Nigerian Journal of Technology (NIJOTECH)
Vol. 41, No. 1 January, 2022, pp.55 –64
www.nijotech.com

Print ISSN: 0331-8443
Electronic ISSN: 2467-8821
http://dx.doi.org/10.4314/njt.v41i1.9

A Review on the Factors Affecting the Properties of Natural Fibre Polymer Composites

C. I. Madueke[1, *], R. Umunakwe[2], O. M. Mbah[3]

[1,2] Department of Materials and Metallurgical Engineering, Faculty of Engineering, Federal University Oye-Ekiti, Ekiti State, NIGERIA.
[3] Department of Mechanical engineering, Faculty of Engineering, Federal University Oye-Ekiti, NIGERIA.

Abstract
Improved quality natural fibre composites cannot be achieved without considering certain factors such as the degree of uniformity of the fibre, wettability of the fibre, fibre length, fibre volume fraction, type of matrix, interfacial bond strength, fibre orientation, compatibility of the fibre with the resin, processing parameters and manufacturing techniques among others. Their influences on the properties of the composites with typical examples from previous works were highlighted. The exact or approximate volume fractions of specific fibres in specific resins for optimal performance in composites are lacking. Epoxy, low density polyethylene, polystyrene and polyester resins were mostly used as matrix for natural fibre composites. Epoxy resins possess higher tensile and flexural strengths than polyester resins. Significant differences in the tensile strength and Young's modulus of natural fibre polymer composites were observed with changes in the orientation and length of the fibres particularly when the differences in length are significant. Other relevant issues affecting natural fibre composites were buttressed with the aim of improving the properties of natural fibre polymer composites for advanced applications.

Keywords: Composites, matrix, natural fibres, processing parameters, tensile properties

1.0 INTRODUCTION

The mechanical properties of polymer composites containing natural fibres as reinforcement are continuously being investigated. These investigations can be attributed to the quest for greener energy and the light weight advantages of natural fibres. This light weight advantage of natural fibres has propelled their adoption in several sectors such as the automotive sector such that natural fibre reinforced polymer composites are currently used in vehicle interior parts such as seat back, interior door panels, spare tyre covers, package trays, map boxes, seat liners, and sun roof frames which weighs 50% less than a metal sun roof frame [1, 2]. With the continuous growth in global motor vehicle production [3] the demand for and the production of natural fibre composites are likely to keep growing. The building, construction and sporting sectors have keyed into the use of natural fibres. Leisure industry stepped up the use of natural fibre via the invention of cellucomp fishing rod made from natural fibre composites [1].

*Corresponding author **(Tel:** +234 (0) 8023536748**)**

Email addresses: chioma.madueke@fuoye.edu.ng (C. I. Madueke), reginald.umunakwe@fuoye.edu.ng (R. Umunakwe), oguejiofor.mbah@fuoye.edu.ng (O. M. Mbah)

Other major key drivers of the use of natural fibre have been sustainability and availability of raw materials [2,4] in addition to low density. Natural fibres are in abundance as shown in Table 1. They possess low density as shown in Table 2 and are therefore considered in low weight applications and for energy savings.

Mechanical properties of natural fibre composites have been studied with different natural fibres and different types of matrices in order to compare their performances with respect to the type of matrix. To achieve improved properties for natural fibre polymer composites, manufacturing method, fibre orientation, fibre volume fraction, type of matrix, and the length of the fibre are all important factor to be given due considerations.

Composites are basically made up of matrices, reinforcements and interfaces. Reinforcements are usually fibres or particulates. Fibers comprise synthetic fibers (glass and carbon) and natural fibers (see Table 1). Natural fibres are mainly from plants, animals or minerals. Some of the factors affecting natural fibre composites are as shown in Figure 1. These factors are explained in the subsequent sections.

© FACULTY OF ENGINEERING, UNN, 2022

Table 1: Global yearly production of technical fibres and their chemical constituents

Type of fibre	Global yearly Production (10^3tonnes)	Av. Cellulose (%)	Av. H/C (%)	Av. Lignin (%)	Av. Moisture content (%)
Ramie	170	76	15	1	8
Coir	650	36-43	10-20	41-45	8
Hemp	214	74	17.9-22.4	3.5-5.7	10
Sisal	378	67-78	10.0-14.2	8-11	11

Sources:[5–8] *H/C=hemicellulose*

Table 2: Density and tensile properties of some natural fibres used for technical applications

Fibre	Tensile strength (MPa))	Young's modulus (GPa)	Elongation at break (%)	Density (kg/m^3) (Wt %)
Ramie	400-938	61.4-128	3.6-3.8	-
Coir	175	4.0-6.0	30	1200
Hemp	690	-	1.6	-
Sisal	511-635	9.4-22	2.0-2.5	1500

Source: [9]

