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REVIEW PAPER

A comprehensive review on the mechanical, physical, and thermal properties of abaca fibre for their introduction into structural polymer composites

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Abstract Abaca is a strong competitor among natural fibres for use as the reinforcement of polymer composites. Due to its high durability, considerable fibre length, flexibility and mechanical strength, abaca shows good potential as a renewable source of fibres for application in technological and industrial fields. Discussing the influence of various treatment strategies, such as alkali and silane, for the preparation of abaca-based composites results in the improvement of their properties over that of bare polymer materials and that of other synthetic fibres. The enhanced characteristics of abaca fibre reinforced composites are widely explored for a variety of applications in automotive and other industries. These include for example roping and woven fabrics, currency notes, cigarette filter papers, vacuum bags, tea bags, cellulose pulp for paper and packaging, and materials for automotive components, etc. In particular, the effective use of abaca fibre reinforced polymer composite in manufacturing external parts of cars, using therefore also thermoplastic matrices, has become popular. The gaps in research from the literature that show the scarcity of studies on topics such as simulation and designing of mechanical characteristics of abaca fibre composites constructed on polymer matrices, such as epoxy, polylactide, high density polyethylene, phenol formaldehyde and polyester are also highlighted. The results indicate that abaca is particularly flexible to be used in different sectors, in combination with various matrices, and in hybrid composites with various fibres. Further work would necessarily involve the larger consideration of abaca textiles with different areal weights in the production of composites, and a widespread introduction of abaca in datasets for the automated selection of natural fibres for composites reinforcement.

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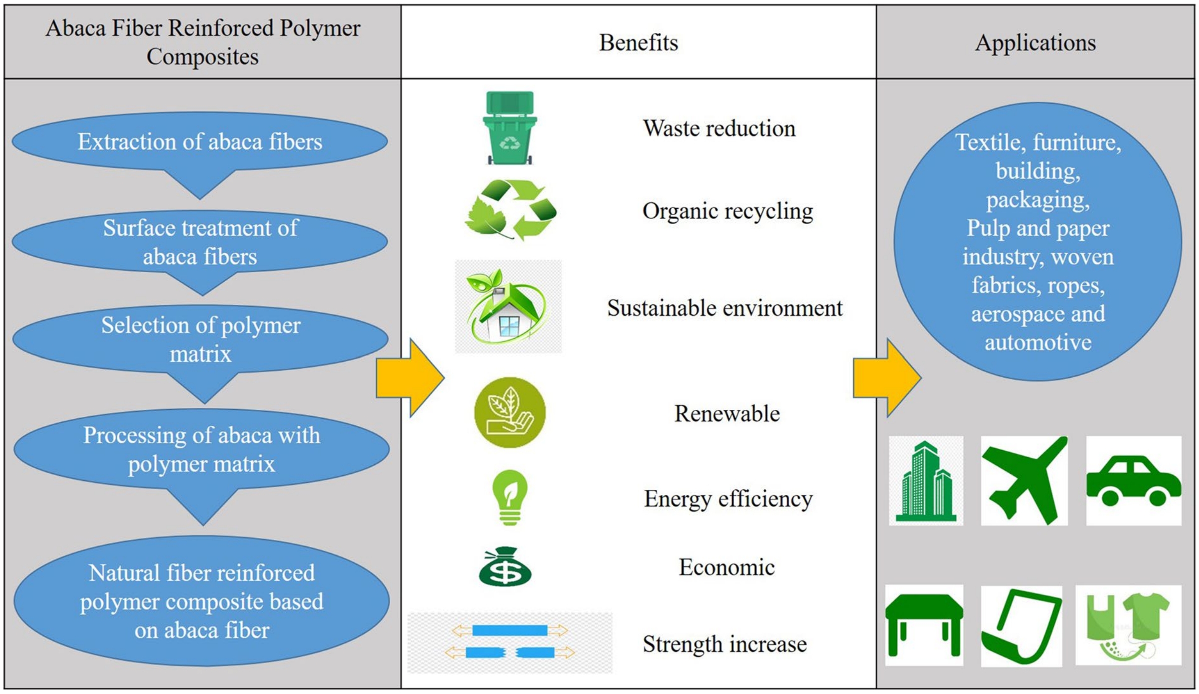
Graphical abstract



Keywords Abaca fibre · Mechanical properties · Thermal properties · Structural applications

Abbreviations

HDPE	High density polyethylene
MAPP	Maleic anhydride grafted polypropylene
NaOH	Sodium hydroxide
NFCs	Natural fibre composites
PE	Polyethylene
PLA	Poly (lactic acid)
PP	Polypropylene
TGA	Thermogravimetric analysis

Introduction

The continuous drive for sustainability suggests using materials originated from the natural world, which are more concisely defined as "bio-based", provided they be, beyond their lightness, sufficiently strong to raise industrial interest in sectors such as construction, automotive, wood replacement, biomedical and packaging (Arif et al. 2022; Hayajneh et al. 2022; AL-Oqla et al. 2023a) and even, more recently, electronic-related applications (AL-Oqla et al. 2022b). For this reason, a move towards more structural applications of natural fiber composites is increasingly sought for and investigated (Lau et al. 2018). This involved also the factorial determination of properties, to try to establish their respective influence on composites' performance (Sallih et al. 2014). Their use is definitely contributing to achieving a cleaner production and possibly to improving the life cycle scenarios, when including pre-production aspects, hence eliciting more sustainable raw materials (Dicker et al. 2014), even secondary, hence waste-derived, ones (AL-Oqla 2023). Circular economy approaches are more generally diffusing in the whole production system centred on composite material, involving e.g., the use of waste also for the development of matrices (Bajracharya et al. 2014). Also, the application of natural fibres is also gradually diffusing in concurrent fields, such as for fiber metal laminates (FML) (Khalid et al. 2021g). A more cautious approach, especially with newly investigated natural fibres, is the production of hybrid laminates, most frequently with glass fiber composites (Sanjay et al. 2015).

These considerations led to a rapid increase in demand for natural fibre reinforced polymer composites (NFCs) (Ku et al. 2011; Sinha et al. 2017a, 2017b, 2018, 2019, 2020a). The main reason for this is that ligno-cellulosic materials for their production are readily available, at a reasonable low price since they come as primary and especially secondary raw materials as by-products or even waste from other productive systems, especially linked to the agro-food sectors. This might be the case for coconut sheath fibres (Kumar et al. 2014), olive fibres from leaves, as a by-product of the shaking process (AL Oqla et al. 2021a; Alshammari et al. 2019), corn leaf fibres, as obtained from corncobs cropping (AL-Oqla et al. 2023b) or various Mediterranean fibres, of which the dielectric properties have also been investigated (Fares et al. 2022). Moreover, they have a higher specific strength in comparison with most structural materials (Sinha et al. 2021a, b). These characteristics are important to find applications for natural fibre composites in most industrial sectors. A number of factors do influence the performance of NFCs, such as the type of manufacturing process, fibre treatment, its orientation, length, loading, the strength of matrix-fibre interface, and obviously the type of reinforcement fibre and matrix used and the possible insertion of nanoparticles, etc. (Sinha et al. 2021a, b). This suggests performing possible weighing measurements on the different factors, as it was for example carried out with promising results on date palm fibre composites in AL-Oqla and Hayajneh (2021), completing the work by AL-Oqla et al. (2022a). As an essential step, properties in a number of categories have been investigated over time, which include mechanical, thermal, tribological, and chemical characteristics, and other physical properties, such as water absorption or moisture sensitivity, which appear essential for their application in NFCs (AL-Oqla et al. 2015b; Khalid et al. 2021a).

