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Structure and properties of some vegetable fibres

Part 2 *Pineapple fibre (Anannus Comosus)*

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The stress–strain curves for pineapple leaf fibre have been analysed. Ultimate tensile strength (UTS), initial modulus (YM), average modulus (AM) and elongation of fibres have been calculated as functions of fibre diameter, test length and test speed. UTS, YM, and elongation lie in the range of 362 to 748 MN m^{-2}, 25 to 36 GN m^{-2}, and 2.0 to 2.8%, respectively for fibres of diameters ranging from 45 to 205 μm. UTS was found to decrease with increasing test lengths in the range 15 to 65 mm. Various mechanical parameters show marginal changes with change in speed of testing in the range of 1 to 50 mm min^{-1}. The above results are explained on the basis of structural variables of the fibre. Scanning electron microscope studies of the fibres reveal that the failure of the fibres is mainly due to large defect content of the fibre both along the fibre and through the cross-section. The crack is always initiated by the defective cells and further aggravated by the weak bonding material between the cells.

1. Introduction

In many parts of the world, besides the main agricultural produce, different parts of plants and fruits of many crops have been found to be viable sources of raw materials for industrial utilization. However, many of these are going to waste since they are yet to be harvested profitably for lack of knowledge about their economic uses. Pineapple fibre is one such material. Proper utilization of indigenously available byproducts will not only solve waste disposal but also open up new avenues for these natural resources. This will help in the proper planning of economic programmes of a country.

Pineapple is largely cultivated in tropical countries, mainly for its fruits. In India about 18 000 acres (7300 hectares) of land is cultivated with pineapple, Assam, Kerala, Tripura and Andhra Pradesh being large cultivators [1]. The pineapple plant has a very short stem and provides 25 to 30 leaves per plant which are 0.90 to 1.50 m long and 0.02 to 0.05 m wide [2, 3]. Each leaf weighs about 0.06 kg and normally yields fibres of about 2 to 3% of the weight of the green leaves [4]. The fibres are extracted by a process of water retting and scrapping or by decortication using raspadors. It is reported that about 5 to 6 kg of fibres can be extracted in about 8 h using a raspador in India [1]. On the other hand, in the Philippines a microbial retting process has been found to be more efficient which results in fibres with better appearance, good strength and the required chemical composition [5].

The main chemical constituents of pineapple fibre are reported to be cellulose (70 to 82%), lignin (5 to 12%) and ash (1.1%) [5–7]. X-ray studies indicate that pineapple fibres have a high degree of crystallinity [8] with a spiral angle of about 14° [9]. Mechanical properties such as UTS, elongation, modulus, flexural and torsional rigidity of fibres and yarns reported in earlier work are given in Table I. These studies do not, however, give details regarding the variation of properties with respect to dimensions (diameter and test length) of the fibre used, the speed at which the test was carried out, nor the sensitivity of the testing machine used. Also, no attempt has been made in these studies to understand the observed physical properties of the fibre in terms of their structural details.

Such an understanding of structure–property relationships will lead to diversified uses for this abundantly available renewable resource which would otherwise go as waste. In fact, attempts have already been made [3, 10] to blend pineapple fibre with other fibres by evolving the processing technology of pineapple leaf fibres in jute, cotton, semi-worsted, worsted and flax systems. A comparative study of the performance of this developmental work is also reported. Yarn produced through hot-water bath spinning indicates the possibilityy of this fibre replacing cotton in cotton belting duck cloth, or for cable yarns, twins and other industrial applications. In fact, pretreatment of pineapple fibres in water for two days followed by treating the fibre in a boiling solution of 1% NaOH resulted in stronger and finer fibre [11]. Other uses of pineapple fibres are for making threads and fabrics for decorative purposes [1]. In the Philippines these fibres have been experimented upon for use in knitted shirts as interlinings, place mats, bags, blankets, insulators and soundproofing materials [12].