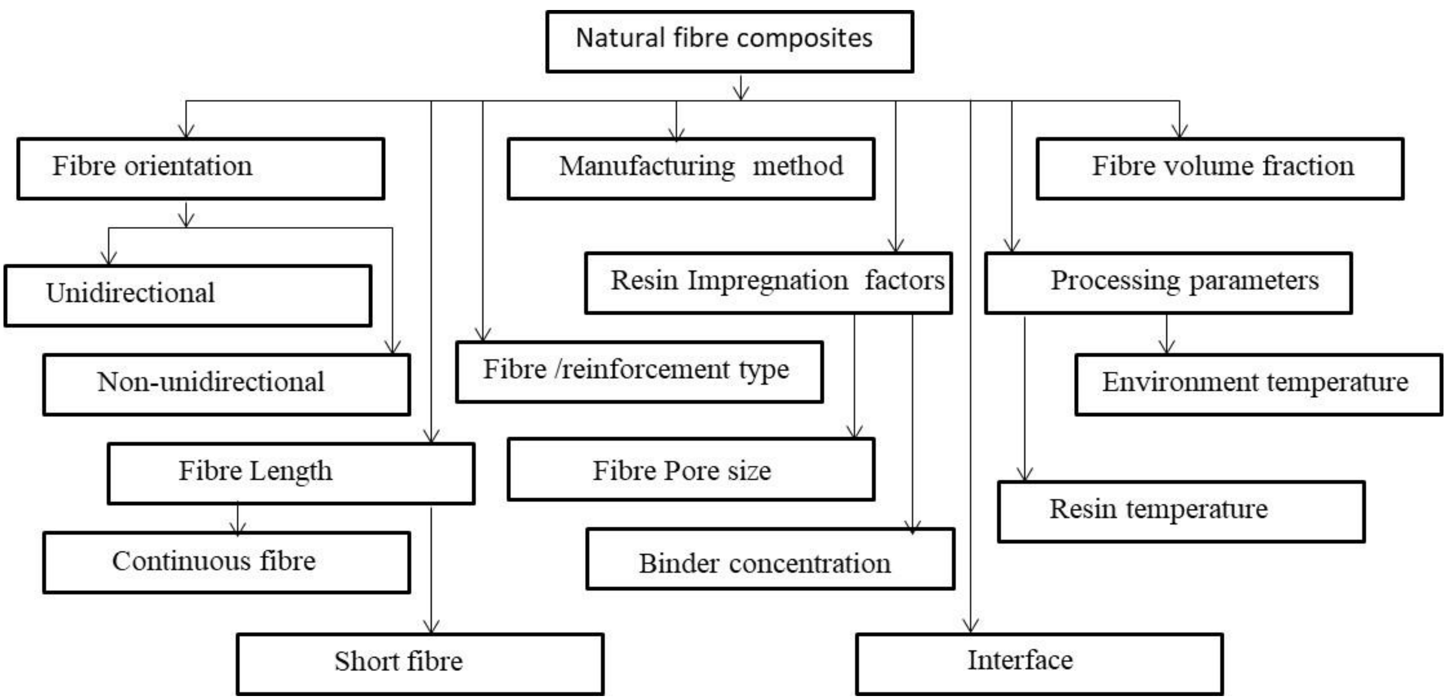

Figure 1: Factors affecting the properties of natural fibre composites adapted from [10,11]

2.0 FACTORS AFFECTING THE PROPERTIES OF NATURAL FIBRE COMPOSITES

2.1 Types of Matrices

Polymer matrix is made up of thermoset and thermoplastics. Thermoplastic polymers such as polypropylene, polystyrene and polyethylene are recyclable and can be heated to melt and solidify on cooling. However, thermosets once they cure cannot be melted hence thermosets are non-recyclable; examples are epoxy, polyurethane and phenolics. Polymers that have been used as matrix to manufacture natural fibre composites include polypropylene, polystyrene, polyethylene, epoxy resin, polyester resin, low density polyethylene (LDPE), polystyrene and many others.

Matrix is used as a binder for reinforcing fibers. Matrix locks the fibres in place and protects the fibre from environmental factors and also protects the fibres from its immediate neighbour transferring the applied stress to the fibre [12–14]. Therefore, to make a suitable selection of the matrix, the type of reinforcement to be used must be given adequate attention. The manufacturing techniques to be adopted are based on the type of resin and fibre as well [10,15,16]. Thermoset resins such as epoxy resins crosslink on curing or by heating. Epoxy and polyester resins have been considerable used for natural fibre polymer composites. Examples of epoxy resins that have been used include Araldite LY 3505, CY205 and Hardener XB 3403, HY951. The epoxy and hardener are usually mixed in a given stoichiometric ratio. End tab resins used include super glue cyanoacrylate general purpose adhesive and Scotch-welds (Parts A and B) blended in a specific ratio. Natural fibres are known for their degradation at elevated temperature and therefore they are required to cure well below their degradation temperature therefore thermoset resins are a choice resin for natural fibres since thermoset resins cure at room temperature coupled with their bond capabilities with natural fibres. Epoxy resins mostly applied for natural fibre composites and most widely used is diglycidyl ether of Bisphenol-A [17] with amine hardener as the curing agent. Table 3 shows the tensile properties of epoxy and polyester resins used as composite matrices. Susceptibility to moisture absorption of natural fibres and poor wettability of the resin have been mentioned as some of the factors that affect natural fibre composites [18,19]. Transition temperature of the matrix is a key factor for selecting the type of matrix to be used with natural fibre reinforcement [20]. The transition temperatures are as follows [20].

Tm= Crystalline melting temperature; Tp = processing temperature

Td =degradation temperature; Tg= glass transition temperature

Matrixes usually used in the natural fibre composites manufacture include polyester and epoxy matrixes among others. Cure sets in after homogenous mixings of the components. The level of cure and viscosity has been noted to increase with time.