Abaca fibre can be obtained from a plant from the Musa family, which includes banana tree as well: as the consequence, some of results obtained on banana, such as from thermal degradation (Indira et al. 2012), are also applicable for abaca Abaca's specific name is *Musa textilis* (Sinha et al. 2020b). Abaca fibre owns higher strength together with several other attractive properties such as resistance to saltwater, high flexibility, and durability (Shahri et al. 2014), though attacks from parasite fungi to the abaca plant have been recently, such as *Fusarium Oxysporum*, have been recently elucidated and effectively challenged (Araya-Gutierrez et al. 2023). As the consequence of properties, diffusion and wide availability, abaca fibres became popular as polymer composite reinforcement henceforth. As the result of its recognised excellence, abaca is amongst the few natural fibres to have been proposed in outdoor automobile elements (Kurien et al. 2020a, b, c; Kurien et al. 2021d). Abaca chemical compound composite were also patented by Mercedes Benz and Daimler Chrysler (Kurien, Biju, et al. 2021). In Philippines, Musa textilis is cultivated as a marketable crop, normally in a context that involves the use of leguminous plants, as cover crops, also as source of above ground biomass (Armecin et al. 2005; Armecin et al. 2012). It also offers a source of employment for the native population since diversification of breeding in cultivation of abaca plants is a great source of income or profit for the farmers for direct selling of the raw abaca fibres to individuals or industries (Lacuna-Richman 2002; Lalusin and Villaviciencio 2015). Curtains, currency notes in Yen, cloths, fishing nets, ropes, twines, sacks, paper, and generally cellulosic products etc., use abaca as a raw material (Unal et al. 2020). Researchers have studied different reinforced polymer composites of abaca (Kurien et al. 2021a, 2021b, 2021c). The hybridization of abaca-based fibre composites along with a number of different fibres is also presented in literature. Examples are studies on hybrids with neem fibres and glass fibres (Kurien et al. 2020a, b, c), or on a typical industrial waste, such as red mud (Banjare et al. 2014; Sinha et al. 2019): further works are conveyed later on in this review. As regards the matrices used, these include, as it is a normal case with lignocellulosic fibres, the most common thermoset system i.e., epoxy (e.g., in Sinha et al. 2017a). However, further studies were carried out with polyolefins, which are still one of the most common choices as for matrix in composites (Shubhra et al. 2013; Xiong et al. 2018). Investigations are namely on polypropylene (PP) (Vilaseca et al. 2010; Wu et al. 2016), which resulted interesting for the capability to accommodate a larger tensile elongation, and more limitedly high-density polyethylene (HDPE) (Kurien et al. 2020a, b, c), with an eye to the automotive industry, where fibre selection through the application of decision-making models has received a particular interest in the last few years (AL-Oqla et al. 2015a, b). Various literature reviews (Sood and Dwivedi 2018; Khalil et al. 2012) are accessible, which can give perceptions on the mechanical properties and manufacturing process of abaca fibre reinforced composites. Despite this, new works on abaca are continuously coming out, which in itself justifies the effort to undertake this further review. More considerations will be offered in the following Section "Scope of the review".

Scope of the review

The principal characteristics of abaca (*Musa textilis*) fibre can be considered its exceptional strength and significant toughness, which make it considerably flexible for the preparation of textiles and very water resistant. The present review, in view of the wealth of studies existing on this fibre, tries to elucidate the variability of properties and characteristics, also in the light of the various treatments experimented and available for their modification so to make them most suitable for the introduction in polymer composites. It is suggested that abaca fibres are likely to be amongst the most used and structural ligno-cellulosic reinforcements, therefore more details are needed about their prospective position in the field of natural fibre composites. In practice, the present review, with respect to other similar ones on abaca, such as Barba et al. 2020, provides a large amount of quantitative data, in the mechanical, thermal, and chemical treatment field with the aim to serve as support for designing using these fibres, especially as regards difficult and exigent fields for application, such as the automotive industry.

Table 1 Abaca fibre: chemical composition

Cellulose	Hemicellulose	Lignin	Pectin	References
60.4–63.6	20.8	12–16	–	Eichhorn et al. (2001)
60.8–68	17.5–21	5–15.1	< 1	Bourmaud et al. (2018)
56–63	20–25	7–9	–	John and Anandjiwala (2008)
56–63	15–17	7–9	–	Li et al. (2007)
56–64	25–59	11–14	–	Cai et al. (2016)
56–68	19–25	5–13	0.5–1	Mussig et al. (2010)
56–63	21.7	12–13	1	Gurunathan et al. (2015)
60.8–64	17.5–21	12–15.1	–	Kurien et al. (2021c)
62.34 ± 3.52	15.18 ± 2.72	6.77 ± 0.32	4.20 ± 1.47	Liu et al. 2013
73.81 ± 0.98	11.32 ± 1.27	6.68 ± 0.40	2.10 ± 0.78	Liu et al. (2013)
67.67 ± 1.05	14.38 ± 0.94	7.25 ± 0.40	2.88 ± 1.39	Liu et al. (2013)

Table 2 Abaca fibre: Physical and mechanical properties

Diameter (μm)	Density (g/cm^3)	Young's Modulus (GPa)	Elongation at Break (%)	Tensile Strength (MPa)	References
114–130	–	12–13.8	–	418–486	Mohammed et al. (2015)
265 ± 62	–	18.6 ± 1.9	4.2 ± 0.2	717 ± 83	Cai et al. (2016)
195 ± 33	–	12.2 ± 3.2	9.9 ± 2.5	682 ± 83	Cai et al. (2016)
179–230	1.5	17.1–18.4	6.2–8.8	755–798	Bourmaud et al. (2018)
198 ± 44	–	25.3 ± 6.3	3.2 ± 0.5	773 ± 119	Cai et al. (2016)
191 ± 50	–	9.4 ± 1.0	12.4 ± 1.2	670 ± 26	Cai et al. (2016)
–	1.5	31.1–33.6	2.9	430–813	Ramnath et al. (2014)
–	1.5	9.8–35.1	3.4–11.1	430–1135	Kurien et al. (2021c)
–	1.5	12	3–10	400	John and Anandjiwala (2008)

Composition of abaca fibres

The properties of a natural fibre are purely dependant on its composition in terms of cellulose, hemicellulose, lignin, and pectin (Bledzki and Gassan 1999). The chemical composition of unprocessed/untreated abaca fibre is shown in Table 1: data reported indicate that an average abaca fibre composition ranges from 56 to 74% cellulose, 10 to 25% hemicellulose, 5 to 16% lignin, and 0.5 to 5.67% pectin. The source and extraction method of abaca fibres could be the cause of chemical composition variation.

Mechanical and physical properties of abaca fibers

The extraction of fibres needs to ensure that they maintain high elasticity to endure the transmitted load by polymer matrix and the possible construction of a solid interface, also in view of the potential application of the most common composite fabrication processes (Khalid et al. 2021b). Mechanical properties and physical properties of abaca fibers investigated by researchers are shown in Table 2. The mechanical properties of fibres include tensile strength, elongation at break, and Young's modulus, whereas the physical properties include fibre density and diameter. It can be inferred from Table 2 that abaca fibres may have Young's modulus 9–33.6 GPa, elongation at break of 2.7–13.6%, tensile strength between 400 and 1135 MPa, average diameter of technical fibres in the region between 100 and 300–327 μm and a quite high density of 1.5 g/cm^3, as suggested from the high cellulose content. A further measurement was that of crystallinity, which was also considerably high (52% for untreated abaca fibres) (Cai et al. 2016). Fibre extraction properties and sources may change according to the treatment methods, which will be the specific subject of section "Chemical treatment of abaca fibres".