In this paper, we report the mechanical properties of pineapple leaf fibres such as initial modulus, UTS and elongation as functions of fibre diameter, test length and speed of testing. The observed results and the fracture mechanism of pineapple fibres are

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TABLE I Properties of pineapple leaf fibre

Ultimate cell [3, 4]	Length L (mm)	3 to 9
	Breadth B (μm)	4 to 8
	L/B	450
Filaments [3, 4]	Gravimetric fineness (Denier)	14
	Tenacity ($MN\,m^{-2}$)	710
	Extension at break (%)	2 to 6
	Torsional regidity ($MN\,m^{-2}$)	360
	Flexural rigidity ($MN\,m^{-2}$)	3 to 8
	Transverse swelling in water (%)	18 to 20
Bundle [4]	Tenacity ($MN\,m^{-2}$)	370
	True density ($kg\,m^{-3}$)	1480.0
	Apparent density ($kg\,m^{-3}$)	1350.0
	Porosity (%)	9.0
	Moisture regain at 65% r.h.	11.8
	Moisture regain at 100% r.h.	41.0

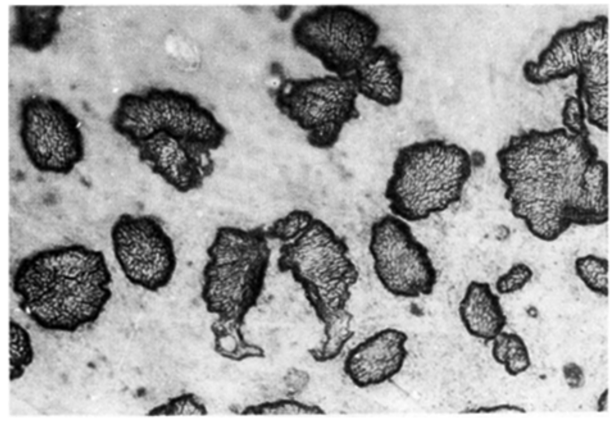


Figure 1 Optical micrograph of cross-section of pineapple leaf fibre, showing multicellular nature of the fibre. $\times 160$.

explained in terms of structural parameters which are studied using optical and scanning electron microscopic (SEM) techniques.

2. Experimental details

The pineapple fibres used in the present study were supplied by Khadi and Village Industries Commission, Trivandrum. An optical microcsope was used to sort out the fibres of different diameters ranging from 45 to 205 μm. A Mettler balance was used to determine the fineness of the fibre of the different ranges of diameter. The density of the fibres was determined using specific gravity bottle with xylene as the liquid. Fibres of 45 to 205 μm diameter and 50 mm gauge length were mounted on cardboard with a central window and tested in an Instron testing machine at a crosshead speed of $10\,mm\,min^{-1}$. Fibres of 150 μm diameter with test length varying between 156 and 65 mm were tested at a crosshead speed of $10\,mm\,min^{-1}$, while fibres of 70 μm diameter and 50 mm test length were tested at various crosshead speeds ranging between 1 and $50\,mm\,min^{-1}$. For taking optical micrographs of the cross-section of the fibre, a bundle of fibres was put vertically in a small glass tube which was then filled with polyester resin and allowed to set. The tube of polyester in which fibres were embedded was then polished gently on the surface using standard methods. The polished flat surface of the tube was then washed, dried and observed under a Metalloplan optical microscope to view the cross-section. For taking SEM photographs of the fractured surfaces, the fibres with fractured tips were mounted on a metallic stud with a hole in it such that the fractured tips projected upwards from the stud. The stud mounted with the fibres was then given a conductive coating of gold in a vacuum coating unit. The fractured tips were then examined with the JEOL SEM (Model 35C). All the tests were carried out at 65% relative humidity (r.h.) at room temperature after conditioning the fibres.

3. Results

3.1. Denier and density of pineapple leaf fibres

The density of the fibres is $1450\,kg\,m^{-3}$. The variation of the denier values with the observed diameter (width) leads us to conclude that the fibres possess a ribbon-type morphology as in sisal fibres [13].

3.2. Optical microscopy

Fig. 1 shows that the pineapple fibre is a multicellular fibre like other vegetable fibres. The cells in this fibre have an average diameter of about 10 μm and mean length of 4.5 mm with a length/diameter (l/d) ratio of 450. The thickness of the cell wall of pineapple fibre is found to be 8.3 μm which lies in between that of sisal (12.8 μm) and banana (1.2 μm).

