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Production of low cost paper from *Pandanus utilis* fibres as a substitution to wood

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Abstract

Indigenous plants are widely abundant in Mauritius and if made proper use of, these renewable plants can contribute largely to the local economic sector. This paper assesses the suitability of producing eco-friendly and biodegradable papers using low-cost raw materials by means of fibre from *Pandanus utilis'* leaves commonly known as 'Vacoas'. The leaves were used along with *Arundo donax* or wastepaper to manufacture composite paper samples in the ratios of 20:80, 40:60, 60:40, 80:20 and 100:0. Chemical pulping was done through Kraft process for a period of 1.5 h at a concentration of 14 wt% NaOH and 4 wt% Na_2S at 90 ± 2.5 °C. The mean thickness of the papers was determined to be 0.261 ± 0.027 mm. It was found that the 100% Vacoas fibres had the highest absorbency rate of 1.8 ± 0.5 s followed by the composite *A. donax* and Vacoas fibre (1.8 ± 0.3 s). The most abrasion resistant paper which also demonstrated the highest burst index of 0.63 kPa $m^2\ g^{-1}$ and tensile index 11.8 N m g^{-1} was observed to be that of 100:0 Vacoas fibre paper requiring 35 turns to get abraded followed by the *P. utilis* and *A. donax* mix where the 80:20 fibre ratio revealed a high bursting index of 0.45 kPa $m^2\ g^{-1}$ requiring 25 turns to get abraded while 40% *P. utilis* and 60% *A. donax* had a high tensile strength of 11.9 N m g^{-1}. Vacoas to wastepaper mix ratios of 20:80 and 40:60 were found to have the highest mean recovery angles of 61.3 and 59.6°, respectively.

Keywords: Vacoas Fibres, Kraft process, Tensile index, Bursting index, Abrasion resistance

Introduction

The manufacture of pulp and paper is primarily made from raw materials consisting of wood chips and recycled paper. The paper industry that utilizes wood as raw material has a significant contribution to deforestation leading to climate change, species loss, perturbation in water cycle, soil erosion only to mention a few [1]. There is a current increment in pulp and paper demand globally which has significantly contradicted the idea of the world going paperless [2]. Mauritius with a population of 1.263 million [3] has no paper and pulp production nor pulp and paper mills while imports account to 41 kt annually. The island has a net consumption of 40 kt of paper on an annual basis and the paper consumption per capita is 32 kg yr^{-1} $person^{-1}$ [4] which is normally used from residential, commercial, institutional as well as industrial areas. Out of the 40 kt, only 5.8 t of the paper consumed were sent for recycling during the period 2013 to 2015 [4, 5]. However, the world is currently witnessing a rising trend in retreating from the dependency of wood towards more sustainable raw materials such as non-wood fibrous plants due to environment consciousness [6]. Plant fibres classified as environmentally friendly material are a promising raw material rich in lignocellulose that can be employed in the paper and textile industries [7, 8]. Plant fibres originate from a vast variety of sources and the most common plant fibres that exist in Mauritius are raffia palm, cotton, Mauritius hemp, kenaf, Vacoas and pineapple fibres. The Vacoas plant contributed in the development of the sugar sector in Mauritius since their leaves were previously being used to manufacture sugar bags. Today, the fresh Vacoas leaves have restricted functions in the production of baskets, yarns, ropes and souvenirs while the dry leaves are disposed of as agricultural wastes. The products

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manufactured from these fibres are found to be of high strength, lasting and have a high service life [9]. However, the practice of producing baskets and souvenirs are only done by a minority of craftpersons and these artisanal works do not create much profit [10, 11]. Since the Vacoas plant is very common all around the island and they are currently being discarded as agro-wastes, it is a sensible idea to utilize these fibres as raw material for paper production while adopting green production methods. Also, the Mauritian economy is driven by textiles, sugar, tourism and financial services along with an inexistent pulp and paper industry, the latter could be a means of boosting the local economy and the sustainable production of paper from these plants would be a means of utilizing these agro-wastes and producing paper that consumes less water, energy and raw materials [4, 6, 11]. Hence, this paper aims to investigate the feasibility of fibre extraction from non-wood lignocellulosic fibres from Vacoas leaves and utilizing the transformed fibres in the production of eco-friendly and recyclable paper. It would case a significant reduction in farming costs, adverse impacts on the environment through fires, pollution, carbon footprint and diverting wastepaper from the Mare Chicose sanitary landfill by transferring them to waste recovery and recycling facilities [1, 11].