Thermal properties of abaca fibres

The assessment of thermal stability (Joseph et al. 2008; Boopalan et al. 2013) of natural fibres requires the measurement through thermogravimetric analysis (TGA) of the highest temperature upon which the decomposition of the fibre is taking place as the consequence of collapse of the cellulosic structure (Zakikhani et al. 2014; Saba et al. 2015). This can be experimented through physical phenomena, such as the discolouration of fibre cell walls, leading to the development of voids within the fibre cross-section (Fan and Naughton 2016). It is also suggested that the high crystallinity of abaca cellulose can also increase the thermal decomposition temperature. In Table 3, temperatures for decomposition of different abaca fibre constituents are reported: it has been suggested that at 370 °C, a mass loss of 78.2% is reached (Malenab et al. 2017), although a progress towards higher temperatures, such as 450 °C, can occur for the thermal degradation of lignin (Asim et al. 2020).

Microstructural properties of abaca fibres

Abaca fibres are extracted from the *Musa textilis* leaves through a sequence of processes, defined as stripping, tuxying (separation of fibre bundles from leaf sheaths) and drying (Bacarra-Tablante and Sabusap 2021). In terms of reproducibility of the properties, spindle stripping allowed obtaining grades of abaca textiles with a more uniform tensile strength than it is the case for hand stripped ones, as reported by Richter et al. 2013.

The stripping procedure allows separating vascular tissues, the gums, and residual leaf structures from the fibres. However, large amount of moisture is found in the fibres after the stripping process, so they need to be dried in the sunlight. The key to understanding the natural fibre's innate hydrophilic nature lies with the structure of the fibre's cell walls.

Table 3 Information on decomposition temperatures of abaca fibers

Abaca fiber	Decomposition	Ref
Waste fiber for geopolymers	245 (side chain hemicellulose), 298 (backbone hemicellulose), 335 (cellulose), 337 (lignin)	Malenab et al. (2017)
Untreated	284 (onset of decomposition), 327 (max. decomposition)	Saragih et al. (2020)
Untreated/alkali treated	345 (untreated), 350 (treated)	Ngo and Promentilla (2018)
Treated abaca	253 (onset of decomposition), 337.90 (max. decomposition)	Paglicawan et al. (2020)

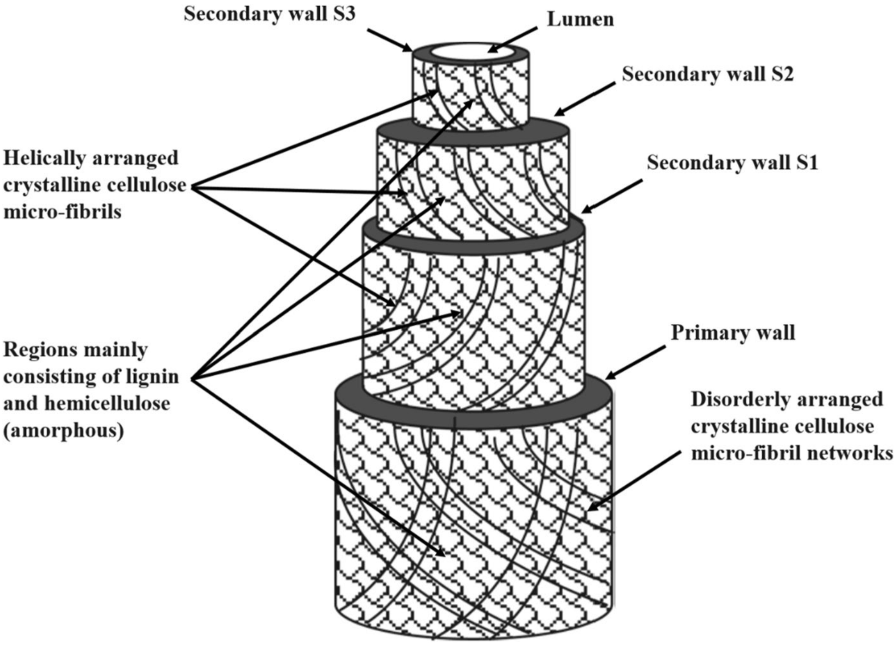


Fig. 1 Natural fiber cell walls. Replicated with consent from Sood and Dwivedi (2018)

Figure 1 shows different cell walls present in natural fibres. The primary cell wall, which is particularly porous, hence most hydrophilic, contains an uneven network made up of cellulose microfibrils, normally with diameter around 10–30 µm, reinforced in hemicellulose-lignin matrix, which give strength and stiffness to the fibre (Custodio et al. 2020). A specific measurement on abaca, intended at the extraction of microcrystalline cellulose, offered a diameter of 23 µm and a 75% crystallinity (Alila et al. 2013). This network of cellulose-hemicellulose acts as the basic structural component for the cell wall of the fibre (Khalid et al. 2021c). Three layers are present in the secondary cell wall: outer layer S1, middle layer S2 and inner layer S3, of which S2 is the thickest and offer the highest mechanical support. In general, the moisture absorption is controlled by the hydroxyl group present in the fibre elements, and is dissolved through chemical treatment (Li et al. 2007; George et al. 2012; Mahjoub et al. 2014; Arju et al. 2014). Hydrophobic lignin enhances the stiffness and is responsible for the binding property of cellulose-hemicellulose composite: in the case of abaca, lignin is particularly rich in syringyl (Sun et al. 1998). This occurrence has been revealed to increase the presence of naturally acetylated lignin (Del Rio et al. 2007), which is normally degraded through alkali treatment (Ray et al. 2001; Cai et al. 2015).

Before thinking to apply abaca fibres as the reinforcement of composites, their microstructural morphology needs to be further elucidated. In particular, the internal porosity of the fibres, as it is obtained from the extension of lumen's area, can be measured, as it is reported in Fig. 2a and b (Liu et al. 2014b, a). Of

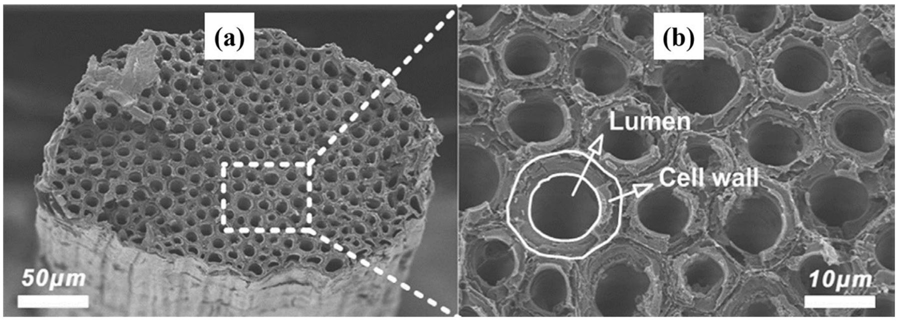


Fig. 2 Abaca fibre (raw) cross-sectional image (Liu et al. 2014b, a)