3.3. Stress–strain characteristics of pineapple fibre

Fig. 2 shows a typical stress–strain diagram of a pineapple fibre of length 50 mm, diameter 115 μm tested at a crosshead speed of $10\,mm\,min^{-1}$. After the initial linear region (characterized by an initial modulus) the curvature observed in the stress – strain curve is found to be very small compared with other vegetable fibres [1]. The fibre finally fails with further increase in stress like brittle materials.

3.4. Effect of diameter/denier of the fibre

Table II illustrates the variation of the different mechanical parameters with diameter, for pineapple fibres of length 50 mm and tested at a crosshead speed of $10\,mm\,min^{-1}$. It can be seen that, unlike banana [14], sisal [13] and coir [15], the initial modulus shows a decrease while the UTS decreases drastically with increasing diameter. On the other hand, the elongation shows little variation with increasing diameter. Fig. 3 shows a linear relationship between breaking strength (σ in $MN\,m^{-2}$) and denier (D) of pineapple fibres given by the regression equation

$$\sigma = 847.5 - 4.72D \qquad (1)$$

with a correlation coefficient of 0.91 significant at the 1% level.

3.5. Effect of test length

Different test lengths of fibres of diameter 0.15 mm were tested at an extension rate of $10\,mm\,min^{-1}$ to determine the effects of test lengths on mechanical properties. Table III lists the different mechanical parameters associated with various test lengths of the

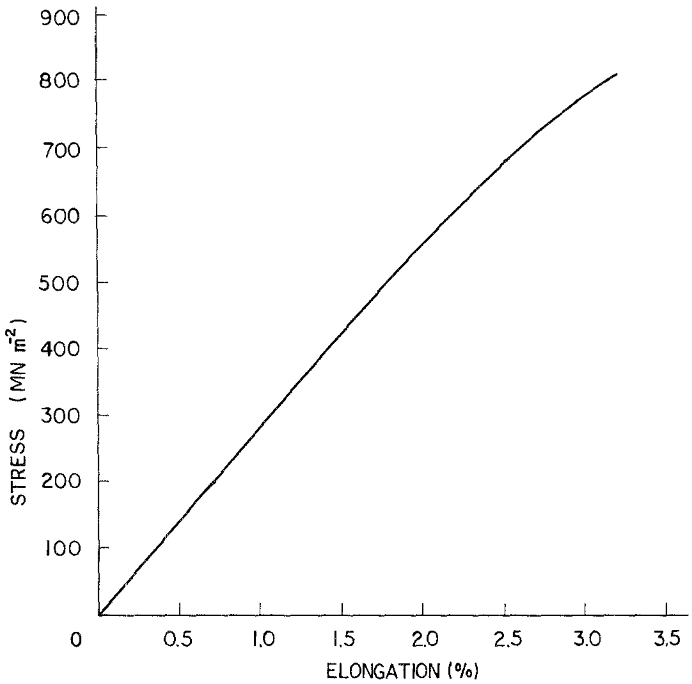


Figure 2 Typical stress–strain curve of pineapple leaf fibre of diameter 115 μm and test length 50mm tested at 10 mm min^{-1}.

fibres. Both UTS and elongation decrease with increase in test lengths, while the modulus shows a marginal increase. Fig. 4 shows a linear relationship [13] between strength σ (MN m^{-2}) and length L (m) of the fibre in the range studied. The equation of the regression line is

$$\sigma = 694.1 - 446.1L \qquad (2)$$

with a correlation coefficient of 0.92 significant at the 1% level.

3.6. Effect of test speed

Table IV lists the observed values of UTS, YM, elongation and average modulus of pineapple fibres of diameter 70 μm and test length 50 mm tested at various test speeds. The results show that there is little variation in the initial modulus and UTS with increase in speed and extension rate. These observations are comparable with those observed with banana fibres [14].

4. Discussion

The observed variation in mechanical properties of these fibres can be explained in terms of structural variables such as the number of cells, cell wall thickness, microfibrillar angle, cellulose content and molecular structure. Other variables such as source, age and processing presumably remain constant in view of the collection of the fibres from the same place.