Pandanus utilis fibre

The reproduction of the plant takes place by its seed which germinates in around 2–3 months [11, 12]. The *P. utilis* tree is pyramidal and irregular in shape with the leaves being spirally arranged around the branches. Also, the plant has a mean height of 25 m and can extend up to 60 m with a spread of 4.5 m [13]. Fragrant flowers are formed by the male plants while the female plants bear green fruits hanging from cords which are 14 to 30 cm in length resembling pine cones or pineapples which turn yellow or orange when they become mature. The fruit being a starchy source of food with a dry and hard covering is edible but lacks flavour [9, 11, 12, 14]. The *P. utilis* plants are very messy since the leaves fall constantly during the whole year and also the plants become denser over time with the leaves reaching the ground. Thus, frequent cuttings of the branches and leaves are required which could have otherwise been employed in the fibre industry. These leaves are biologically degraded and composted in forests but then in urban areas, they are still regarded as agricultural wastes that need to be discarded in landfills [10, 11]. Also, the Vacoas leaf is normally not attacked by pests but it can be attacked and killed by viruses as well as fungi which cause diseases and yellow streaks on the leaves [13, 14].

Materials and methods

Raw material preparation

Collection of fresh leaves of *P. utilis* was made at Highlands (Fig. 1), *Arundo donax* stems and leaves at Souillac and recycled wastepaper at the University of Mauritius Press at Réduit in Mauritius from August to October 2017. The red spiny edges and mid rib of the Vacoas leaves were carefully removed in order to prevent injuries followed by washing and chopping into small pieces of around 1–2 cm. The samples were oven-dried at 60 °C for approximately 4 consecutive days till a constant weight was attained. After the drying process, the samples were stored in an air-tight plastic bag for further cooking and pulping processes.

Chemical pulping process

A white liquor was prepared from 14 wt% NaOH and 4 wt% Na_2S in a bath ratio of 3:1. 40 g of sample was prepared for pulping process where *P. utilis* fibres were utilized in definite ratios of 20:80, 40:60, 60:40, 80:20 and 100:0 with either *A. donax* or wastepaper to produce composite paper sheets. The raw material was then submersed in the beaker containing the white liquor in a liquid to solid ratio of 17.5:1 and placed on a hot plate set

Fig. 1 Collection of Vacoas leaves

on a range of 250–300 while the temperature was monitored at 90.0 ± 2.5 °C for a period of 1.5 h. After cooking and cooling, the black liquor subsequent to delignification was filtered and the solid brown residue retained. The latter was then washed meticulously under tap water for 45 min for the removal of the black liquor and hot water was added to increase the imbibition. The pH of the clear liquid obtained after washing was measured to ensure that the pH was around 7. The washed pulp was then mechanically beaten and manually inspected as well as screened to remove any dirt, undigested fibres and knots present. The resulting pulp was oven-dried at 60 °C for a period of 24 h to obtain pulp having a dry mass ready for paper-making.

Paper manufacturing from Vacoas fibres

A pair of bolts and nuts was unscrewed in order to open the deckle (upper part of the paper making apparatus) and the latter was allowed to rest on the fixed hinges at the back. The mould was removed from the apparatus, washed with water in order to remove any pulp present from previous usage and it was replaced back. The mould was ensured to be at 180° to the horizontal by means of a spirit level and the voids present between the mould and the apparatus were filled with the aid of rubber strips to prevent the loss of pulp. The pair of bolts and nuts were then tightened by pliers in order to prevent leakages from the apparatus and water was allowed in the apparatus up to a height of 35 cm. The oven-dried pulp was then blended with water and introduced into the apparatus. The mixture was allowed to stand for approximately 12 min until all the pulp had settled down on the mould. Once settled, the water was drained leaving the pulp on the mould. The bolts and nuts were then unscrewed and the mould carefully lifted to be placed on a felt material (Fig. 2). The sheets were dewatered by means of sponges followed by a roller (couching) through gentle movements without applying too much pressure and the wet paper sheets were eventually allowed to dry at ambient conditions for a period of approximately 48 h and the dry ironed sheets were conditioned for physical and mechanical tests (Figs. 3 and 4).

Determination of mass of pulp for paper-making (Tappi T205 Sp-12)

A grammage of 60 g m^{-2} on an oven-dried basis of sample was considered for the determination of the physical properties of the paper sheets. The total mass of pulp to be used for the sheet preparation was determined from specific calculations. The area of mould screen was calculated by multiplying 0.33 m by 0.27 m to give 0.0891 m^2. Thereafter, the amount of oven-dried pulp required was calculated by multiplying the grammage value of 60 by the area (0.0891 m^2) to give 5.35 g. Since, there were gaps between the mould and the paper-making apparatus, a total mass of 8.0 g was considered to cater for the pulp losses.