Table 3: Comparisons of the tensile and flexural properties of epoxy and polyester thermoset matrices

Type of Matrix	Tensile strength and Modulus		Flexural strength and modulus	
	Av. strength (MPa)	Av. modulus (GPa)	Av. strength (MPa)	Av. modulus (GPa)
Epoxy	47.29 ± 2.02	2.24 ± 0.11	69.26 ± 3.96	2.14 ± 0.04
Epoxy	24.78	N/A	N/A	N/A
Polyester	39.80 ± 3.05	2.44 ± 0.14	55.85 ± 2.91	2.19 ± 0.08
Polyester	24.0 ± 0.96	2.8 ± 0.27	65.1 ± 2.62	3.0 ± 0.06

Sources [21–23]. Av=average

2.2 Reinforcements

Reinforcements in form of fibres carry the applied load and provide strength and support to the composites. Reinforcements carry more than 70% of the applied load [24,25]. Some of the reinforcements that have been used in natural fibre composites are classified in Figure 2. Fibres with very high length-to-diameter ratio (continuous fibres) offer better strength and stiffness than discontinuous fibres. Discontinuous fibres, (fibres whose lengths are up to 100 x their diameter) are mostly used for large scale production [26]. Thin fibres are noted for improved strength properties provided they are mechanically well-attached or embedded in the matrix.

The presence of void/gaps within the fibre layout have been reported to result in reduced tensile strength see Figure 3 where coir fibres for composite manufacture were aligned manually; the reported tensile strength after composite manufacture using these manually aligned coir fibres was 30.44 MPa.

2.3 Fibre/matrix interface

Interface plays significant role in the properties of manufactured composites and should be given considerable attention. Interface can be described as the meeting points of the matrix and the fibre reinforcement (enclosed region between the constituents of the matrix and the fibre reinforcement). The interface permits load transfer and dictates the failure mode of the composites. The interaction of the fibres and matrix gives rise to an additional behaviour of the composite. The interface has rather been described by the interfacial energy (J/m^2) and the interfacial frictional shear stress (MPa). Wetting is necessary for fibre-matrix adhesion. The degree of adhesion controls the efficiency of stress transfer from the resin to the fibre at the interface region [30].

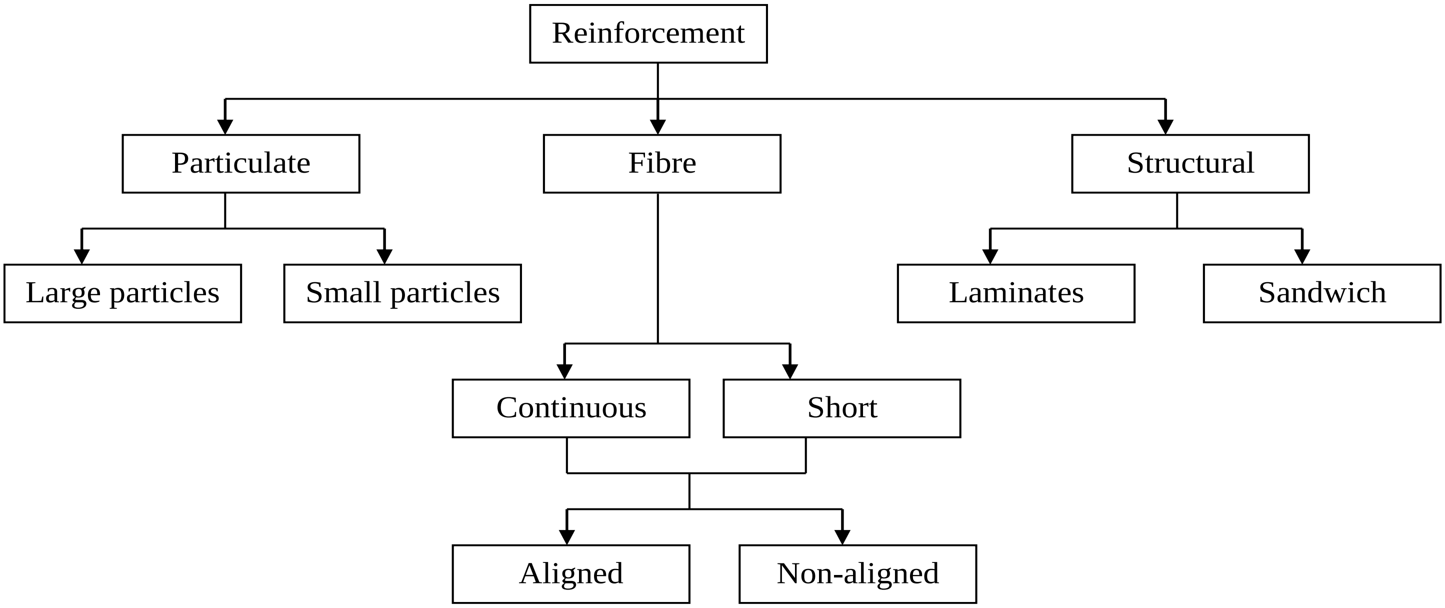

Figure 2: Various forms and orientations of reinforcements adapted from [27,28].

