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Impact properties of glass/plant fibre hybrid laminates

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Abstract The use of plants fibre reinforced composites has continuously increased during recent years. Their low density, higher environmental friendliness, and reduced cost proved particularly attractive for low-tech applications e.g., in building, automotive and leisure time industry. However, a major limitation to the use of these materials in structural components is unsatisfactory impact performance. An intermediate approach, the production of glass/plant fibre hybrid laminates, has also been explored, trying to obtain materials with sufficient impact properties, whilst retaining a reduced cost and a substantial environmental gain. A survey is given on some aspects, crucial for the use of glass/plant fibre hybrid laminates in structural components: performance of hybrids when subjected to impact testing; the effect of laminate configuration, manufacturing procedure and fibre treatment on impact properties of the composite. Finally, indications are provided for a suitable selection of plant fibres with minimal extraction damage and sufficient toughness, for introduction in an impact-resistant glass/plant fibre hybrid laminate.

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Significance of impact properties in plant fibre composites

Impact resistance in composites is the study of damage induced by striking of a foreign body on a material and the factors affecting it, which is generally recognised as the most severe threat to composite structures. This includes the study of the failure modes, initiation, development and extent of impact damage. Impact damage is normally initiated in laminated composites as a transverse matrix cracking, followed by delamination, fibre/matrix debonding and fibre fracture [1]. Damage due to impact substantially reduces the residual strength after impact of a composite structure, even when damage cannot be visually observed: for this reason, residual mechanical properties after impact are often measured. The principal mechanism of compressive strength reduction is local buckling of the sub-laminates formed in the delaminated area, whilst in tensile loading the strength reduction mechanism is dominated by fibre fracture [2].

Two approaches are used to predict impact damage on laminated composites reinforced with man-made fibres (E-glass, carbon, Kevlar). The former is based on estimating the overall size of impact-damaged area, considering stress distribution in the area surrounding the impact point, and the latter on the detection of the appearance of the first matrix crack, followed by the study of the initiation and propagation of delamination.

When dealing with plant fibre composites, both these approaches appear viable, at least in principle: however, a number of difficulties can be perceived in their application. First, the measurement of impact-damaged area can be considered particularly difficult, as an effect of the fibres becoming loose and suffering early debonding around the

Fig. 1 Slight appearance of impact damage (energy = 10 J) on the surface of a jute/polyester laminate

impact point, even at low stress. As a consequence, impact damage is often not visible, even at energy not much lower than penetration energy (an example of this is given in Fig. 1). Secondly, the study of impact damage initiation is based on two assumptions: that the laminate shows limited presence of defects prior to impact and that the direction of impact, whether mono- or bi-dimensional, determines the damage propagation mode.

In biological materials, the combined presence of stronger and weaker parts is a natural procedure selected during evolution to obtain the maximum possible impact resistance [3]. This means that plant fibres can work effectively through the limited and controlled occurrence of defects, which are irregularly spaced along their length. As a result, the tensile strength of the fibres decreases with their length, and a pronounced strain rate effect would also be observed [4]: this has of course an effect, albeit not easily predictable, also on impact properties of plant fibre composites. Most studies so far have been concerned with either improving fibre quality or reducing the effect of the presence of fibre defects on the final material via improved processing or fibre treatment [5, 6].

It can be suggested that defects have a more central role in affecting impact properties in plant fibre composites than in glass fibre composites. In particular, the presence of defects reduces the possible effect of bridging from the fibres, as can be observed in Fig. 2. As a consequence, the fibres are often likely to bend and precociously pull out of the matrix rather than fracture under impact loading [7].

More in general, dealing with plant fibre composites, the microstructural perspective needs to be different, in that

Fig. 2 Impact damage, triggered by sub-surface defects, on the surface of a flax-epoxy laminate

biological fibres are formed by microfibrils and therefore partly oriented in the direction of the loading, and partly randomly oriented. Natural fibres have usually a hollow space, referred to as *lumen*, variable in dimensions, in some cases also wider that the cell walls, and in irregular distances there are nodes dividing the fibre into individual cells. It should also be noted that the irregular shapes of plant fibres and fibre bundles can more easily lead to non-uniform resin impregnation and increased void content.