Physical analysis

Grammage determination (Tappi T410 OM-08)

The grammage of a paper depends upon the size as well as the mass of the sheet. Different grammages of paper have different functions in the market such that paper having a small mass per unit area can be used as wrapping paper in the food industry or as toilet paper while those having a larger mass per unit area can be used as posters or cardboards [15]. Samples were cut in dimensions of 5 × 5 cm from different sheets of paper followed by weighing on an electronic weighing balance. The grammage was then determined as follows:

$$g = \frac{m}{A \times n}$$

where, g is the sheet grammage in g m^{-2}, m is the mass of paper sample in g, A is the paper sample area in m^2, and n is the number of samples.

Thickness determination (Tappi T551 PM-12)

In order to determine the thickness of the paper specimen more accurately without compressing the paper surface, a Shirley thickness tester was utilised. Hence, the tester was calibrated via a metric load to eliminate the occurrence of any zero error and the paper sample was inserted under a small pressure foot measuring 50 cm^2 whereby loads of 10, 30, 50, 100,

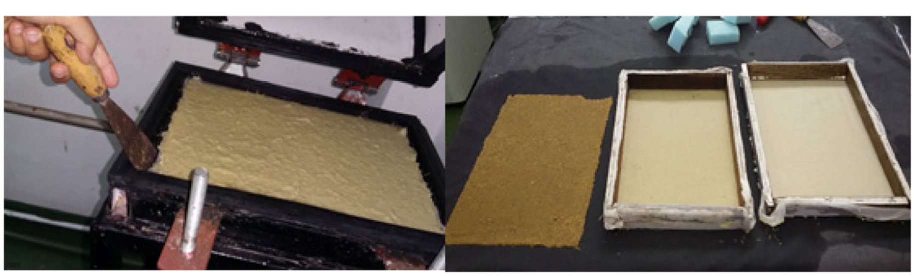

Fig. 2 Lifting of mould by a blunt putty knife and placed on felt material

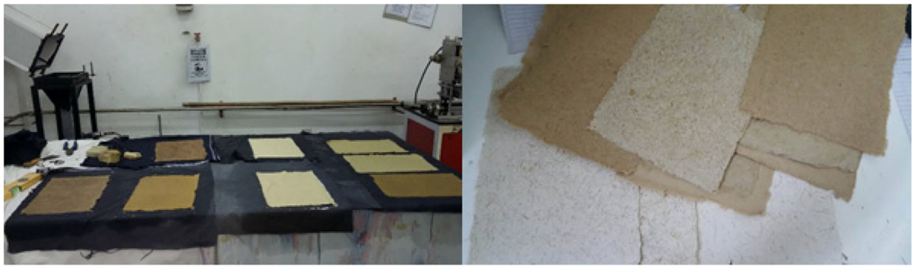

Fig. 3 Sheet of paper left to dry at ambient conditions and dry ironed sheets of paper

Fig. 4 Paper samples

300, 500, 1000, 1000, 1000 and 1000 g were cumulatively added while allowing a stabilization time of 60 s between the addition of each load before recording the thickness. Consequently, a compression curve was plotted for each cumulative load against their resulting respective thicknesses. The weights were then removed in the reverse order and a recovery curve (cumulative weight against thickness) was plotted. The point of intersection of these two curves gave the real thickness of the paper.

Chemical analysis

Moisture content (Tappi T550 OM-8)

Sampling and quartering were done on the samples and placed on aluminium plates prior to weighing on an electronic balance. The samples were then oven-dried at 60 °C for a period of four consecutive days till a constant weight was obtained and the values were recorded. The moisture % was calculated as follows:

$$Moisture\% = \frac{W1 - W2}{W1} \times 100$$

where, W1 is the initial wet weight of the sample in grams and W2 is the final dried weight of sample in grams.

Lignin content and kappa number (Tappi T 236)

The *P. utilis* and *A. donax* samples were pulverised and screened through a 0.5 mm sieve. 0.5 g of the pulverised sample was then mixed with approximately 600 mL of distilled water and allowed in a mixture of 75 mL H_2SO_4 and 75 mL $KMnO_4$ continuously stirred on a magnetic stirrer for approximately 10 min followed by the addition of 15 mL KI to the mixture. Furthermore, 25 mL of the mixture was pipetted to be titrated against $Na_2S_2O_3$ until a pale colour was observed. Hereafter, 2 drops of starch indicator were added to the mixture and titrated till a colourless solution was observed.

The lignin content and Kappa number were calculated using the following formulas:

$$\mathrm{P-No} = 75 - \mathrm{v}$$

$$\mathrm{K-No} = \frac{P - No \times f}{w}$$

$$\%\mathrm{Lignin\ Content} = \mathrm{K-No} \times 0.155$$

where, P – No is the Permanganate Number, K-No is the Kappa Number, v is the titre value in mL, f is the correction factor, 0.5 and w is the weight of sample mixed with distilled water in g.