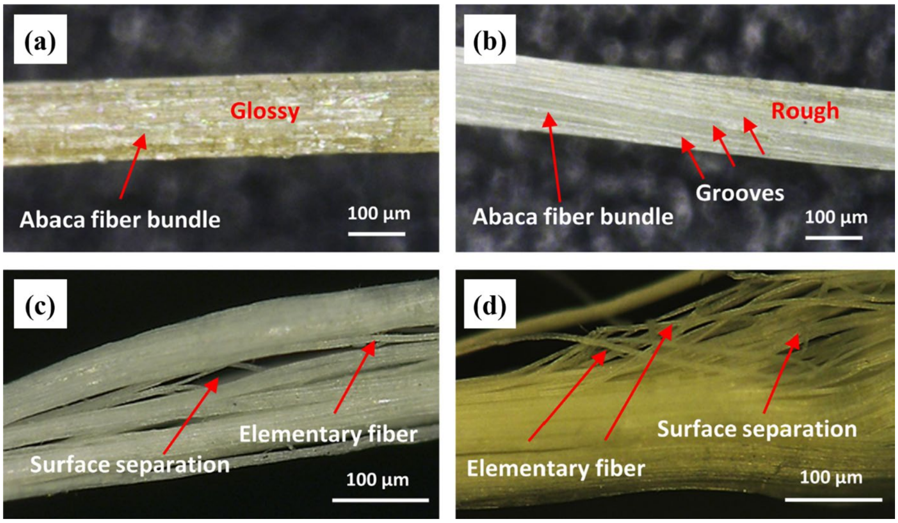


Fig. 3 Images of surface-longitudinal section of abaca fibre bundles: **a** untreated abaca fibre bundle, **b**–**d** 5 wt.%, 10 wt.%, and 15 wt.% NaOH treated abaca fibre bundles for 2 h (Cai et al. 2016)

course, the possible application of chemical treatment, such as the typical mercerization of the fibres using different concentrations of sodium hydroxide, which is intended in the first place to remove the quite abundant waxy substances present in abaca fibres, does on the other side also considerably modify their microstructural properties (Ramadevi et al. 2012). In particular, it was noticed that a level of concentration of NaOH exceeding 5%, did result in a collapse in the cell wall lumen structure ((Cai et al. 2016), therefore, as demonstrated also in Khalid et al. 2021d, a 5% NaOH treatment was deemed sufficient for the application of abaca in composites. In other words, the integrity of fibre bundles is negatively affected by 10% and 15 wt.% NaOH treatment, where the largest part of binding material present between the fibres was removed, as shown in Fig. 3. This caused bundle fibrillation i.e., the breaking of bundle into elementary fibres.

Another rationale for application of chemical treatment to ligno-cellulosic fibres, and specifically on abaca, is the need to favour achieving a more balanced roughness of their surface, which would foster the creation of some interlocking effect when the fibres are to be put into contact with a polymer matrix (Sinha et al. 2021a). This is particularly of interest when the application of biomatrices, such as polylactide, does result in limited wear resistance of the relevant composite (Goriparthi et al. 2012). Achieving a sufficient roughness is especially necessary wherever some specific application of abaca fibre composites are performed, possibly in the tribology field (Santulli et al. 2022), which is essential to open the field of application into automotive consumables, such as brake pads, to natural fibre composites (Nirmal et al. 2015). A specific study has been carried out by Milosevic et al. (2022), where it was demonstrated that the introduction of abaca fibres in an epoxy matrix along different orientations did not produce any particular change into the wear resistance of the composite.

The aforementioned considerations do obviously result in limitations into the potential for treatment, as it will be discussed more precisely also in section "Chemical treatment of abaca fibres", including also the consideration of other possible treatment methods for abaca.

Methods for manufacturing abaca fibre composites

For the manufacture of abaca fibre composites, a number of different methods have been used. These include:

- Hand layup technique, which is an ancient yet possibly the easiest method for manufacturing polymer composites (Khalid et al. 2021e, 2021f)
- Resin transfer moulding (RTM), in which the resin with the curing agent is moved into a heated, closed mould that contains prepared reinforcement, on which the resin is transferred under pressure (Robertson 1988; Liu et al. 2012)

Table 4 Fabrication process, amount, and length of fibres of abaca polymer composites

Matrix	Fabrication	Fibres wt.%	Length (mm)	References
Epoxy/Red mud	Hand layup	2.6, 5.26 and 7.9	Bidirectional mat	Sinha et al. (2019)
Epoxy	Resin transfer moulding	10–20–30–40–50	110	Liu et al., (2014a)
Polypropylene (PP)	Injection moulding	30		Bledzki et al. (2010)
PP	Injection moulding	20–30–40	Less than 5	Vilaseca et al. (2010)
PP	Single screw extrusion and injection moulding	10–15–20–25	1–1.5	Rahman et al. (2009)
Biodegradable polymers (PCL, PBS, PHBV, PLA)	Melt mixing and injection moulding	10	5	Teramoto et al. (2004)

- Injection moulding using short fibres, which proved useful to disperse uniformly the reinforcement in natural fibre composites (Arao et al. 2015; Shalwan and Yousif 2013)
- Compression moulding using short fibres (Bledzki et al. 2008)
- Extrusion, again on short fibres, but often with potential to increase aspect ratio, depending on the process parameters (Bledzki et al. 2009; Gallos et al. 2017)

In the following Table 4, a number of composites fabricated using abaca fibres according to different manufacturing methods and with different fibre amounts, only to offer examples of possible productions. In these, abaca fibres were normally treated, a subject which will be examined in section "Chemical treatment of abaca fibres".

Chemical treatment of abaca fibres

Among the methods for natural fibre surface modification, alkali treatment, also known as mercerisation, which uses sodium hydroxide, is the most popular, especially on thermosetting matrix composites: it has been used in a number of instances on abaca, such as referred to as in Table 5.

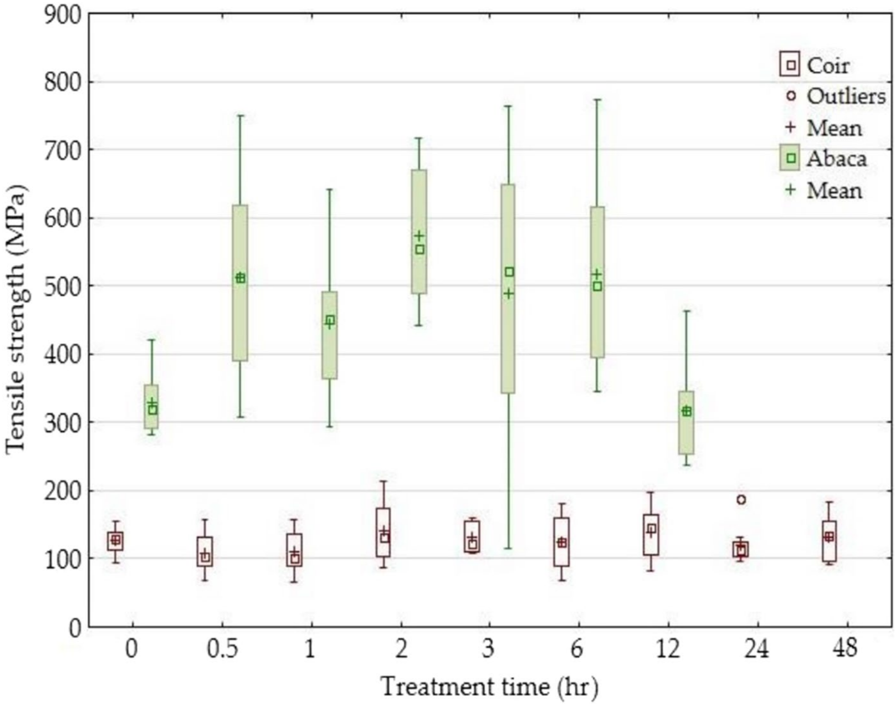
The removal of waxy residuals, non-cellulosic matter and hydroxyl ions can be done by the alkali treatment on natural fibre and it in turn improves the polymer matrix-fibre interlocking and surface roughness (Paglicawan et al. 2014). This can also have consequences on the mechanical strength of fibre depends on cellulose crystallinity, which is also enhanced by alkali treatment. It is seen that, when abaca is treated with 5 wt. % NaOH, it gives better flexural strength over untreated abaca fibre reinforced composite (Sinha et al. 2018). In particular, the influence of time of treatment has been revealed to be significant, as shown in Fig. 4, where a comparison with coir is also reported (Valášek et al. 2021).