To apply therefore to natural fibre composites the classical approach to polymeric composite materials, it is essential to measure the interfacial shear stress i.e., to obtain a measure of the forces acting between the fibres and matrix. In natural fibres reinforced composites improving the strength at the interface does not always result in a tougher composite. Large stress concentrations can be observed in presence of fibre defects, and local stress concentration can also give rise to the propagation of cracks into the matrix [8]. Some studies on interfacial shear stress have been carried out in recent years, which allowed demonstrating as concentration of stresses occurs in the interphase region, in proximity of defects in the cell wall of plant fibres, such as hemp and flax [9, 10]. These defects are similar to those appearing on the tracheid walls of compression-damaged wood, which also act as regions where damage initiation takes place [11]. The influence of defects has been investigated in relation to the stiffness of the obtained composite, especially on flax fibres, which as most bast fibres, is particularly sensitive to the decortication method adopted [12]. Improvements in properties, especially stiffness, can be obtained using chemical treatments of the fibres [13]: this will be discussed in more detail later.

The assessment of impact properties in a composite consists of a number of aspects, which will be briefly exposed with reference to the work done on E-glass/plant fibre hybrid composites. Most studies, a good example of which is [14], are limited so far to the measurement of work of fracture using Charpy or Izod mono-dimensional impact tests, comparing it with properties under monotonic loading. There is also limited coverage in literature of other equally important aspects, such as penetration energy and damage area measurement in two-dimensional impact tests and post-impact residual properties. A general overview of the factors and process parameters affecting impact properties of plant/glass hybrids laminates is depicted in Fig. 3.

Hybrid glass/plant fibre laminates

Scope and definitions

The main reason for using hybridisation is the capability of combining or tailoring more than one type of reinforcement to exactly suit the needs of the structural applications. The hybrid effect was first observed by inserting two types of reinforcement fibres in the composite, of which one is stiffer (carbon) and the second more compliant (glass, Kevlar). In this case, the strain to failure of the stiffer fibre appears to be enhanced and the effect is larger when the proportion of the stiffer fibre is small and it is finely dispersed in the composite. In practice, dealing with monotonic loading, a positive and negative hybrid effect has been defined, by the deviation of the monotonic properties of the hybrid laminate with respect to the rule of mixtures [15].

The hybrid effect has been demonstrated also in post-impact residual properties, appearing to slow down the residual compressive strength versus impact energy and reducing the extent of the delaminated area by effect of the introduction of the second type of fibre [16]. Typically, the mechanical properties of hybrid composites are decreased as far as a larger volume of plant fibres is introduced. Curves can be drawn showing the decline in mechanical properties against the glass/plant fibre ratio in the composite [7]. The trend of this decline can be possibly modified, by acting on one or more of the factors discussed in section 'Effect of different factors on impact resistance'.

Hybrid composites including different types of plant fibres have also been obtained (References in Table 1). In this way, two fibres with different microfibrillar angles, hence different inherent tensile properties, and different diameter, hence different degree of stress transfer between fibre and matrix, can be intimately mixed [17]. Fibre-matrix adhesion and internal stress transfer has an influence also on the impact strength and the damping behaviour, so that a positive hybrid effect can be achieved, by selecting the appropriate ratio between the volumes of the two plant fibres used.

In particular, E-glass/plant fibre hybrid laminates do not need to be perceived as a possible step back as far as environmental friendliness is concerned. In contrast, hybrids can allow disposing strategies to pass from cosmetic to structural use of plant fibre composites in industry. In this regard, one basic question, whenever using plant fibres as reinforcement, remains the improvement obtained over the impact strength of the pure matrix, even with very low fibre content. This has been demonstrated e.g., for sisal/E-glass hybrids [18–20]. Impact testing on hybrids over a wide range of fibre contents would allow designers to evaluate the increase in thickness to be applied on a component to obtain the same crashworthiness for different proportions of glass-to-plant fibre replacement.