Mechanical analysis

Absorbency rate (TAPPI T831 Om-93)

The water absorbency experiment is carried out in order to determine the time taken in seconds for a drop of water to get entirely absorbed into a paper specimen and damp the bottom side of the sample when placed on the surface of the paper with the aid of a 10 μL micropipette inclined at an angle of 30° to the horizontal [16]. The absorbency rate is a measure of the suitability and quality of wrapping, packaging, tissue and towel paper for sorbing processes [17].

Tensile index (T 494 om-01 N)

The ultimate tensile force necessitated by the test strip to fracture into 2 pieces due to excessive stress under specified test conditions is termed as tensile strength. The latter is a measure of the strength resulting from the fibre strength, length as well as the linkage between the fibres in the framework [18, 19]. 4 test samples measuring 25.0 ± 1 mm wide and 180 ± 5 mm long were cut for each composite type and a testometric material testing machine was used to evaluate the tensile properties such as force at break, young modulus, percentage strain at break and peak, time to failure and peak which are instrumental for the determination of the tensile index ($N\,m\,g^{-1}$). A tensile load of 0.01 kN was used along with a fixed jaw separation rate at $5\,mm\,min^{-1}$ and thickness of 0.4 ± 0.1 mm.

The Tensile Index, I was determined using the following equation:

$$\mathrm{I} = \frac{F}{wg}$$

where, F is the mean tensile force at break in kN, w is the width of the sample in metres and g is the grammage of the sample in $g\,m^{-2}$.

Bursting strength and bursting index (TAPPI T403 OM-15)

Bursting strength of paper specimens is a property directly related to the tensile strength as well as stretching capacity of that particular sample. It is dependent on several additional properties such as the percentage of fibres in the paper sheet, the method of fibre extraction and preparation, mechanical refining time, length and size of fibres as well as the utilization of sizing and additives. The bursting test measures the strength of the paper by subjecting the sample to an increasing pressure until the paper sample ruptures. The longer the time the sample takes to rupture and the greater the pressure it takes to burst the sample, the more stress resistant the paper specimen is [18, 20]. The Burst Index, B is calculated by the following equation:

$$B = \frac{p}{g}$$

where, p is the mean bursting strength in kPa.

Abrasion resistance (TAPPI T476 om-11)

Abrasion resistance test is carried out by rubbing the paper specimens under test against another surface which is usually the same kind of paper or emery grade zero polishing paper in order to determine the lifetime of the paper when the latter is predominantly being subjected to friction. The weighed samples were each placed in a sample holder along with a sponge backing due to the grammage being smaller than 500 g m^{-2} and a Eureka abrasion tester was used along with 200 g load cells to determine the abrasion resistance and loss of the sample.

Crease recovery (TAPPI T511 OM-02)

Crease is a crinkle or fold brought involuntarily on a sheet of paper when being handled and crease recovery is the capacity of that paper to return to its former point or restore its original shape just after being subjected to creasing for a definite period of time. A good crease resistance paper will have a full angle recovery and will be able to resist any rupture at folds and fold lines. In order to perform the crease recovery angle test, 10 random paper samples from each of the different composites were conditioned and the tests were carried out at standard atmospheric conditions using a Eureka crease recovery tester.

Results and discussion

Physical testing

Grammage determination

Table 1 depicts the mean grammage for the different paper admixtures tested. As observed from the table, there are small deviations in the values of the grammage which have gone beyond the desired grammage of 60 g m^{-2}. The slight differences may be due to the 33.1% excess pulp which had been taken during the paper making process in order to compensate for the losses in the apparatus.

Thickness determination

The thickness of the samples varying from 0.234 to 0.288 mm was observed to increase proportionally with grammage ranging from 59.1 to 62.5 g m^{-2}. This might be due to the existence of more cellulosic fibre concentration in the sample per unit area. As observed on Fig. 5a, the mean thickness of the 80% *A. donax* is the highest followed by the 60% *A. donax*. Overall, the *A. donax* and Vacoas fibre mix has a greater thickness than the wastepaper and Vacoas fibre mix owing to less losses and greater bonding in *A. donax* and Vacoas fibres mix as compared to wastepaper and Vacoas fibres mix or uneven surface of paper as a result of different fibre concentrations at the 5 various spots where the paper sample was tested.

Chemical analysis

Moisture content

The drought tolerant leaves of *P. utilis* (Vacoas) was found to have a moisture content of 51.7%. The moisture content of 39.0% obtained for the *A. donax* stems including the nodes and internodes was in the range of 36.1 to 42.0% as reported by [21]. The smallest moisture content observed was with wastepaper exhibiting 7.2% of moisture. However, as mentioned earlier the moisture contents for the different materials vary according to the maturity of the plant, climate, soil conditions, geographic location, variety as well as the agricultural practices. Cellulose being the major composition in the fibre has the ability of absorbing as well as releasing moisture whenever required depending on climatic conditions. Also, the moisture content of the fibre changes with temperature. An increase in moisture in the paper might cause curling, printing troubles and bad quality paper.