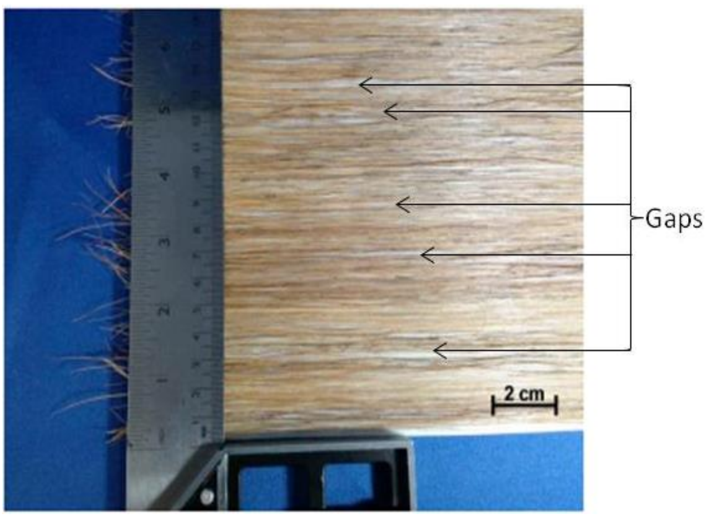

Figure 3: Coir fibres aligned without special means showing holes/gaps in-between the aligned fibres [29].

The adhesion at the fibre-matrix interface can be explained through an interaction of physical adhesion through a good wettability between the fibre and the matrix, chemical bonding with
mechanical interlocking is also essential for good interfacial adhesion. However these interactions are dependent on the functional groups on the surface of the fibre and matrix at the interfacial contact area [31]. The level of adhesion of fibre and matrix is determined by their interfacial shear strength (IFSS). The IFSS is measured by using the fibre pull-out test [32,33].Treatment of fibre has been well reported to improve the interfacial bond strength. For example, NaOH treatment has been reported to create rougher surfaces on the fibre thereby making possible the interlocking of the fibres with the matrix [34–36] . Other such surface treatments include acetylation, use of coupling agent such as silane.

2.4 Processing parameters

Natural fibres are still far behind synthetic fibre composites both in production and in application owing to a number of reasons. The reasons include: lack of technical advancements and standardization in the raw materials manufacturing process, non-availability of enhanced equipment in the processing of natural fibre which reduces efficiency and rate of production. Natural fibres have been noted to be influenced by processing temperatures and are therefore subject to different levels of degradation with increase in temperature. Natural fibres can begin to degrade at temperatures within the range of 170-200 ºC [37–39] resulting to changes on their properties hence transition temperature of the matrix is a key factor for selecting the type of matrix to be used with natural fibre reinforcement. An indirect variation of tensile strength with mixing temperature and time has been reported on research consisting of composites using polypropylene matrix and wood fibre reinforcement [14].

2.5 Impregnation using resin

Natural are highly porous [40,41]. Fibre impregnation by resin application can considerably be influenced by the presence of pores and the manner in which the pores are distributed. According to [42], the degree of wetting and permeability by resin and the uniformity of the resin within the fibre as well as the application pressure of the resin affects to a large extent the outcome and the properties of the composites. This can be described using the Navier Stokes equation for motion of fluid;

$$\gamma_u \left(\frac{\partial v}{dt} + v.\nabla v\right) = \eta.\nabla^2 v + f \quad (1)$$

γ_u = fluid viscosity
v =velocity of flow within the time (t)
η = the dynamic viscosity
f= forces exerted on the fluid

2.6 Manufacturing methods

Natural fibres are known for their non-uniformity, porosity and moisture affinity, they are susceptible to temperature. They are therefore affected by the manufacturing method used in the manufacture of their composites. According to [20] the factors mitigating the manufacturing techniques for natural fibre composites include the hydrophilicity of the fibre, its sensitivity to temperature and the resin rheological properties of the impregnating resin. Spray and hand lay up are adopted for low performance composite parts, however this can result to increased void percentage in the formed composites. For more expensive and higher performance composites parts, vacuum bagging, compression moulding, hot compaction using steel mould plates and autoclave have been recommended. Resin transfer moulding (RTM) has been used to produce small to medium sized parts of some complicated shapes. Others include; hot-pressing, hand lay up and compression moulding among others [43,44] . The factors for concern in hot press include the pressure, dwell time, temperature, the thickness of the specimens as well as the viscousity of the matrix to reduce to the barest minimum; residual stresses, spurtouts, warpage, scorchinm and sink marks [10].

In hand layup, impregnation of the fibres are manually carried out therefore hand lay up are affected by the expertise and experience of the manufacturer. The materials usually used to aid hand lay up for even and smooth impregnation includes rollers, resin injectors and brushes. After impregnation, the samples can be left to cure at room temperature for a day or more depending on the temperature and humidity of the environment however, post cure usually takes place in air or vacuum oven for a specific period of time. Critical factors in the manufacture of natural fibre composites include processing temperature and mixing time. Table 4 shows the tensile properties obtained using different manufacturing techniques such as film stacking and injection moulding to compare the tensile properties of flax/Polylactic acid (Flax/PLLA). Film stacking displays better tensile properties than injection moulding. This can be attributed to exposure of the fibres to more uniform spreading and hence more efficient impregnation and reduced sharing while fibre build up from injection pressure could have resulted to lower tensile properties of the composites manufactured using injection moulding method.