In some cases, alkali treatment can act as a first treatment, then combined with others. In Iucolano et al. (2015), abaca fibres are treated with 10 wt.% NaOH solution, which resulted in the removal of hemicellulose and lignin with a weight loss around 10%. Following this, further treatment with ethylene diamine tetra-acetic acid (EDTA) is also applied, where EDTA acts as a chelating agent, thence leading to the solubilisation of pectin (see also in Custodio et al. 2020).

Table 5 Alkali treatment in abaca fibre composites

Matrix	Parameters for alkali treatment	References
Epoxy	5, 10, 15 wt.% for 2 h	Cai et al. (2016)
Thermoset	3 wt.% for 80 min + H_2SO_4 1 wt.% for 40 min	Liu et al. (2019)
Epoxy + waste tyre particles	For 5 h (concentration not known)	Yogeshwaran et al. (2021)
Epoxy	1 and 3 wt.% for 1 h	Sinha et al. (2017b)
Vinylester	8 wt.%	Kumar et al. (2017)

Fig. 4 Tensile strength of abaca and coir fibres treated in a 5 wt.% NaOH solution: effect of treatment time (Valášek et al. 2021)



However, a higher concentration of the alkali solution, such as 15 wt.%, can also lead to producing mechanical damage to the abaca fibres and in the best case are no further effective (Cai et al. 2016). Fibrillation phenomenon is also prevented by this treatment, which effect is specifically important in the case of short, chopped abaca fibres, where it can affect the performance of final composites.

However, a number of other treatments have been applied to abaca fibres: in particular, treatments based on acetylation have been proposed, such as with peracetic acid (Jiménez et al. 2008), or acetic anhydride (Mamun et al. 2015). In practice, acetylation does enable a polyester to encounter the surface of the fibre, so that it may become less hydrophilic (Barba et al. 2020). However, many other treatments have been experimented, such as benzoylation with benzene diazonium salt, which is normally only applied as a further treatment following an alkali pre-treatment (Punyamurthy et al. 2014), or cyanoethylation, which showed some effect when the matrix was based on biodegradable polyesters (Shibata et al. 2002).

The optimal completion for alkali treatment, also on abaca, is the silanization process e.g., with trimethoxysilane, which offers some coverage (Seki 2009), in being absorbed to the fibre whenever the material asportation has been too heavy and destructive (Sreenivasan et al. 2014), or as the preparation for the action of coupling agents, such as maleic anhydride on polypropylene (Vilaseca et al. 2010). In another work, the combined alkali-silane treatment was completed through the action of plasma, which offered in 10–20 s the maximum improvement over the tensile properties of an unsaturated polyester-abaca composite (Pagliwacan et al. 2014).

Use of maleic anhydride grafting in abaca fibre composites

A number of studies on abaca did concern the use of polyolefin matrices, such as polyethylene and polypropylene, especially aimed at potential applications in the automotive sector. In that sense, the use of maleic anhydride grafting is considerably common to improve fibre-matrix compatibility. Maleated polypropylene (MAPP) has exhibited its importance by enhancing the NFC's mechanical properties (Wang et al. 2004). In abaca fibre reinforced PP composite, the flexural strength is enhanced when MAPP is used as a coupling mediator, typically introduced in a 4–6% range (Gironès et al. 2011). To increase flexural, impact and tensile strength of abaca fibre reinforced polypropylene composites, 5 wt. % of MAPP was used along with benzeneduazonium chloride in the treatment of fibre (Punyamurthy et al. 2014; del Río et al. 2004). For enhancing the damping and mechanical properties of flax-polypropylene, jute-polypropylene and abaca-polypropylene, as a coupling agent, 5 wt. % MAPP copolymer was used (Kurien et al. 2020b). More specifically, in the case of banana fibre composites, also fibre configuration was examined (raw fibers, yarn, and mat) and ideally tailored according to the tenor of maleinization (Amir et al. 2017). From the study it was found that the damping and mechanical properties of the abaca polypropylene under various fibre loadings had a significant enhancement of 30–120% and 30–80%, respectively, by incorporating coupling agents. The adhesion between both polypropylene and abaca were increased by treating the fibres in hexadecyltrimetoxysilane combined along with MAPP, however stiffness of the abaca-polypropylene composites remained unaffected with little to no substantial enhancement (Vilaseca et al. 2010). Other properties can also be improved by the use of MAPP, such as it is the case for fire retardancy, which is also assisted by hybridization with nanoclay (Lee et al. 2013), a quite common and inexpensive hardening procedure on other natural fibres, such as sisal (Ibrahim et al. 2017). A very recent study, aimed at elucidating the performance of bio-polyethylene(bio-PE) not obtained from petroleum against HDPE in abaca reinforced composites, did employ maleinization (2–10%) for polyethylene grafting after treating abaca fibres with silane (Seculi et al. 2022).

Table 6 Abaca polymer composites-mechanical properties

Matrix/other filler	Impact Strength (kJ/m^2)	Young's modulus (GPa)	Flexural strength (MPa)	Elongation at break (%)	Tensile strength (MPa)	Fibre content (wt.%)	References
Epoxy/Red mud	4.39	–	36.54	–	18.83	5.26	Sinha et al. (2019)
Epoxy/Red mud	5.46	–	40.25	–	17.51	7.9	Sinha et al. (2019)
PP	5.3	4.93	72	–	44	30	Bledzki et al. (2010)
PP	3.46	2	54	–	30.5	10	Rahman et al. (2009)
PP	3.94	2.2	54.5	–	29.5	15	Rahman et al. (2009)
PP	3.98	2.4	54.9	–	28.7	20	Rahman et al. (2009)
PP	4.01	2.8	55.2	–	28.5	25	Rahman et al. (2009)
PP	4.1	–	52	2.2	32	30	Bledzki et al. (2010)
PP	–	6.1	–	2.1	40	40	Vilaseca et al. (2010)
PP	–	5.1	–	2.4	34.7	30	Vilaseca et al. (2010)
PP	–	3.1	–	3	29	20	Vilaseca et al. (2010)
PP	3.8	–	52	–	32	30	Punyamurthy et al. (2014)
PP	6.2	–	70	–	40	40	Punyamurthy et al. (2014)
PP	5.2	–	51	–	35	45	Punyamurthy et al. (2014)
PP	4.4	–	48	–	30	50	Punyamurthy et al. (2014)
PP	6.6	–	70	–	–	40	Kurien et al. (2021c)
PP	9.8	–	56.5	–	–	20	Sinha et al. (2020b)
PP	6.8	–	78.9	–	–	50	Sinha et al. (2020b)
PP	8.8	–	64.4	–	–	30	Sinha et al. (2020b)
PP	7.2	–	72.7	–	–	40	Sinha et al. (2020b)
PLA	5.3	8.03	124	–	74	30	Bledzki et al. (2009)