4.1. Stress–strain curves

The pineapple fibre contains about 82% cellulose [5–7]. Fig. 1 shows very little curvature of the stress–strain curve as well as small elongation, which are characteristics of crystalline fibres. The initial modulus of the fibres can be given by the equation due to McLaughlin and Tait [16]:

$$E_f = W_c E_c \cos^2\theta + W_{nc} E_{nc} \qquad (3)$$

where E_c and E_{nc} are the modulus values of crystalline and non-crystalline regions, taken to be 45 and 4 GN m^{-2}, respectively [16]. For pineapple fibres W_c and W_{nc}, the weight fractions of crystalline and non-crystalline components, are 0.85 and 0.12, respectively, and the microfibrillar angle θ is about 14° [9]. The observed strength of pineapple fibres (24 to 36 GN m^{-2}) agrees well with that calculated (E_f (calc) = 42 GN m^{-2}) using Equation 3.

The initial modulus is due to the resistance of the cellulose molecules to slip past one another. Intermolecular forces present between the cellulose molecules due to hydrogen bonding and van der Waals

TABLE II Variation of mechanical properties with fibre diameter/denier

Diameter/ denier	Initial modulus (GN m^{-2})		Ultimate tensile strength (MN m^{-2})		Elongation at break* (%)
	Mean	S.D.	Mean	S.D.	
0.045/23	35.70	1.42	747.30	99.12	
0.070/33	33.60	4.06	611.10	103.20	
0.090/50	31.50	4.13	628.70	59.00	2.00 to 2.78
0.115/69	28.70	4.60	568.50	97.10	
0.150/76	27.60	3.40	412.00	111.20	
0.205/94	24.30	3.32	361.50	70.77	

S.D. = standard deviation; test length 50 mm; speed of testing 10 mm min^{-1}.
*No significant systematic variation was observed.

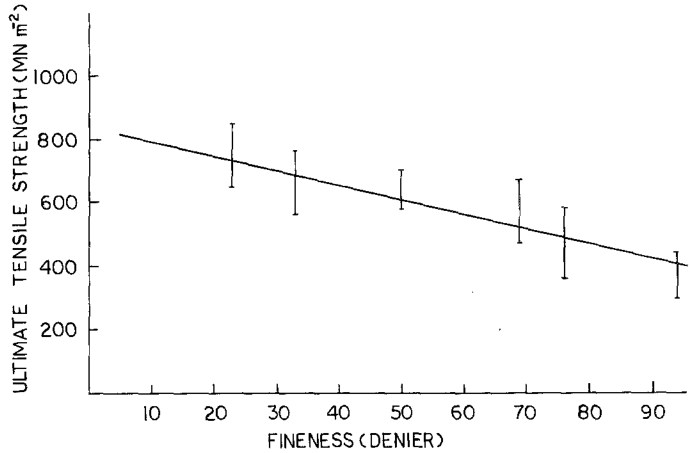


Figure 3 Variation of UTS with fineness (denier) of the fibre tested at 10 mm min^{-1}. Correlation coefficient = −0.91.

forces are the cause of this resistance in the initial region of extension. As the stress is increased further occasional slipping and breakage of the cellulose molecules start especially near the defective regions. In pineapple fibre, having maximum crystallinity, the major share of the load is being taken up by the crystalline fibrils resulting in extension of the helically wound fibrils along with the matrix. With further increase in stress the matrix yields, the primary wall collapses and the cells slip past one another. In pineapple fibres, since maximum load is shared by the crystalline fibrils, the fracture takes place mainly at the defective portion of the crystalline fibrils and through the weak bonding material. The fracture initiated by the defective cells results in stress concentration and finally in fracture of the fibres.

The observed stress–strain curve for pineapple fibres can be understood by the simple two-element viscoelastic model of Maxwell [17] as explained in the case of sisal fibres [13]. However, in the case of pineapple the Hookean nature is more pronounced, indicating a large contribution from the crystalline regions.

4.2. Effect of diameter/denier

Unlike banana [14], sisal [13] and coir [15] fibres, pineapple fibres show a distinct decrease in strength with increasing diameter. A change in the diameter of a fibre is generally accompanied by a change in (a) the microfibrillar angle, (b) the volume fraction of strength-rendering cells, and (c) the flaw or weak-link density. These changes in the physical parameters are likely to affect the strength properties. The decreasing initial modulus with diameter indicates higher elongation for the same applied stress with diameter. This higher elongation associated with larger diameter of the fibre is due to higher microfibrillar angle [9]. However, the large decrease in strength is not due to an increase in microfibrillar angle alone. The number of defects in the cross-section of the fibre increases with diameter, and these defects may be the major cause of the decrease in UTS with diameter. The defects are mainly the voids present in the weak bonding material of the cells.