Table 4: Comparisons of tensile properties of natural fibre composites manufactured using different manufacturing techniques

Natural fibre composite type	Manufacturing method	Volume fraction of fibre (%)	Av. Tensile strength (MPa)	Av. Tensile Modulus (GPa)	Av. elongation at break (%)
Flax/PLLA	Injection	26	53.1	7.32	1.2
Flax/PLLA	Film-stacking	25	81.3	8.86	1.2
Coir/epoxy	Hand layup	NA	17.86	N/A	N/A
Coir/epoxy	Hand lay up	30	30.44	2.82	1.00

Sources:[45–49].

2.7 Fibre orientation

Orientation of fibres for composite manufacture plays a significant role in the properties of the manufactured composites. Fibres could be randomly or unidirectionally arranged. The degree of fibre orientation has been obtained using image analysis and sagittal image processing to determine the extent of fibre orientation of polished crisp image. Equal fibre volume fractions of Sisal/LDPE composites were manufactured with the fibres unidirectionally arranged and with fibres randomly arranged; the tensile strength and Young's modulus of the unidirectional fibre composites were found to be 53 and 75% higher than the composites with randomly arranged fibres respectively [50]

An increase in the tensile strength and Young's modulus were observed for longitudinally aligned fibre composites because the fibres were in perpendicular orientation to the crack propagation resulting to increase in both the tensile strength and the Young's modulus of the composites [51]. Lower tensile properties were observed in composites containing fibres with transverse orientation, the stresses were not uniformly distributed but they were highly localized leading to significant reduction in strength as shown in Table 5.

Higher efficiency in the transfer of stress has been observed when fibres are in parallel alignment to or in the same direction (0°) with the direction of applied force.

Table 5: Comparisons of the tensile properties of natural fibre composites with different fibre orientations

Type of composite	**Fibre orientation**	**Tensile Strength (MPa)**	**Young's Modulus (GPa)**	**Elongation at break (%)**	**Fibre volume fraction (%)**
Banana stem & Natural rubber	0°	3.7	-	42	N/A
Sisal & LDPE	Random	14.70	0.78	7.00	
Sisal & LDPE	UD	31.12	3.09	2.00	30
Kenaf & PLA cross ply (Composite A)	0° & 90°	66.5	4.2	2.3	
Kenaf & PLA (Composite B)	45° & -45°	54.0	3.5	2.2	N/A
Kenaf & PLA	UD at 0°	111.6	5.9	2.7	
Sisal & polystyrene	Longitudinal	45.06	1.00	7	
Sisal & polystyrene	Transverse	11.04	0.58	2	N/A
Sisal & polystyrene	Random	20.42	0.62	4	

Sources:[50–53]. UD = unidirectional

2.8 Fibre length/diameter

The variable diameter of natural fibres has been reported to affect their mechanical properties such as their tensile strength. An inverse relation between the diameter and the strength has been well reported [32,54,55]. A hyperbolic inverse correlation of the fibre diameter and the strength of the fibre has been stipulated (56) and it is given in equation (2):

$$\sigma = \frac{A}{d} - B \tag{2}$$

where σ is the variation of strength, d is the diameter of the fibre and A and B are constants. The relationship between the fibre Young's modulus and diameter is displayed by Griffith's as shown in equation 3:

$$E_f\left(d_f\right) = A + \frac{B}{d_f} \tag{3}$$

.

where the diameter and the Young's modulus of the fibre are denoted by d_f and $E_f\left(d_f\right)$ respectively and A and B are constants. An increase in the tensile strength by 64% as the coir fibre diameter decreased has been reported [57], similar findings was reported by [55] on Brazillian fibres. Increase in gauge length has been reported to result to decrease in strength [58]. In the sisal/LDPE composites at 30% volume fraction of the fibre, the difference in both tensile and Young's modulus of the composites at different fibre lengths is negligible [56] however on changes in fibre length from 2.1mm to 5.8mm, a significant increase in tensile strength and modulus were recorded [50],on further increase of the fibre length (to 9.2 mm), a significant drop in the tensile strength and Young's modulus was reported (see Table 6). According to [51] as the fibre length increases, the orientation of the fibres improves and an improvement in the tensile properties is observed. Different critical fibre lengths exist for different fibres

Table 6: Comparisons of the tensile properties of natural fibre composites at different fibre lengths

Type of composite	Length of the fibre (mm)	Av. Tensile Strength (MPa)	Av. Young's Modulus (GPa)	Av. Elongation at break (%)
	113.00	19.20	0.84	8.8
Flax/polyester	181.00	19.40	1.11	6.1
	226.00	21.40	1.23	7.2
	2.10	20.50	1.69	4.0
Sisal/LDPE	5.80	31.12	3.09	2.0
	9.20	25.90	1.72	4.0
Polystyrene/ Sisal fiber	2.00	21.12	0.67	6.0
	6.00	21.30	0.63	9.0
	10.00	25.06	0.66	N/A

Sources: [50–52,59].

2.9 *Volume fraction of the fibre*

Volume fractions of the fibre in composites have been reported by several authors to have a significant impact on the tensile properties of the resulting composites. On a 100% increase of the volume fraction of sisal fibre in Low density polyethylene matrix (LDPE), the tensile strength increased from 15.61 to 21.66 MPa, the Young's modulus jumped from 1.43 to 2.09 GPa, however, the elongation at break of the composites were observed to decrease [60].