When using the aforementioned relationships, based on the rule of mixtures, to measure unidirectional strength values of hybrid composites, the experimental values obtained are considerably lower than the predicted ones throughout, such as e.g., in [21] for compressive loading. This suggested that also for impact properties, the hybrid effect could result in an even more deceiving performance of the composite. As a consequence, the range of plant fibre

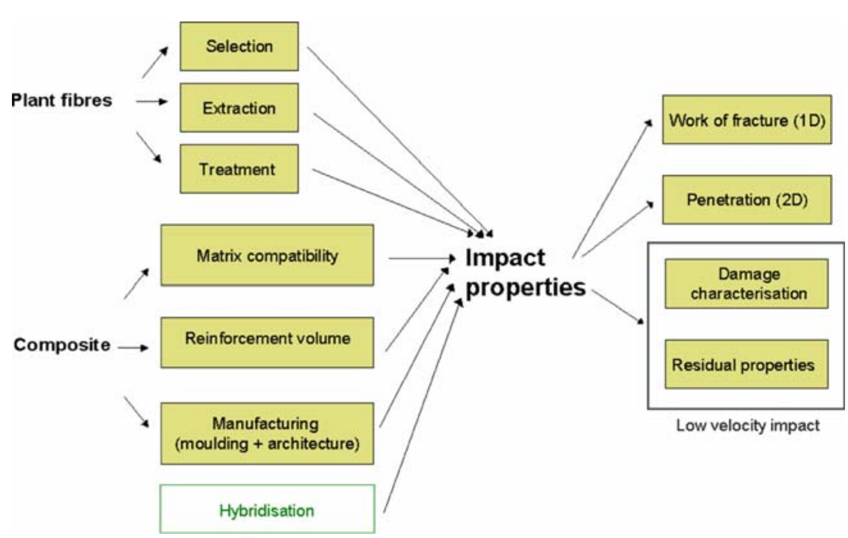

Fig. 3 Factors affecting impact properties of plant fibre composites

Table 1 Hybrid laminates with two types of plant fibres

Plant fibres	Matrix	Reference
Banana/sisal	Polyester	[17]
Jute/cotton	Novolac	[48]
Sisal/oil palm	Natural rubber	[49]
Cotton/kapok	Polyester	[50]
Ramie/Cotton	Polyester	[51]

volume that result beneficial in a global evaluation of costs, environmental friendliness, and mechanical and impact properties appear to be pretty limited and needs to be carefully evaluated for every hybrid laminate. More reasonably, a maximum amount of plant fibre compatible with the obtainment of a sufficiently impact-resistant composite is often defined. For example, in [22], where for bamboo/glass hybrid, the maximum fibre content suitable for an impact-resistant replacement of glass fibres in bulk moulding compounds does not exceed a 30% in weight of the total volume of the reinforcement fibres.

Effect of different factors on impact resistance

Hybrid configuration

To achieve a positive ''hybrid effect'' in glass/plant fibre hybrid laminates, it is essential for both fibres to be effectively dispersed in the matrix. In general, two routes appear to be viable and effective for this aim. The first possibility is the introduction in the resin of a small volume of short glass fibres, highly dispersed in a bulk of short plant fibres, and the second is the manufacturing of composites comprising glass fibre reinforced skins and plant fibre reinforced cores or more complex configurations.

The former method can require the adoption of specific manufacturing techniques, such as e.g., intermingling, which implies introduction and agitation of the dispersed fibres in a hydroforming process, followed by compression of the loose mat obtained. Intermingling, albeit not adopted generally, represented a step in the right direction, because it allowed a better exploitation of the higher work of fracture specific of plant fibres, due to their helically wound microfibrillar structure. In addition, composites with much lower (up to 4–5 times) moisture absorption were obtained, when using coir fibres [23].

