.

Elemental analysis

Table 5 Elemental analysis of *A. seyal*, *Z. christi* and *T. Indica*

Material	C(%)	O (%)	F (%)	Mg (%)	Al (%)	Si (%)	Na (%)
A. seyal	49.49	43.17	0.90	0.02	0.12	0.07	0.13
Z. christi	49.93	42.24	1.19	0.05	0.04	0.10	0.08
T. indica	49.38	43.41	1.35	0.08	0.07	0.11	0.29

The detailed analyses of the elemental components of the tested papers are summarised in Table 4. It appears that the studied materials constituted of mean elements such as carbon (C), oxygen (O), aluminium (Al), fluorine (F), silicon (Si), magnesium (Mg), and sodium (Na). However, predominant elements in paper obtained from the studied materials were C and O (Machmud, Fadi, Fuadi, & Kokarkin, 2013). Moreover, a few amounts of mineral elements of F, Mg, Al, Si and Na were also observed Fig. 4 (a,b,c). The amount of these elements was relatively low, considering that the amount of ashes in these paper sheets was very low. However, the most significant is that the silica content is very low in the three species 0.11%, 0.10% and 0.07 in *T. indica, A. seyal* and *Z. Christi,* respectively. However, this lower silica content is expected to reduce the amounts of alkali required during pulping and bleaching processing.

Surface Morphology Analysis

Scanning electron microscopy (SEM) analysis of the papers produced from *T. indica A. seyal* and *Z. Christi,* fibres were magnified at 1000X are shown in Fig.4 (A,B,C). The analysis reveals the structure and arrangement of the fibre bundles inside the handsheets. However, the strength of the fibre can be explained according to the order and formation of the fibre pattern (Daud *et al*., 2013). From Fig 4 (A), *Z. Christi* paper's fibres are parallel, aligned and closed to each other rather than that of *A. seyal* Fig 4 (B) and *T. indica* Fig.4 (C). This is may be due to the higher fibre content as well as long fibres in *Z. Christi* compared to the other species. This fibre structure could increase the fibre mechanical properties and the quality of the paper produced. (Saeed *et al*., 2017). Moreover, the compactness and arrangement of fibres play an important role in the quality of the produced paper beside the other parameters such as cellulose content in the non-wood materials.(Daud, Hatta, & Awang, 2015).

CONCLUSION

The high cellulose content of *Acacia seyal* (*A. seyal*), *Ziziphus spina-christi* (*Z. Christi*) and *Tamarindus indica* (*T. indica*) in the range of (48.50%- 44.60%) and relatively low lignin content, led to high pulp yield and good mechanical properties of the produced paper. The relatively high average fibre length 0.88 mm of *Ziziphus spina-christi* (*Z. Christi*) with low fibre diameter led to good mechanical properties (tensile strength, tear index, and fold test) of the produced paper compared to that made of *A.seyal* and *T. indica*. Morphological analysis shown that *Z. Christi* handsheet fibre are parallel, aligned and closed to each other rather than *A. seyal* and *T. indica.* Considering kappa number and pulp yield of the kraft and soda-AQ pulping, *Z. Christi* was the most suitable lignocelluloses material for pulp production among the three studied species. Morphological analysis and chemical composition of *Acacia seyal* (*A. seyal*), *Ziziphus spina-christi* (*Z. Christi*) and *Tamarindus indica* (*T. indica*) show their suitability for producing paper of various grades including writing and printing paper as well as packaging applications.

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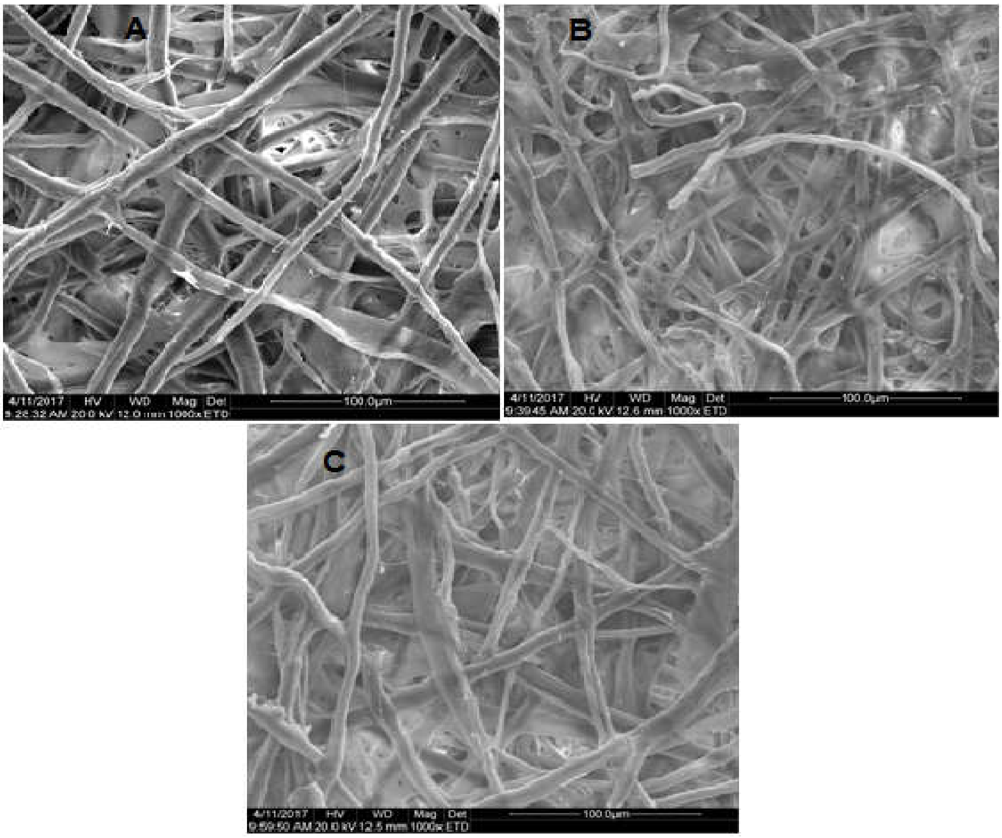

Fig 4 Scanning electron microscope images of *T. indica* (A), *A. seyal* (B) and *Z. Christi* (C).

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