Table 7 shows that when the volume fraction of sisal fibre was increased by more than 20%, the tensile strength and stiffness of the composite increased from 21.3 to 45.06 MPa and from 0.63 to 1.00 GPa respectively. The explanation is that as the fibre content increases in the composite, a more uniform stress distribution is experienced and hence considerable improvement on the tensile properties [50,51,61].However, definite increase in the fibre loading does not result to definite increase in the tensile properties of the composite because there exists a critical volume above which further increase in the volume of the fibres results to decrease in the tensile properties. According to findings, at much lower fibre content of about 2.7 and 10% for sisal and pineapple leaf respectively, the fibres act only as flaws in the composites and they are not sufficient to restrain the matrix leading to low stresses and consequently debonding of the fibres [51,61].

Table 7: Comparisons of the tensile properties of natural fibre composites at different volume fractions of the fibre

Natural fibre composite type	Av. Tensile strength (MPa)	Av. Young's modulus (GPa)	Av. Elongation at break (%)	Volume fraction of the fibre (%)
Sisal & LDPE	15.61	1.43	4	10
	21.66	2.09	3	20
	31.2	3.02	2	30
Sisal &Polystyrene	21.30	0.63	9	10
	43.20	1.00	8	20
	45.06	1.00	7	30
Pineapple leaf & PP	36	0.55	17	2.7
	37	0.62	15	5.4
	38	0.70	13	10.8

Sources:[50,51,60]

3.0 CONCLUSION

For enhanced quality natural fibre composites to be achieved certain factors such as the degree of uniformity of the fibre, wettability of the fibre, fibre length, fibre volume fraction, processing parameters and fibre orientation among others must be given due considerations. The effects of these factors on the tensile properties of natural fibre polymer composites have been highlighted. The exact or approximate volume fractions of specific fibres in specific resins for optimal performance in composites are lacking. Significant differences in the tensile strength and Young's modulus of natural fibre polymer composites were observed with changes in the orientation and length of the fibres particularly when the differences in length are significant. The effects of the above mentioned factors on other mechanical properties other than tensile properties need to be reviewed with aim of improving the overall properties of natural fibre polymer composites for advanced use.

REFERENCES

[1] Suddell, B. C. "Industrial fibres: Recent and current developments". *Proc Symp Nat Fibres*, 44(0), 2008, pp. 71–82.

[2] Chauhan, V., Kärki, T and Varis, J. "Review of natural fiber-reinforced engineering plastic composites, their applications in the transportation sector and processing techniques". *J Thermoplast Compos Mater*, 2019, pp. 1-41.

[3] International Organization of Motor Vehicle Manufacturers (OICA), 2019, pp. 2018–9

[4] Khan, T., Hameed, S., Bin, M.T and Ariffin, A.H. "The challenges of natural fiber in manufacturing, material selection, and technology application: A review". *J Reinf Plast Compos*. 37(11), 2018, pp. 770–9.

[5] Satyanarayana, K.G., Sukumaran, K., Mukherjee, P.S and Pillai, S.G.K. "Materials science of some lignocellulosic fibers". *Metallography*. 19(4), 1986, pp. 389–400.

[6] Mwaikambo, L.Y and Ansell, M.P. "The determination of porosity and cellulose content of plant fibers by density methods". *J Mater Sci Lett*. 20(23), 2001, pp. 2095–6.

[7] Malkapuram, R., Kumar, V and Negi,Y.S. "Recent Development in Natural Fiber Reinforced Polypropylene Composites", 28(10), 2009.

[8] Varma, D.S., Varma, M and Varma, I.K. "Thermal behaviour of coir fibres". *Thermochim Acta*. 108(C), 1986, pp. 199–210.

[9] Vijayan, R and Krishnamoorthy, A. "Review On Natural Fiber Reinforced Composites". *Mater Today Proc*. 16, 2019, pp. 897–906.

[10] Ho, M., Wang, H., Lee, J.H., Ho, C., Lau, K., Leng, J., et al. "Critical factors on manufacturing processes of natural fibre composites". *Compos Part B Eng*. 43(8), 2012, pp. 3549–62.

[11] Thakur, V.K., Thakur, M.K and Gupta, R.K. "Raw Natural Fiber" – B*ased Polymer Composites*, 2014, pp. 256–7.

[12] Brothers, J and Lanka, S. "Composite Applications using Coir Fibres in Sri Lanka Final Report partners : Development". 2003.

[13] Doan, T., Gao, S and Ma, E. "Jute / polypropylene composites I". *Effect of matrix modification*. 66, 2006, pp. 952–63.

[14] Cheung, H., Ho ,M., Lau, K., Cardona, F, Hui D. "Natural fibre-reinforced composites for bioengineering and environmental engineering applications". *Compos Part B Eng*. 40(7), 2009, pp. 655–63.

[15] Saheb, N and Jog, J. "Natural Fiber Polymer Composites : A Review". *Adv Polym Technol*. 2329, 2015, pp. 351–63.

[16] Gassan, J and Bledzki, A.K. "Possibilities for improving the mechanical properties of jute/epoxy composites by alkali treatment of fibres". *Compos Sci Technol*. 59(9), 1999, pp. 1303–9.