In practice, to compensate for the lower volume of glass fibres introduced in the former case, a higher strain plant fibre can be introduced (e.g., coir, sisal, bamboo), whilst in the latter case, also to reduce inherent costs, a lower strain fibre could be also used (e.g., jute, flax, hemp). In the case an intermingling technique is adopted, resin impregnation is the critical factor for composite resistance; the manufacturing of a sandwich hybrid structure would in contrast move the attention towards interlaminar adhesion. More recently, the production of commingled flax fibre composites, addressed to the automotive industry, has developed the idea of intermingling, transferring it to long fibres, with more than appreciable results from a mechanical point of view [24].

Some of the first attempts to produce glass/plant fibre hybrid laminates involved the use of untreated jute fibres as reinforcement for a core laminate interposed between E-glass fibre reinforced facings, or vice versa [15, 21, 25, 26]. This also for the obvious consideration, confirmed in literature (e.g., in [7]), that two-sided hybrid laminates are much more impact resistant (up to four times for the same laminate thickness) when impacted on the E-glass side. Therefore the real question appears to be the ability of impact damage dissipation in the plant fibre reinforced non-impacted face, whenever the glass fibre reinforced face is penetrated [4]. This might suggest that in general for simple manufacturing procedures, such as hand lay-up, the sandwich configuration (E-glass reinforced skins, plant fibres reinforced cores), can still be considered the most suitable to provide a higher impact resistance.

However, early studies were not aimed specifically at impact-resistant applications, and considered insufficient failure strain to be the main limitation in the use of plant fibres. Including jute fibres facings (J) and E-glass fibres (G) core in a J/3G/J geometry led to maximising the work of fracture at a value around 45 kJ/m^2 for the effective crack propagation blunting at glass/glass interfaces; however, this geometry showed an insufficient environmental resistance. Conversely, placing glass fibres skins over a jute fibres laminate (geometry G/J/G) leads to only a slight increase in the work of fracture, and increasing the thickness of the core by passing to a G/3J/G scheme proved ineffective in providing a higher resistance to impact. The reason for that was that typically only one glass fabric was fracturing and only one jute/glass interface was effective in stopping crack propagation through the laminate. This was explained by the low volume fraction of the reinforcement introduced, not exceeding 20%. A higher impact resistance was equally obtained by interposing a glass fabric layer in a scheme G/J/G/J/G, which presented very good environmental stability [26].

In many cases, the deceiving impact properties of hybrid laminates are due to insufficient interfacial adhesion, whilst the laminates present a high work of fracture for the laminate, was confirmed by a further study on glass/sisal [19]. In a study on glass/coir hybrids, a substantial increase in impact strength by up to 100% by the introduction of only a 5% volume fraction of glass was obtained by ensuring an intimate mix between coir and glass fibres in the core of a laminate with glass reinforced skins. This was explained with the higher failure strain of coir fibres [23]. More in general, the benefit obtained via the introduction of a very small volume of glass fibres would largely depend on their uniform incorporation in the composite with adapted techniques [27].

The emphasis put on interfacial adhesion suggested in a more recent work on flax/glass hybrids to try to compare Charpy impact tests with penetration energies obtained from falling weight impact tests [28]. It is noteworthy, in particular, that since the unidirectional mode of failure of the laminate considerably changes with plant fibre content [26], Charpy impact tests can supply in some cases quite inaccurate results, or at least need a very large tests database to be reliable. The study in [28] compared the effect on penetration energy of hybridising a flax/polypropylene composite either with discontinuous cellulose (®Lyocell) or with glass fibres. The obtained results confirm that penetration energy grows with an increased volume of the hybridising fibre content. However, when the glass fibre content exceeds 15%, the curve tends to level off (Fig. 4). This might suggest that a further addition of glass fibres can be less effective.