Table 1 Mean grammage for the different test specimens

Fibre composition	Percentage composition of fibre	Grammage (g m^{-2})	Nearest deviation (g m^{-2})	Furthest deviation (g m^{-2})	Range (g m^{-2})
Wastepaper:Vacoas	20:80	60.5	59.7	60.9	60.5 ± 0.44
	40:60	62.2	61.2	62.9	62.2 ± 0.66
	60:40	62.0	60.4	62.7	62.0 ± 0.73
	80:20	61.1	60.1	61.9	61.1 ± 0.67
Arundo donax:Vacoas	20:80	61.1	60.0	62.0	61.1 ± 0.68
	40:60	61.3	60.2	62.0	61.3 ± 0.69
	60:40	62.3	61.3	62.5	62.3 ± 0.37
	80:20	62.5	61.0	62.7	62.5 ± 0.53
Vacoas	100	59.2	59.0	61.1	59.2 ± 0.66

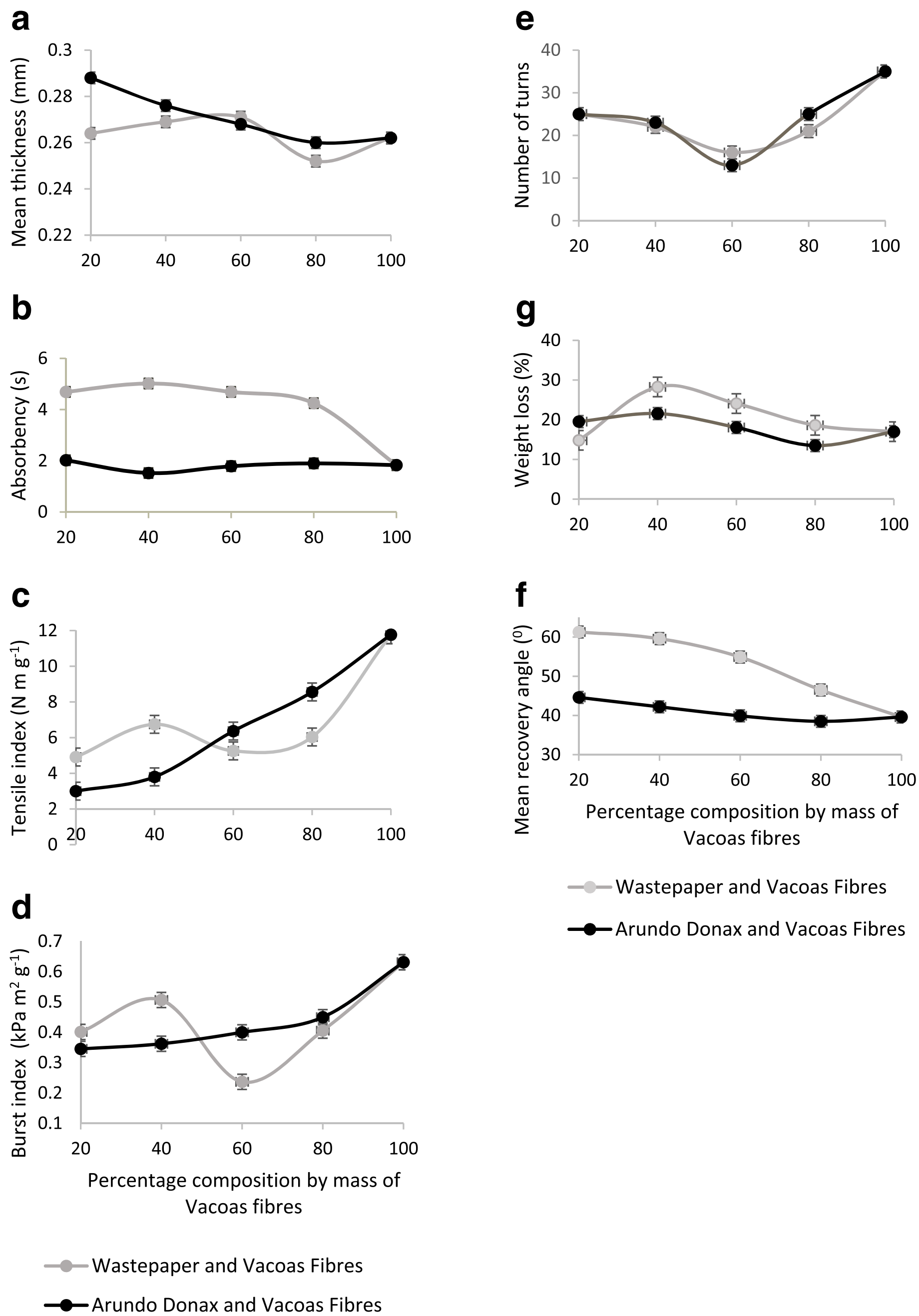

Fig. 5 Physical, chemical and mechanical properties as a function of mass percentage of Vacoas fibres