[17] Pei, Y., Wang, K., Zhan, M., Xu, W and Ding, X. "Thermal-oxidative aging of DGEBA / EPN / LMPA epoxy system : Chemical structure and thermal e mechanical properties". *Polym Degrad Stab*. 96(7), 2011, pp. 1179–86.

[18] Peças, P., Carvalho, H,. Salman, H and Leite, M. "Natural Fibre Composites and Their Applications: A Review". *J Compos Sci*. 2(4), 2018, pp 66.

[19] Dhaliwal, J. "Natural Fibers: Applications". *Intech* . 2019.

[20] Summerscales, J and Grove, S. "Manufacturing methods for natural fibre composites" . *Natural Fibre Composites: Materials, Processes and Applications. Woodhead Publishing Limited*; 2013, pp. 176–215.

[21] Dos Santos, J.C., Siqueira, R.L, Vieira, L.M.G., Freire, R.T.S., Mano, and Panzera, T.H. "Effects of sodium carbonate on the performance of epoxy and polyester coir-reinforced composites". *Polym Test*. 67, 2018, pp. 533–44.

[22] Elbadry, E.A., Aly-Hassan, M.S and Hamada, H. "Mechanical properties of natural jute fabric/jute mat fiber reinforced polymer matrix hybrid composites". *Adv Mech Eng*., 2012.

[23] Akash, S., Rao, K .V., Venkatesha Gupta, N.S., Arun, K. "Mechanical Properties of Sisal/Coir Fiber Reinforced Hybrid Composites Fabricated by Cold Pressing Method". *IOP Conf Ser Mater Sci Eng*. 149(1), 2016

[24] Gu, H. "Tensile behaviours of the coir fibre and related composites after NaOH treatment". *Mater Des*. 30(9), 2009, pp. 3931–4.

[25] Sonparote, P.W and Lakkad, S.C. "Mechanical properties of carbon/glass fibre reinforced hybrids".

Fibre Sci Technol. 16(4), 1982, 309–12.

[26] Hill, C.A.S and Khalil, H.P.S.A. "Effect of fiber treatments on mechanical properties of coir or oil palm fiber reinforced polyester composites". *Appl Polym Sci*. 78, 2000.

[27] Yang, Y., Boom, R., Irion, B., van Heerden, D.J., Kuiper, P and de Wit, H. "Recycling of composite materials". *Chem Eng Process Process Intensif*. 51, 2012, pp. 53–68.

[28] Kumar, S and Mallesh, D.S.G. "Evaluation of Mechanical Properties of Sisal / Glass Fiber Reinforced Epoxy Composites". *Int J Eng Res Technol*. 9(07), 2020, pp. 1122–7.

[29] Kim, H. "Hybrid composites with natural fibres. dessertation", 2014.

[30] Tran, L.Q.N., Fuentes, C.A., Dupont-Gillain, C., Van Vuure, A.W and Verpoest, I. "Understanding the interfacial compatibility and adhesion of natural coir fibre thermoplastic composites". *Compos Sci Technol*. 80, 2013, pp. 23–30.

[31] Tran, L.Q.N., Fuentes, C.A., Dupont-Gillain, C., Van Vuure, A.W and Verpoest, I. "Wetting analysis and surface characterisation of coir fibres used as reinforcement for composites". *Colloids Surfaces A Physicochem Eng Asp*, 377(1–3), 2011, pp. 251–60.

[32] Fiore, V., Scalici, T., Nicoletti, F., Vitale, G., Prestipino, M and Valenza, A. "A new eco-friendly chemical treatment of natural fibres: Effect of sodium bicarbonate on properties of sisal fibre and its epoxy composites". *Compos Part B Eng*. 85, 2016, pp. 150–60.

[33] Bakri, Putra, A.E.E., Renreng, I., Arsyad, H and Mochtar, A.A. "Sodium bicarbonate treatment of coir fiber on wettability and shear strength of coir fiber-epoxy composite". *J Phys Conf Ser*. 1242(1), 2019.

[34] Yan, L., Chouw, N., Huang, L and Kasal, B. "Effect of alkali treatment on microstructure and mechanical properties of coir fibres , coir fibre reinforced-polymer composites and reinforced-cementitious composites". *Constr Build Mater*. 112, 2016, pp. 168–82.

[35] Nam, T.H., Ogihara, S., Tung, N.H and Kobayashi, S. "Effect of alkali treatment on interfacial and mechanical properties of coir fiber reinforced poly(butylene succinate) biodegradable composites". *Compos Part B Eng*. 42(6), 2011, pp. 1648–56.

[36] Shehu, U., Isa, M.T., Aderemi, B.O and Bello, T. K. "Effects of NaoH modification on the mechanical properties of baobab pod fiber reinforced ldpe composites". *Niger J Technol*. 36(1), 2017, 87–95.

[37] Van Dam, J.E.G., Van Den Oever, M.J.A., Teunissen, W., Keijsers, E.R.P and Peralta, A.G. "Process for production of high density/high performance binderless boards from whole coconut husk. Part 1: Lignin as intrinsic thermosetting binder resin". *Ind Crops Prod*. 19(3), 2004, 207–16.

[38] Ezekiel, N., Ndazi, B., Nyahumwa, C and Karlsson, S. "Effect of temperature and durations of heating on coir fibers". *Ind Crop Prod*. 33(3), 2011, pp. 638–43.