4.3. Effect of test length

The decrease in UTS and elongation with increase in test length is due to the increase in the probability of occurrence of defects or weak links with test length. Similar observations were also made in the case of sisal [13], banana [14] and coir [15] fibres. The measure of the defect density as determined from the slope of the UTS against gauge length curve is found to be maximum in pineapple fibre, as shown in Table V. With the increase in test length, the stress is distributed over a larger length of the fibre and the total effective resistance offered by the fibre to the applied stress is higher resulting in a smaller elongation initially and hence an increase in initial modulus.

4.4. Effect of speed of testing

The absence of any appreciable change in the mechanical parameters with speed of testing is a clear

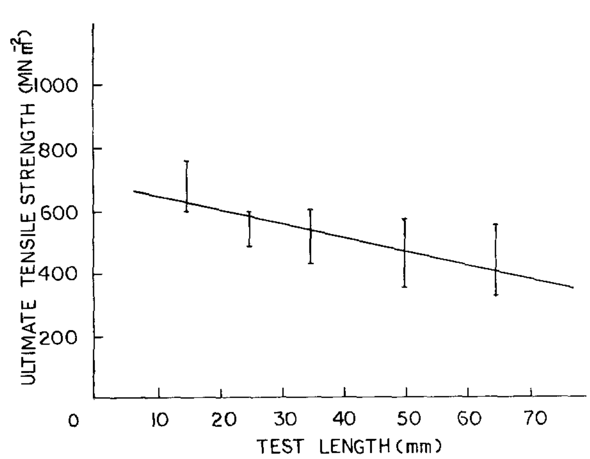
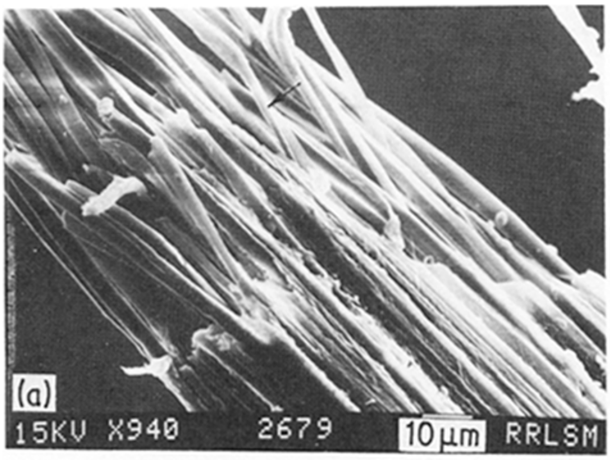


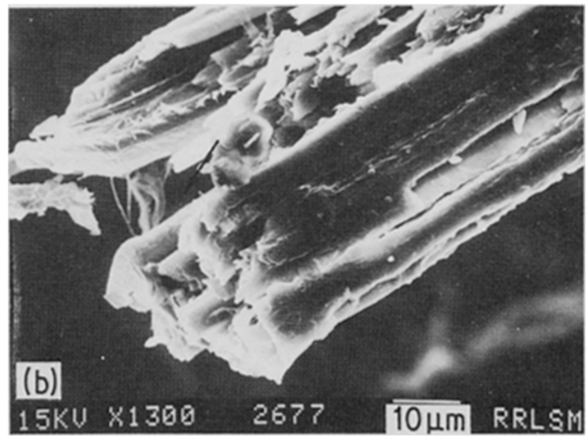
Figure 4 Variation of UTS with test length of the fibre tested at 10 mm min^{-1}. Correlation coefficient = −0.92.

TABLE III Variation of mechanical properties with test length

Test length (mm)	Initial modulus ($GN\,m^{-2}$)		Ultimate tensile strength ($MN\,m^{-2}$)		Elongation at break (%)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
15	16.20	1.57	679.20	80.14	4.93	0.83
25	17.80	0.80	542.50	54.20	3.68	0.64
35	23.30	1.34	509.50	85.20	3.20	0.55
50	27.60	3.40	462.00	111.20	2.45	0.52
65	24.60	2.66	429.50	117.80	2.24	0.47

Diameter of fibres 150 μm; speed of testing 10 mm min^{-1}.