Characteristics of abaca fiber reinforced composites

Mechanical properties

It is by the consideration of impact, tensile and flexural strength that the mechanical characteristics of NFCs are especially found out. ASTM D790, ASTM D638 and ASTM 256 respectively can be followed for determining the flexural, tensile and impact strength of NFCs, respectively. The mechanical properties of abaca reinforced polymer composites are shown in Table 6. The two main factors that influence the results are the amount of fibre and the type of polymer matrix used for the purpose, and also the fluctuations in the mechanical properties of abaca fibre reinforced composites may be significant. The three main matrix systems experimented with abaca fibre composites are epoxy, polypropylene and more limitedly poly(lactic acid). In contrast, the available number of investigations on hybrid abaca reinforced polymer composite is very limited. Hybridisation of abaca with particulates (Kurien et al. 2021a; Adesina et al. 2022) and with other fibres, such as jute and glass (Ramnath et al. 2013, 2014) can improve the mechanical characteristics of abaca composites, and can possibly be applied with thermoplastic matrices to obtain extruded pieces, subjected to well-known conditions, presented e.g., by Ariffin and Ahmad (2011), though in such cases to tailor the chemical treatment to composites' properties might prove critical if not cumbersome. In the context of thermosetting matrices, also resin transfer moulding (RTM) processes (Liu et al. 1996) have been obtained interest in natural fibre composites. In general terms, mechanical characteristics of NFCs depend on several factors including fibre length (Bisaria et al. 2015; Amuthakkannan et al. 2013), particle size of filler (Uthayakumar et al. 2014; He et al. 2013), laminate stacking sequence (Yahaya et al. 2015; Karaduman et al. 2014), weight percent of filler (Biswas and Satapathy 2010, 2009; Shalwan and Yousif 2014) and fibre orientation (Srinivasan et al. 2014; Retnam et al. 2014; Ramesh and Nijanthan 2016).

Morphological and structural properties

While compared to abaca fibre (untreated) reinforced polypropylene composite (Rahman et al. 2009), better interfacial adhesion between matrix and fibre and improved distribution of abaca over the matrix is shown by chemically treated abaca fibre reinforced polypropylene composite, also with alternative treatments to alkali ones. This was observed by diazo-treated abaca fibre composites and is generally able to explain the enhancement, also in terms of toughness, of the obtained composites' properties (Punyamurthy et al. 2017). However, limitations are still present in the application of abaca: e.g., in hybrids including E-glass, jute and abaca fibres, the latest offered evidence of intra-fibre delamination with respect to the other types of reinforcement (Ramnath et al. 2013). Factors like incompatibility between hydrophobic matrix and hydrophilic fibre and presence of impurities over fibre surfaces also determines limits to interfacial adhesion (Cai et al. 2016). The bonding with polymer matrices is prevented by these smooth surfaces of the fibre and thus resulting in voids, (K. Liu et al. 2014b, a) further leading to fibre pull-outs (Rahman et al. 2009; Shalwan and Yousif 2014). When compared to fibres having untreated smooth surface, the fibres with treated surface allow for a much better adhesion to the polymer matrix (Lu et al. 2014)

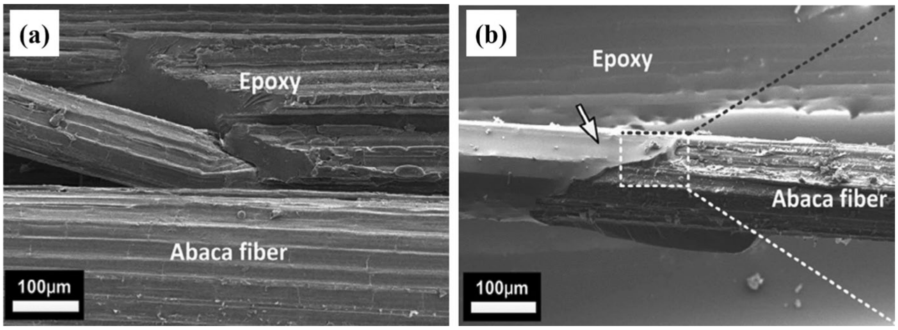


Fig. 5 **a** Abaca fibre (untreated) as reinforcement in epoxy- SEM image; **b**Abaca fiber (treated) as reinforcement in epoxy-SEM image (Liu et al. 2014b, a)

as they have a wax free surface which thus increases cross sectional area (Kabir et al. 2011). A particularly effective removal of the waxy substances from abaca fibre surfaces with increase of mechanical performance of the relevant polypropylene matrix composites was obtained by enzyme treatment in Bledzki et al. (2010).

Figure 5a illustrates abaca fibre (untreated) as reinforcement in epoxy using a SEM image. The effect of treatment on the composite properties, as regards abaca fibre surface can be observed from Fig. 5 (Liu et al. 2014b, a). Very low wettability of fibre is observed in the interfacial area between the untreated abaca fibre and polymer matrix, as from Fig. 5a, representing untreated abaca fibres. This results in the development of a gap between fibre and matrix. Poor mechanical characteristics of polymer composites is caused due to the decrease in fibre and matrix interfacial adhesion. Figure 5b indicates the morphological properties of alkali treated abaca fibre as the reinforcement in an epoxy matrix. It can be observed that there is a higher-level of bonding between the epoxy matrix and the reinforcing abaca fibres, which indicates the interfacial adhesion between them.

Thermal properties

Flash method has been used to identify the thermal conductivity of abaca composites (Liu et al. 2014b, a), in the understanding that the higher content of abaca fibre in the epoxy composite progressively increases the thermal anisotropy of the material. In other words, it enhances its longitudinal thermal conductivity while decreasing its transverse thermal conductivity, as the function of its morphological characteristics, such as lumen and cell wall dimensions with an effect particularly significant with abaca, due to its being a fibre with particularly large lumens (Takagi et al. 2012). This effect on the enhancement of thermal anisotropy has also been confirmed in hybrids with more compact fibres, such as bamboo (Liu et al. 2012).