[39] Dicker, M.P.M., Duckworth, P.F,, Baker, A.B., Francois, G., Hazzard, M.K and Weaver, P.M. "Green composites: A review of material attributes and complementary applications". *Compos Part A Appl Sci Manuf*. 56, pp. 280–9, 2014.

[40] Luz, F.S., Paciornik, S., Monteiro, S.N., Silva, L.C and Tommasini, V.I.O.J. "Porosity Assessment for different diameters of coir lignocellulosic fibers". *Miner Met Mater Soc Porosity*. 69(10), 2017, 2045–51.

[41] Tran, L.Q.N., Minh, T.N., Fuentes, C.A., Chi, T.T., Van Vuure, A.W and Verpoest, I. "Investigation of microstructure and tensile properties of porous natural coir fibre for use in composite materials". *Ind Crops Prod*. 65, 2015, 437–45.

[42] Nieves Bogonez, F.D. "Fibre spreading and impregnation monitoring". PQDT - UK & Ireland. 2014.

[43] Rao, K.M.M., Rao, K.M and Prasad, A.V.R. "Fabrication and testing of natural fibre composites : Vakka , sisal , bamboo and banana". *Mater Des*.31(1), 2010, 508–13.

[44] Joseph, P .V., Rabello, M.S., Mattoso, L.H.C., Joseph, K and Thomas, S. "Environmental effects on the degradation behaviour of sisal fibre reinforced polypropylene composites". 62, 2002, pp. 1357–72.

[45] Bodros, E., Pillin, I., Montrelay, N and Baley, C. "Could biopolymers reinforced by randomly scattered flax fibre be used in structural applications ?" 67, 2007, pp. 462–70.

[46] Garkhail, S. "Composites based on natural fibres and thermoplastic matrices". *PhD Thesis Univ London*. (October), 2001.

[47] Ouagne, P., Bizet, L.B and Baley, C.B. "Analysis of the Film-stacking Processing Parameters for PLLA / Flax Fiber Biocomposites". *J com*. 44(10), 2010.

[48] Rait, G.K. "Effect of Surface Treatments on the Mechanical Properties of Coir Fibres and Coir Fibre Reinforced Composites". 2014.

[49] Harish, S., Michael, D.P., Bensely, A., Lal, D.M and Rajadurai, A. "Mechanical property evaluation of natural fiber coir composite". *Mater Charact*. 60(1), 2009, pp.44–9.

[50] Joseph, K and Thomast, S. "Effect of chemical treatment on the tensile properties of short sisal fibre-reinforced polyethylene composites". 37(23), 1996, pp. 5139–49.

[51] Nair, K.C.M., Diwan, S.M and Thomas, S. "Tensile properties of short sisal fiber reinforced polystyrene composites". *J Appl Polym Sci*. 60(9), 1996, pp. 1483–97..

[52] Ben, G., Kihara, Y., Nakamori, K and Aoki, Y. "Examination of heat resistant tensile properties and molding conditions of green composites composed of kenaf fibers and PLA resin". *Adv Compos Mater Off J Japan Soc Compos Mater*. 16(4), 2007, pp. 361–76.

[53] Ezema, I.C., Edelugo, S.O., Omah, A.D and Agbo, I.U. "Ply tensile properties of banana stem and banana bunch fibres reinforced natural rubber composite". *Niger J Technol*. 31(1), 2012, pp. 25–30

[54] Mukherjee, P.S and Satyanarayana, K.G. "Structure and properties of some vegetable fibres - Part 1 Sisal fibre". *J Mater Sci*.19(12), 1984, pp. 3925–34.

[55] Tomczak, F., Sydenstricker, T.H.D and Satyanarayana, K.G. "Studies on lignocellulosic fibers of Brazil. Part II: Morphology and properties of Brazilian coconut fibers". *Compos Part A Appl Sci Manuf*. 38(7), 2007, pp. 1710–21.

[56] Monteiro, S.N., Lopes, F.P.D., Barbosa, A.P., Bevitori, A.B., Amaral, Da Silva, I.L and Da Costa, L.L. "Natural lignocellulosic fibers as engineering materials-An overview". *Metall Mater Trans A Phys Metall Mater Sci*. 42(10), 2011, pp. 2963–7.

[57] Mathura, N and Cree, D. "Characterization and mechanical property of Trinidad coir fibers". *J Appl Polym Sci*.133(29), 2016, pp. 1–9.

[58] Alves Fidelis, M.E., Pereira, T.V.C., Gomes, O.D.F.M., De Andrade Silva, F and Toledo Filho, R.D. "The effect of fiber morphology on the tensile strength of natural fibers". *J Mater Res Technol*. 2(2), 2013, pp. 149–57.

[59] Baiardo, M., Zini, E and Scandola, M. "Flax fibre – polyester composites". 35, 2004, pp. 703–10.

[60] Arib, R.M.N, Sapuan, S.M and Ahmad, M.M.H.M. "Materials & Design Mechanical properties of pineapple leaf fibre reinforced polypropylene composites". 27, 2006, pp. 391–6.

[61] Geethamma, V.G, Thomas Mathew, K., Lakshminarayanan, R., Thomas, S. "Composite of short coir fibres and natural rubber: effect of chemical modification, loading and orientation of fibre. Polymer (Guildf)". 39(6–7), 1998, pp. 1483–91.