Conversely, another study demonstrated that the manufacture of a laminate including flax/epoxy layers sandwiched between E-glass/epoxy skins, in different proportions, results in a moderate reduction of impact properties, when flax fibres do not exceed the proportion of 1/3 of the total fibres (60% vol.). In this proportion, flax fibres in the core proved able to protect the non-impacted side from delamination up to falling weight impact energies approaching 50 J [4]. However, exceeding that amount

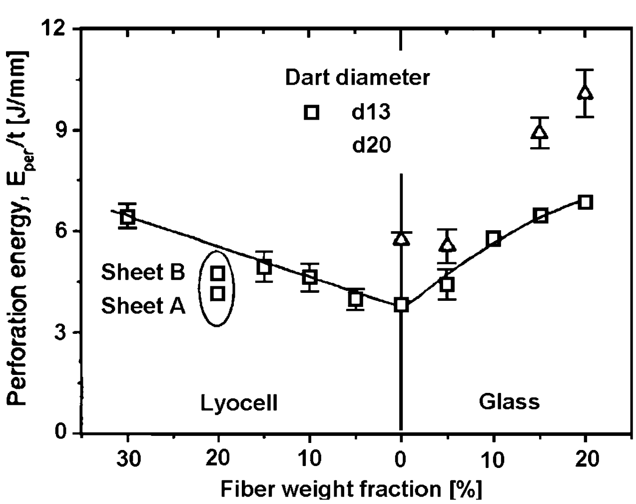

Fig. 4 Effect of the reinforcement type and testing conditions of the impact energy (Reprinted from Benevolenski OI, Karger-Kocsis J, Mieck KP, Reussmann T, Instrumented perforation impact response of polypropylene composites with hybrid reinforcement flax/glass and flax/cellulose fibres, Journal of Thermoplastic Composite Materials 13, 2000, pp. 481–496, with permission from Sage Publications)

of flax fibres has a more severe effect on impact strength, and this is due to the adoption of a hand lay-up procedure for laminate manufacturing. In spite of this, flax composites generally show higher impact energy than the other natural fibre composites, due to the existence of the effective energy dissipation mechanisms, like pullout and axial splitting of the fibres [28].

These results would suggest that the ideal reinforcement content could be identified for both glass and plant fibres in hybrid laminates to possibly optimise their impact properties, once of course the two reinforcing fibres are uniformly incorporated in the matrix.

Manufacturing method

The methods used to produce different hybrids in literature are exposed in Table 2. It appears as the manufacturing methods adopted would either concentrate on the simplification of the manufacturing procedure, or on the adoption of methods well established in the automotive industry, such as compression moulding of polypropylene matrix composites (see for example in [29]). This can be applied preferentially with polymer grafted using maleic anhydride with the benefits presented in section 'Scope and definitions'.

The use of hand lay-up procedures, although sometimes improved by vacuum impregnation or conversely by pressure application with the aim of reducing void content, does not offer comparable results, especially in terms of introduction of large fibre volumes (exceeding 60% wt.). The need to reduce as much as possible the void content is particularly important, since impact damage has been shown to propagate into plant fibre reinforced laminates mainly starting from surface and sub-surface defects due to insufficient impregnation [30]. Vacuum impregnation can represent a solution [25], although its efficacy appears limited in terms of achievement of higher interface strength when the quantity of glass fibres exceeds a few percents.