Lignin and kappa number

Kappa number is dependent upon the digestion technique, the constituents of the fibre as well as the method of delignification opted. It assesses the amount of lignin in the fibre, the bleachability of the resulting pulp as well as the quantity of reagents that would be required for chemical pulping. Softwoods tend to delignify at high Kappa number of approximately 90 while hardwoods defiberize at lower Kappa number around 30. Kappa numbers of 83.8 and 79.4 have been obtained for *P. utilis* and *A. donax,* respectively implying that the fibres can be further delignified by bleaching. Also, the lignin content of Vacoas fibres and the giant reed accounting to 13.0 and 12.3% respectively are considerably lower than that of softwoods which have a lignin content ranging from 26 to 34%. The lower lignin content of the fibres means that less energy is needed for pulping process and stronger intermolecular forces of attraction are formed in between the fibres which are responsible for good physical and mechanical properties of the final product [22].

Mechanical analysis

Rate of absorbency

During this experiment, it was observed that different paper compositions absorb the same amount of water at different rates (Fig. 5b). A lower water absorbency time was observed with composite ratios of *A. donax* and Vacoas fibres varying between 1.5 and 2.0 ± 0.5 s implying that they are most suitable to be used as tissue and towelling paper. A slight drop in absorbency time was observed for the composite paper consisting of 40% Vacoas fibre and 60% *A. donax* possibly due to the formation of an admixture constituting of a higher amount of lignin or hemicellulose and thus resulting in a higher rate of moisture absorption [23, 24]. Moreover, an increasing ratio of Vacoas fibres in wastepaper admixtures proved to be more favourable regarding the absorbency time which may be explained by a decline in the hydrophilic property of the sample due to a decreasing amount of cellulose in the admixture. 100% Vacoas fibres have the highest absorbency rate of 1.8 ± 0.5 s due to greater intermolecular forces of attraction between the particles in the crystalline arrangement which aids in repelling water and thus reducing the water absorption rate [23, 24].

Tensile strength and tensile index

As depicted on Fig. 5c, an optimum tensile index of 12.0 $N\,m\,g^{-1}$ was obtained from paper manufactured from 100% Vacoas fibres which may be due to the availability of a higher amount of cellulose or presence of micro-fibrillar sized fibres in the framework [25] while a minimum tensile index of 0.2 $N\,m\,g^{-1}$ was observed with paper samples constituting of 20% Vacoas fibres and 80% *A. donax*. In addition, the tensile indexes for paper admixtures of *A. donax* and Vacoas fibres were observed to have a rising trend with increasing percentage of mass of Vacoas fibres specifying that Vacoas fibres and *A. donax* have a greater bonding and hence a higher stress-resistant paper is achieved when the percentage of Vacoas fibre is greater than that of *A. donax* in the pulp mix. As for the wastepaper and Vacoas fibre composite, the line peaked up at 6.5 $N\,m\,g^{-1}$ signifying that the incorporation of 40% of Vacoas fibres in the paper composite resulted in the strongest paper sample in the waste paper and Vacoas fibre mix.

Bursting strength and bursting index

A similar trend can be observed between the results (Table 2) obtained from the burst index (Fig. 5d) test and the tensile strength test. The maximum burst index in kPa $m^2\,g^{-1}$ obtained was from paper produced from 100% Vacoas fibres while the minimum burst index was observed with paper admixtures of 60% Vacoas fibres and 40% wastepaper. The high burst index discerned may be explained by a more effective distribution of fibres as well as greater intermolecular forces of attraction between the fibres in the framework [26]. Moreover, it can be discerned that with paper admixtures of *A. donax* and Vacoas fibres, an increase in the percentage by mass of Vacoas fibres led to a greater burst index specifying that Vacoas fibres form a greater bonding with *A. donax* than with wastepaper and increasing percentage of Vacoas fibres produce stronger paper sheets. The optimum burst index observed with wastepaper was that from admixtures of 60% wastepaper and 40% Vacoas fibres.