Interfacial shear strength (ISS) and critical length

By single fibre pull-out test, the composite's interfacial shear strength (ISS) (Joseph et al. 1996) was also found out. For carrying out this experiment, a fibre strand that is entrenched inside the polymer matrix is taken out. Critical length of fibre is defined

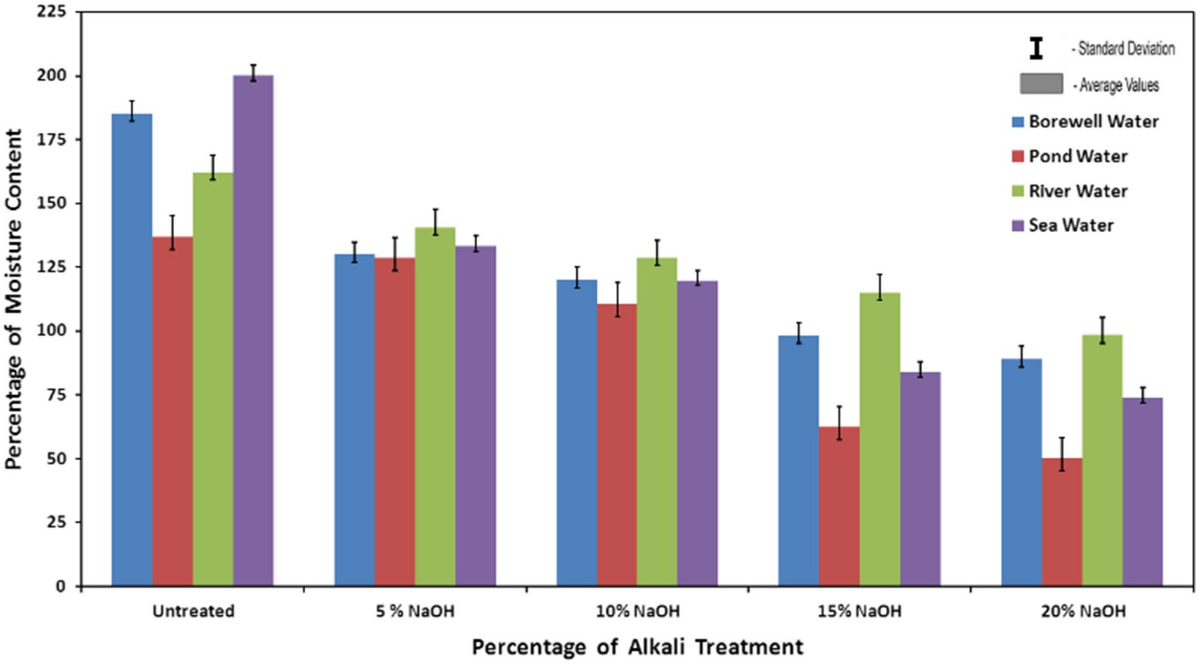


Fig. 6 Water absorption (%) of abaca fibres with alkali treatment in different conditions

as the highest length of this particular fibre at which they break (Adeniyi et al. 2019). Fragmentation test and fibre push-in tests also help in the determination of interfacial shear strength of the composite (Monette et al. 1993). Dealing with abaca, there is a 32% increase in ISS for the abaca-epoxy composite which has been treated with 5 wt. % NaOH compared to the untreated composite (Cai et al. 2016). In contrast, the increase in concentration of NaOH (exceeding 5 wt. % of NaOH) will result in a decrease in the ISS of the abaca epoxy composites as observed in the results. The study shows that with an incrimination in MAPP content, results showed an increase of ISS. An ISS of 17.6 MPa along with 1.5 mm critical length was found for a composite of abaca and polypropylene with 8 wt. % MAPP. The results shows that there is 60% increase in ISS of the abaca fibre treated composite with 8% MAPP while comparing with untreated abaca reinforced composite. 1.843 mm and 35.96 MPa are the interfacial shear strength and the critical length of reinforced abaca fibre composite (Bledzki et al. 2009). Various researchers found that, highest ISS value is exhibited by abaca when epoxy is added, as suggested by Delicano (2018).

Water absorption characteristics

As natural fibres are hydrophilic in nature, it is important to check the water absorption quality of these fibres. ASTM570 (Badyankal et al. 2021; Balan and Ravichandran 2020; K. Ray et al. 2020) and EN ISO 62 (Bledzki et al. 2010) are used to determine the water absorption property of natural fibres.

In the case of abaca, as with other natural fibres, the amount of chemical treatment, in particular alkali, has an important effect on the decrement of water absorption: this is clearly indicated in a study, which serves as a significant reference, such as Ramadevi et al. 2012: main data from it are depicted in Fig. 6.

(Ramadevi et al. 2012).

A higher content of abaca fibre in reinforced polypropylene composite significantly enhanced water absorption, due to the increase in hydroxyl groups, from just above 30% for 10 wt.% fibres, to slightly below 50% for 25 wt.% fibres, which is somewhat reduced when using treated fibres (Rahman et al. 2009). The composites of untreated abaca-polypropylene has more water absorption capability compared to abaca-polypropylene composites where abaca fibre naturally digesting system (NDS) and enzyme showed a 20% and 45% decrement in the

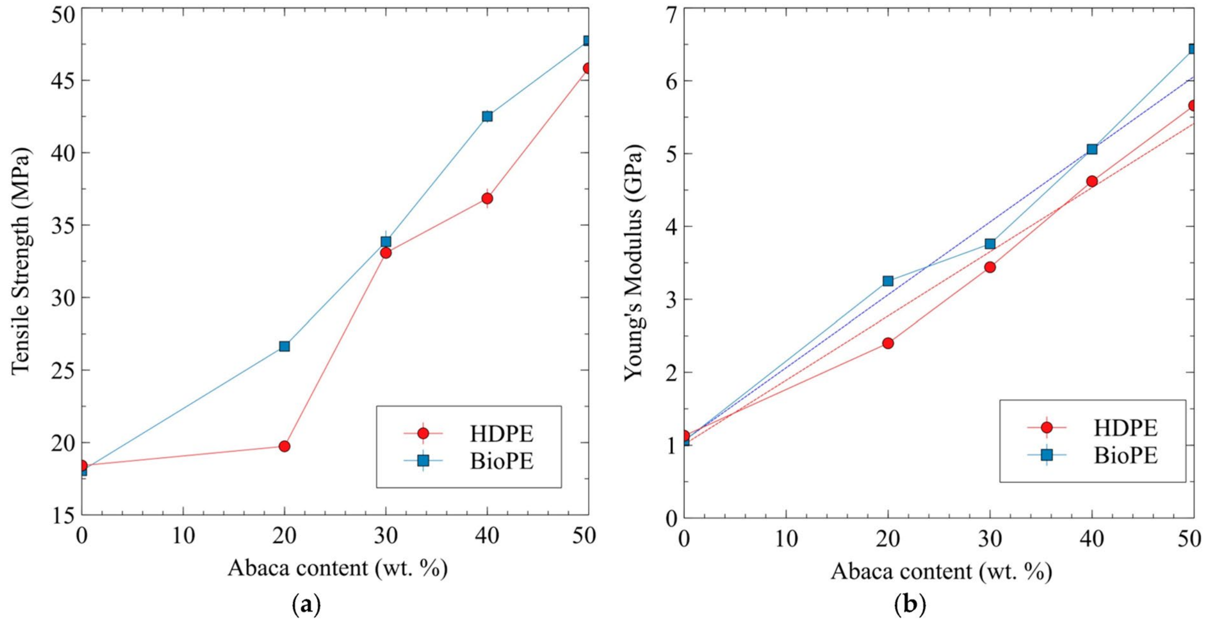


Fig. 7 Abaca composite strength (**a**) and stiffness (**b**) with different amounts of fibres for HDPE and Bio-PE matrices (Seculi et al. 2022)

water absorption capability, respectively (Bledzki et al. 2010). Hence, it could be concluded that the interfacial adhesion between the matrix and fibre directly affects the abaca composites' water absorption (Sinha et al. 2017b).