Fibre treatment

The relation between the chemical or physical treatment of fibre surface and impact properties of the composite obtained appears to be quite complex: treatments are aimed at enhancing the load-bearing capacity of plant fibres in composites by improving fibre/matrix compatibility and therefore bonding. Single fibre fragmentation tests (SFFT) often confirm this result, however suggesting cautionary considerations, when dealing with the variations of properties of the fibres, due e.g., to time and place of harvest, and defects introduced with fibre extraction [8]. A study on the agronomic characteristics of ramie and Spanish broom fibres confirmed their potential, yielding high interface

Table 2 Hybrids configurations and manufacturing methods in literature

Plant fibre	Plant fibre % wt.	Max. total fibre % wt.	Manufacturing method	Reference
Bamboo	15–35	40	Injection moulding	[42]
Bamboo	9–15	30	Compression moulding	[22]
Banana	25–37	40	Vacuum impregnation & hand lay-up	[32]
Coir	30	45	Pre-preg and punch pressing	[23]
Flax	20–45	50	Hot pressing	[28]
Jute	16–33	75	Filament winding	[21]
Jute	14.5–31	30	Hand lay-up	[26]
Jute	25–27	35	Compression moulding	[25]
Oil palm	4–36	40	Vacuum impregnation & hand lay-up	[10]
Oil palm	8–32	40	Pre-preg & Intermingled mats	[51]
Palmyra	48	58	Hand lay-up	[52]
Sisal	6–14	20	Compression moulding after solution mixing	[53]
Sisal	2–6	14	Hand lay-up	[18–20]
Sisal	4–16	20	Injection moulding after intimate mixing	[54]
Flax	6–31	41	Compression moulding	[59]

strength, possibly superior to glass and carbon fibres, a result which was attributed to a mechanical lock mechanism [31].

Proposed treatments include, among others, NaOH bleaching, also termed as alkalisation [32], acetylation [33], graft copolymerisation of vinylic monomers into cellulose, on its own [34] and following treatment with fatty acid derivatives [35], silane treatment [36–38], ultraviolet radiation [39], maleic anhydride [40], acetic anhydride [41] and plasma-treatment [42]. As a general point, impact behaviour is generally affected by chemical treatments, since these were reported to contribute to decrease the rigidity of the impacted composite [33, 43]. However, cases in contrast with this trend also exist, especially when applying bio-matrices, such as in [44], where acetylation and alkalisation were reported to

Table 3 Fibre treatment and effect on impact properties of plant fibre laminates

Plant fibre	Matrix	Fibre treatment	Impacted	Obtained/predictable effect	Reference
Bamboo	Polypropylene	MAPP	No	Positive (improved interfacial adhesion)	[43]
Sisal	Polyethylene	Various tried[a]	No	Max. increase in tensile properties from NaOH	[56]
Sisal	Unsaturated polyester	NaOH (surface) Silane (coupling)	Yes	No significant improvement	[18–20]
Sisal	LDPE[b]	Various tried[c]	No	Max. overall increase in properties from CTDIC[d]	[55]
Sisal	Polyethylene	Various tried[e]	No	Max. increase in fibre-matrix adhesion from peroxide	[26]
Sisal	Polyester	Alkali Cyanoethylation	Yes	Alkali improved impact resistance	[57]
Jute	Polyester	Various tried[f]	No	Max. overall increase in properties from titanate	[24]
Pineapple leaf	Polyester	Alkali Cyanoethylation	Yes	Alkali improved impact resistance	[57]

[a] Sodium hydroxide (NaOH), acetylation, permanganate, stearic acid, peroxide, silane (on both glass and sisal fibres), Maleic anhydride modified polypropylene (MAPE)

[b] Low density polyethylene

[c] Alkali, isocyanate, BP, DCP, potassium permanganate ($KmnO_4$), peroxide and cardanol derivative of toluene diisocyanate (CTDIC)

[d] Cardanol derivative of toluene diisocyanate

[e] Stearic acid, maleic anhydride, silane, and peroxides

[f] Silane, titanate and toluene diisocyanate (TDI)