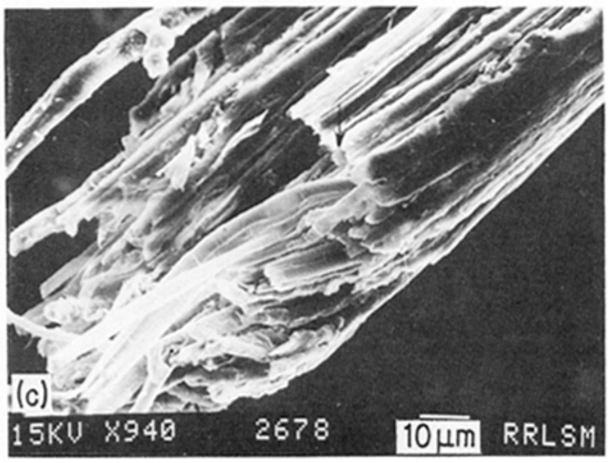


Figure 5 Scanning electron micrographs of the fractured tips of pineapple leaf fibre tested at (a) 1 $mm\,min^{-1}$ showing separation of cells from the weak bonding material; (b) 10 $mm\,min^{-1}$ showing vertical split between the cells; (c) 50 $mm\,min^{-1}$ showing crack initiation through weak and defective cells.

indication of the high crystalline content of the fibres. Such behaviour is observed in metals and crystalline fibres. In the present study with pineapple fibre, the defect content is very high both along the fibre and along the cross-section of the fibre, as revealed from gauge length and diameter variation studies. These defects cause a decrease in strength with increasing strain rate. The role of these defects in the fracture mechanism of this fibre is also clear from the SEM photographs shown in Fig. 5, taken at different speeds. The fracture is always initiated by the defective weak cells along the cross-section, and the crack also propagates later between the cells along the weak bonding material of the fibre irrespective of the speed of testing.

5. Conclusions

1. The observed stress–strain curve for pineapple fibre is largely characterized by its linear nature with very small curvature at higher extension, indicating the presence of a large cyrstalline content.

2. The experimentally observed values of elastic modulus, UTS, and elongation are in the range of 25 to 36 $GN\,m^{-2}$, 362 to 748 $MN\,m^{-2}$ and 2 to 2.8%, respectively, for fibres of diameter 45 to 205 μm. Such a large variation (especially in UTS values) with the diameter of the fibres indicates the presence of considerable defects in the fibres.

3. The elongation and UTS of the fibre decreased from 4.9% and 679.2 $MN\,m^{-2}$ for 15 mm test length to 2.24% and 429.5 MN^{-2} for 65 mm test length, respectively.

4. The mechanical parameters showed marginal changes with change in speed of testing from 1 to 50 $mm\,min^{-1}$. Assuming Maxwell's viscoelastic model, such behaviour is expected in the presence of a large crystalline content in the viscoelastic fibres, as in the present case.

5. The failure mechanism in pineapple fibre is conclusively found to be mainly due to the defects initiating the failure, the crack being propagated both along the fibre and the cross-section of the fibre, resulting finally in fracture of the fibre due to stress concentration.

6. From both the diameter variation as well as the gauge length variation it has been concluded that pineapple fibres have a maximum defect density compared to other natural fibres.

TABLE IV Variation of mechanical properties with test speed

Speed of testing ($mm\,min^{-1}$)	Initial modulus ($GN\,m^{-2}$)		Ultimate tensile strength ($MN\,m^{-2}$)		Elongation at break* (%)
	Mean	S.D.	Mean	S.D.	
1	24.40	1.28	512.90	68.34	
2	27.60	2.15	536.60	66.02	
5	27.20	1.37	584.00	70.54	2.27 to 2.58
10	33.60	4.06	611.10	103.20	
50	34.50	3.12	680.60	108.65	

Diameter of fibres 70 μm; test length 50 mm.
*Systematic significant variation was not observed

TABLE V Density of weak links in plant fibres

Fibre	Density of weak-link (slope of σ against L curve) ($MN\,m^{-3}$)	Correlation coefficient	Significance level (%)
Pineapple	4461.00	0.87	1
Coir [15]	2320.40	0.98	1
Sisal [13]	2368.00	0.80	1
Banana [14]	1376.70	0.77	1

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