Abrasion resistance and abrasion loss

The data obtained for mean abrasion weight loss and abrasion resistance are shown in Fig. 5e and f, respectively. As observed on Fig. 5e, both paper admixtures showed a nearly similar trend where the number of turns the paper took to get abraded decreased with increasing percentage by mass of Vacoas fibres and then increased again with 80 and 100% by mass of Vacoas fibres. Paper samples produced from 100% Vacoas fibres

Table 2 Mean burst index of the different paper samples

Fibre composition	Percentage composition of fibre	Grammage ($g\,m^{-2}$)	Bursting strength (kPa)	Burst index (kPa $m^2\,g^{-1}$)
Wastepaper:Vacoas *Arundo donax*:Vacoas	20:80	60.5	25	0.41
	40:60	62.2	15	0.24
	60:40	62.0	31	0.51
	80:20	61.1	25	0.40
Arundo donax:Vacoas	20:80	61.1	28	0.45
	40:60	61.3	25	0.40
	60:40	62.3	23	0.36
	80:20	62.5	22	0.35
Vacoas	100	59.07	37	0.63

requiring 35 turns to get abraded turned out to have the highest abrasion resistance property while sample admixtures of 60% Vacoas fibres and 40% wastepaper as well as admixtures of 40% *A. donax* and 60% Vacoas fibres proved to be the least abrasion resistant requiring only 16 and 13 turns respectively to get abraded. The low abrasive property of the fibres achieved by 100% Vacoas fibre paper may be explained by a better arrangement and linkage of the fibres to each other as well as the presence of microfibrillar sized fibres in a strong network [27].

Figure 5f shows that both wastepaper and *A. donax* mix again have a similar trend. Nonetheless, paper samples from admixtures of wastepaper and Vacoas fibres experienced a greater percentage weight loss as compared to paper produced from admixtures of *A. donax* and Vacoas fibres. The *A. donax* and Vacoas fibre mix having experienced between 13.5 to 21.6% weight loss has the highest abrasion resistance property indicating a better bonding between the fibres. Moreover, the optimum mix percentages obtained were that of 80% wastepaper, 20% *A. donax* and 100% Vacoas fibres due to their small percentage weight losses of 13.5, 14.8 and 17.0% respectively.

Crease recovery

In order to perform the crease recovery angle test, 10 random paper samples from each of the different composites were conditioned and the tests were carried out at standard atmospheric conditions. The mean angles obtained by each paper composite are shown in Fig. 5g.

It can be observed that paper produced from admixtures of *A. donax* and Vacoas fibres have lower recovery angles than paper made from admixtures of wastepaper and Vacoas fibres. Moreover, both mixes have a declining recovery angle with increasing percentage of Vacoas fibres. However, the mean angle recoveries of all the paper samples are higher than that of a normal A4 paper which is 25°. The paper specimen having the highest mean recovery angle was found to be the one constituting of 20% Vacoas fibres and 80% wastepaper (61.3°) followed by paper specimen comprising of 40% Vacoas fibres and 60% wastepaper (59.6°). The paper sample with admixtures of 80% Vacoas fibre and 20% *A. donax* as well as the 100% Vacoas fibre paper were found to have the smallest recovery angle of 38.5 and 39.6° respectively. Hence, the paper specimens depicting a high recovery angle such as admixtures of wastepaper and Vacoas fibres can be used as writing materials while those having a lower recovery angle can be used as wrapping paper.

Conclusions

The study demonstrated that fibre extraction from non-wood lignocellulosic feedstocks such as from Vacoas leaves and utilizing the transformed fibres in the production of an eco-friendly, low-cost, printable and writable paper is a feasible comeback to the *P. utilis* leaves which are usually left to degrade on the ground and disposed of as agricultural wastes to end up in the landfill. Furthermore, satisfactory experimental results were observed with the different paper admixtures even though no binding agent was used as glue to aid the bonding process. Nonetheless, there are several challenges that need to be tackled such as the cost of transportation of the agricultural residues to the paper mill as well as water minimisation. The tensile, burst index and abrasion resistance tests revealed that the *A. donax* and Vacoas fibre pulp mix had a better compatibility in terms of the strength characteristics of the paper due to the higher bonding capacity of these 2 specific admixtures. Nonetheless, 100% Vacoas fibre paper depicted the most favourable results with the highest absorbency rate of 1.8 ± 0.5 s, highest bursting index of 0.63 kPa $m^2\ g^{-1}$ with an optimum tensile index of 12.0 N m g^{-1} requiring 35 turns to get abraded. The mean thickness of all the paper specimens tested varied between 0.234 to 0.288 mm which depicted a rising trend with grammage varying between 59.1 to 62.5 g m^{-2}. The bulk density of the paper samples ranged between 217 to 252 kg m^{-3}. In addition, the paper specimens having the highest mean recovery angle being suitable for writing materials were found to be the one constituting of 20% Vacoas fibres and 80% wastepaper (61.3°) followed by paper specimens comprising of 40% Vacoas fibres and 60% wastepaper (59.6°). The sustainable production and consumption of paper made from non-wood fibres has an upper hand on deforestation minimisation along with a reduced impact on the ecological balance. Since Mauritius has no existent pulp industry, the production of paper from agro-wastes using less water, energy and raw materials could be a means of boosting the local economy. Also, the raw materials are readily available and a low expertise is required in this particular process. Hence, it can be concluded that low cost non-wood paper can be manufactured from Vacoas fibres that meets the standard for paper.