Abaca reinforced polymer composites in the manufacturing industry

In general terms, natural fibre composites are currently striving to meet the rising demands of the automotive components, not only concentrating on the interiors. This would imply taking into consideration various aspects like acoustic absorption, crash behaviour and processing sustainability processing to obtain acceptable mechanical properties while still maintaining lower cost of production, better fuel economy and reduced weight in automobiles which makes them very much favourable in the automobile industry (Ahmad et al. 2015; Holbery and Houston 2006; Mohammed et al. 2015).

For the use of composites in the automotive industry, the use of polyolefins, such as polyethylene and particularly polypropylene, as matrices is particularly desirable. These matrices are usually petroleum-based: bio-based polyolefins ones are increasingly diffuse, nonetheless. Very recently, also a study comparing the performance of abaca composites with HDPE and bio-PE matrices offered more indications about the potential substitution with bio-based but not bio-degradable as such matrices (Seculi et al. 2022).

Fig. 8 Various natural fibre composite components of Mercedes-Benz A—class (Monteiro et al. 2010)

As from results reported in Fig. 7, it was noticeable that the differences at the different tenors of fibres are quite modest, especially in terms of stiffness, where also some regularity, hence tracing an intercept, is possible.

The very first production which was built using composites reinforced with natural fibres was Trabant, a car manufactured in East German had a chassis which was a polyester composite with cotton reinforcement (Wagenführ 2017). From the 1990's lignocellulosic fibres were used in manufacturing of BMWs. They used car seats of wood fibre and acoustic absorption was achieved using cotton fibre. For better resistance to impact and strength, panelling and door linings were made with the help of sisal and flax fibres (Kalia et al. 2011). Daimler Chrysler is the popular European company to use natural fibre composite in their Mercedes-Benz vehicles as shown in Fig. 8. In door panels, they used composites including jute fibre. For transmission cover and engine flax fibre composites were used. Sisal, hemp, wood and abaca composites for the underbody panels, rear cargo shelf, pillar inners, cargo shelf, thermal insulation and trunk components, which will reduce the total weight about 34% (Holbery and Houston 2006). In Asia, automotive manufacturer Toyota started using corn, bamboo and kenaf for manufacturing their interior components. After that Honda, Fiat, Volkswagen and General Motors were the principal car manufacturers who used natural fibre composites in their products. Methods for intelligent selection of natural fibres in automotive applications, therefore coupling them with the archetypal matrix in this sector, hence polypropylene were also proposed (AL-Oqla et al. 2016).

The possibility of employing abaca fibres as reinforcing fillers in the composite materials for prospective automotive applications was very soon comprehended, first by Zakrzewski et al. 1989, and Janicki et al. (1990). In the specific case, untreated and short abaca fibre in thermoset resins were employed as reinforcement, together illustrating the significance of loading and length of fibre in the optimization of tensile and impact strength. Further down the line, Shibata et al. 2002 employed abaca fibres along with a thermoplastic matrix. In their research, entirely biodegradable composite materials were formed from short abaca fibres and PHBV (poly 3-hydroxybuterate-co-3-hydroxyvalerate) by melt-mixing and injection moulding. It was observed that a 20% abaca fibre loading offered outcomes comparable to composites reinforced with glass fibres. Because of an increase in the interfacial adhesion with the polyester, enhanced flexural strength was shown when the fibre was pretreated with pyridine (benzoylation) and butyric anhydride, but it was not effective in the improvement of tensile modulus. Daimler Chrysler collaborated with Manila Cordage in 2003 to start the so-called abaca initiative. This was aimed at developing superior quality automobile parts and components using composites which are reinforced using abaca fibres. By the year 2004, Mercedes-Benz A-Class cars were having under floors fully panelled using polypropylene/abaca composites. Composites with natural fibre reinforcement had been only utilized in interior components and hence this one was recognized as the first one in its kind from Benz. The work done by them was able to uncover the true potential of the strength of abaca fibre which enabled utilize it also for components outside the interior of the car where there is much greater risk like weathering and increased load due to stress (Fuqua et al. 2012). The most excellent enhancement on the impact strength has been shown by the abaca fibres and since then the formulation has been patented (Ferreira et al. 2010). Comparison between PP/abaca and PP-composites with jute and flax indicated that excellent and comparable flexural strength and damping characteristics are provided by the abaca composite materials for a fibre load maximum up to 40% (Singha and Thakur 2008). In comparison with composites reinforced with jute, cotton, banana, bamboo and ramie, enhanced tensile properties were shown by abaca reinforced emulsion based biodegradable resins (Ochi 2006). The flexural and tensile strength increased with use of MAPP, which enhanced the adhesive properties (Gironès et al. 2011). Use of sodium hydroxide, enzymes and benzene diazonium salt were the other treatments reported, which when optimized properly enhanced the mechanical properties (Rahman et al. 2009; Kumar et al. 2019a, b; Cai et al. 2016). With moderate success, abaca was also used in combination with high impact polystyrene, polylactic acid, urea formaldehyde, epoxy resin and furan resin (Tumolva et al. 2009; Niranjan et al. 2013; Suvarna et al. 2015; Bledzki and Jaszkiewicz 2010; Agung et al. 2011). Abaca fibre which have undergone plasma treatment showed very low tensile strength even after silylation and supplementary mercerization, however the adhesion of the fibres with unsaturated polyester has significantly increased (Paglicawan et al. 2014). Creation of hybrid composites comprising of more than two fibres have also been attempted. Abaca-jute-glass composite showed better impact toughness (Ramnath et al. 2013). Whereas, abaca-glass composite showed higher elongation, better ductility, modulus and flexural strength (Venkatasubramanian et al. 2014). From the literature reported, it is clear that for thermoplastic polymers and thermosetting polymers the abaca fibre has shown immense potential to be utilized as a reinforcement component. There is still room for improvement in various mechanical characteristics of the composites comprising impact strength, flexural strength, elastic modulus, and tensile strength. Generation of various chemical residues, base integrity losses and low efficiency of fibres are some of the major drawbacks of surface modification in fibres.

Conclusion

Properties of abaca fibres and its application in composites are emphasized. Studies also showed that the treatment on fibres has great effect in enhancing the characteristics of abaca fibre polymer composites. The two most used methods for abaca modification are MAPP (on polyolefin-based matrices) and alkali treatment, mainly in epoxy, in both cases reducing pull-out occurrence and improving interface strength. Quality products having improved mechanical characteristics are provided by injection moulding whereas hand layup is popular for its low cost and simplicity. In practice, introduction of high abaca fibre contents, up to 40%, had been possible in matrices, such as polypropylene or epoxy. In particular, abaca-polypropylene composites possess great tensile and impact strength along with better flexural strength. It has applications in the automotive, light weight constructional, structural, housing industries. Hybrids have also been produced including abaca with other natural fibres, such as jute, hemp, sisal, banana, Sunn hemp, etc., and also with glass fibres. Polymer composite properties can be improved by further hybridization of abaca with waste-derived fillers, such as red mud and fly ash.

As for other properties than mechanical ones, transverse thermal conductivity of abaca composites decreases, when there is increase in abaca content and chemical treatment, the latter also reduces the water absorption capacity by reducing the number of hydroxyl groups. Abaca fibres could be seen as a viable reinforcement agent in various materials in the transportation industry and in manufacturing of wind turbines if the water absorption issues of the fibre could be rectified. Abaca fibre composites finds their application not only in the automotive industry, but also in aerospace, electronics, ships, packaging, textiles, sports items, and various other products.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest.

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