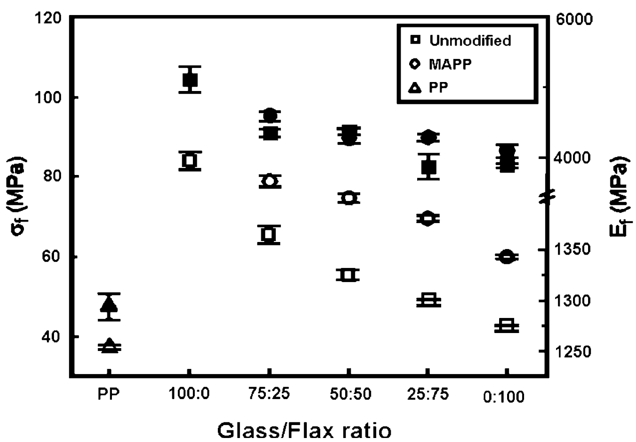

Fig. 5 Effect of glass/flax ratio on the flexural strength (open symbols) and modulus (solid symbols) of hybrid composites. (Reprinted from Arbelaiz A, Fernandez B, Cantero G, Llano-Ponte R, Valea A, Mondragon I, Mechanical properties of flax fibre/polypropylene composites. Influence of fibre/matrix modification and glass fibre hybridisation, Composites Part A **36**, 2005, pp. 1637–1644, with permission from Elsevier)

improve the impact properties. The effect of alkalisation is deemed in general positive in hybrids including sisal fibres, as suggested in Table 3: however, the environmental impact of the use of sodium hydroxide to treat fibres is suggested not to be negligible. As a whole, fibre treatments other than alkalisation do not appear to lead to a substantial improvement of impact properties. In [45], interfacial adhesion appears to be increased from maleic anhydride treatment, a promising result if coupled with a substantial reduction of fibre defects, so that the laminates comes to failure when the ultimate fibre strength is reached.

This decline can be partially compensated for with some treatment, such as the aforementioned grafting of maleic anhydride polypropylene copolymer (MAPP) [46]. MAPP acts essentially in lowering the surface energy of the fibres, reducing it to a level much closer to the surface energy of the matrix. In practice, MAPP-modification of the polypropylene matrix allowed an improved interfacial adhesion between the matrix and both flax and glass fibres, which was reflected in better flexural properties of the hybrid laminates (Fig. 5). An even higher improvement of mechanical properties was revealed after treatment with maleic anhydride directly grafted onto PP matrix or silane treatment [47]. However, the effect of these treatments on impact properties of hybrid laminates would need to be related to the optimal glass and plant fibres content, and investigated on a range of plant fibres, with the idea of selecting the best available fibre for impact resistance purposes.

Discussion

In Table 4, a number of studies on E-glass/plant fibre hybrids including impact testing are reported. When a number of configurations have been tested, only the one offering the best impact properties is reported in the table. The two routes suggested from Table 2, simplification of production procedure (hand lay-up, possibly with vacuum impregnation), typically with polyester resins, and production of polypropylene matrix laminates with methods adopted in the automotive industry, appear here to generate hybrids comparable in terms of impact properties. The drawback of simplified manufacturing procedures is that the inclusion of a limited volume of plant fibres (largely inferior to those of glass fibres) is required.

However, these data should also be complemented by other considerations. Dealing with impact fracture, one of the aspects appearing more difficult to be generalised, in studies on E-glass/plant fibre hybrids, is the occurrence of plant fibre pullout during fracture. This is directly connected to the unpredictable presence of defects in the fibres: problems with defects are found to affect particularly long fibre reinforced composites, and are shown to vary with fibre cross-section and irregularities in fibre bundles [5]. In addition, pullout depends also on the strain rate, and may also disappear for higher impact velocity, as observed in [12]: here, oil palm fibres fractured at the crack plane with no pullout.