Authors' contributions

NJ carried out the production of paper samples and drafted the manuscript. PJ participated in the design of the study, coordinated the study and did the sequence alignment. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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References

1. Okoro M. Environmental impact analysis of pulp and paper production. Munich: GRIN Verlag; 2012.
2. SM. Mauritius in Figures. Port Louis: Statistics Mauritius; 2004-2016.
3. TWB. Mauritius Population. Washington, DC: The World Bank; 2017.
4. MCCI. DOE Manufacturing–What Strategy for a New Generation of Growth. Port Louis: Mauritius Chamber of Commerce and Industry; 2012.
5. CJCO. Sustainability Report. Port Louis: Currimjee Jeewanjee & Co Ltd; 2015.
6. Bowyer J, Howe J, Pepke E, Bratkovich S, Frank M, Fernholz K. Tree-free Paper: A Path to Saving Trees and Forests? Minneapolis: Dovetail Partners Inc; 2014.
7. Wayman M. Part II: technical information on raw materials and pulp and paper manufacture. In: Wayman M, editor. Guide for planning pulp and paper enterprises. Rome: Food and Agriculture Organisation of United Nations; 1973. p. 219–310.
8. Chen H. Biotechnology of lignocellulose: theory and practice. Dordrecht: Springer; 2014.
9. Brink M, Achigan-Dako EG. Plant resources of tropical Africa 16. Fibres. Wageningen: PROTA Foundation; 2012.
10. Soocheta AV, Teli M, Rosunee S. Extraction of *'Pandanus utilis'* leaf fibre and its potential for eco friendly product development. In: Sustainable Innovation 2013. Epsom; 2013 Nov 4–5.
11. Soocheta AV. Investigation of extraction, processing and potential for product development of '*Pandanus utilis*' leaf fibre [Ph.D. Dissertation]. Moka (Mauritius): University of Mauritius; 2014.
12. DT. Plant lists. Desert Tropicals; 2007.
13. Gilman EF, Watson DG. *Pandanus utilis*: Screw-pine. Fact sheet ST430. Gainesville: Institute of Food and Agricultural Sciences, University of Florida; 1994.
14. Galea P. The aloe fibre industry. In: Macmillan A, editor. Mauritius illustrated: historical and descriptive, commercial and industrial facts, figures and resources. New Delhi: Asian Educational Services; 2000. p. 240–4.
15. Gulsoy SK, Simsir S. The effect of hand sheet grammage on strength properties of test liner papers. J Bartin Fac Forest. 2017;19:117–22.
16. Mahale S, Goswami-Giri AS. Environmental friendly approach in paper making using natural organic waste. Chem Sci Rev Lett. 2015;4:489–93.
17. SP. Water Absorbency. Surrey: Smithers Pira; 2017.
18. Deng SQ, Ye L, Mai YW, Liu HY. Evaluation of fibre tensile strength and fibre/matrix adhesion using single fibre fragmentation tests. Compos Part A-Appl S. 1998;29:423–34.
19. Roylance D. Uniaxial mechanical response. Mechanical properties of materials. Cambridge: Massachusetts Institute of Technology; 2008.
20. Meredith R. Properties of textile materials. I—tensile strength, breaking extension and stress-strain relations of fibres. J Text Inst Proc. 1952;43:755–64.
21. ECN.TNO. Phyllis 2. Database for biomass and waste: *Arundo donax* (giant reed) (#1992). Hague: ECN.TNO; 2001.
22. Klash A, Ncube E, du Toit B, Meincken M. Determination of the cellulose and lignin content on wood fibre surfaces of eucalypts as a function of genotype and site. Eur J Forest Res. 2010;129:741–8.
23. Sibaly S, Jeetah P. Production of paper from pineapple leaves. J Environ Chem Eng. 2017;5:5978–86.
24. Dwan A. Paper complexity and the interpretation of conservation research. J Am Inst Conserv. 1987;26:1–17.
25. Khalil HPSA, Alwani MS, Omar AKM. Chemical composition, anatomy, lignin distribution, and cell wall structure of Malaysian plant waste fibers. Bioresources. 2006;1:220–32.
26. Suhr M, Klein G, Kourti I, Gonzalo MR, Santonja GG, Roudier S, et al. Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board. Luxembourg: Publications Office of the European Union; 2015.
27. Müssig J, Fischer H, Graupner N, Drieling A. Testing methods for measuring physical and mechanical fibre properties (plant and animal fibres). In: Müssig J, editor. Industrial applications of natural fibres: structure, properties and technical applications. Chichester: John Wiley & Sons; 2010.

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