Table 4 E-glass/plant fibres hybrids and impact properties (only the configuration showing the best properties in each case is shown)

Plant fibre	Matrix	Plant fibre (% wt.)	Glass fibre (% wt.)	Impact strength (kJ/m^2)	Reference
Bamboo	Unsaturated polyester	6.2	18.8	32	[21]
Coir	Unsaturated polyester	15	30	40	[13]
Jute	Unsaturated polyester	6	8	44	[25]
Sisal	Unsaturated polyester	2.7	5.3	5.76	[16]
Flax	Polypropylene	30	20	43.2	[27]
Flax	Soybean oil	16	25	33.6	[59]
Hemp	Polypropylene	30	10	75 J/m (notched)	[58]

More in general, two aspects appear to be not sufficiently investigated in literature, both crucial in the development of E-glass-plant fibre hybrids: reduction of defects in fibres, and fibre selection for improved impact properties.

Extraction from plants leads to the majority of defects in fibres. This problem can be avoided, for example by introducing enzyme retting, which appears to be promising for some fibres, such as flax [48], although the effect of the introduction of enzyme-retted fibres on the impact properties of the laminate would need to be quantified.

For as regards fibre selection, a number of fibres proved suitable for introduction as reinforcement for polymer matrices: an indicative list is reported in Table 5. However, to pass to an adapted selection of plant fibres for higher impact-properties would require a number of studies to be carried out on the comparison of impact properties from hybrids composite laminates obtained with different plant fibres, such as in [29]. It is noteworthy that fibre extraction would need to provide fibres with comparable quality, ideally the best possible quality for all fibres examined, for the comparison results to be reliable.

Table 5 Plants used to produce fibres for reinforcement in composites

Plant	Botanic name	Fibres extracted from...
Abaca	*Musa textiles*	Leaf
Banana	*Musa sapientum*	Leaf
Bamboo	*Various species*	Stem
Betelnut	*Araca catechu*	Seed hair
Coir	*Cocos nucifera*	Fruit hair
Date palm	*Phoenix dactylifora*	Leaf
	Phoenix sylvestris	Leaf base (netted structure)
Esparto	*Lygeum spartum*	Stem
	Stipa tenacissima	
Flax	*Linum usitatissimum*	Stem
Hemp	*Cannabis sativa*	Stem
Henequen	*Agave fourcroydes*	Leaf
Indian grass	*Sorghastrum nutans*	Stem
Jute	*Corchorus* sp.	Stem
Kapok	*Ceiba pentandra*	Fruit hair
	Ceiba occidentalis	
Kenaf	*Hibiscus cannabinus*	Stem
Lady's fingers	*Abelmoschus esculentus*	Bark
New Zealand flax	*Phormium tenax*	Stem
Oil palm	*Elaeis guineensis*	Fruit hair
Piassava	*Attalea funifera*	Leaf
Pineapple	*Ananas comosus*	Leaf
Ramie	*Boehmeria nivea*	Stem
Roselle	*Hibiscus sabdariffa*	Stem
Royal palm	*Roystonea regia*	Leaf
	Oreodoxa regia	
Sisal	*Agave sisalana*	Leaf
Spanish Broom	*Spartium junceum*	Stem
Sunn hemp	*Crorolaria juncea*	Stem
Switchgrass	*Panicum virgatum L.*	Stem

Conclusions

To summarise, the successful development of glass/plant fibre hybrid laminates would benefit from fulfiling the following objectives:

- Introduction of a larger (global) volume of fibres in the composite
- Improved effectiveness of interfaces in dissipating impact damage or improved intermingling of fibres
- Modification of the geometry or study of the configurations in order to maximise impact properties

The importance of fibre treatment on impact properties is still controversial: whilst it was not possible to describe a general trend, in some cases of specific fibres (e.g., MAPP for sisal fibres, or alkali treatment on flax fibres) the treatment is deemed to be successful in improving impact properties.

Moreover, the controlling factor for impact resistance appears still to be the presence of defects in plant fibres, even in presence of the introduction of large volumes of glass fibres.

The limits of the literature so far are in particular related with natural fibre selection to achieve higher impact properties, bi-dimensional impact testing (falling weight, ballistic impact). Also the imaging of impact cracks in glass/plant fibre hybrid laminates would help investigating the role of fibre bridging, interface strength and fibre defects in the final impact properties of the composite.

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