Potential of natural fibres and their composites for South Asian countries: Moving towards sustainability

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Abstract

Increased environmental concerns and depletion of petroleum-based resources arising from the use of non-renewable resources have increased the demand of natural fibre reinforced composites (NFRCs). Composite materials reinforced with glass and carbon fibres have limited end-of-life (EoL) options, which is a major concern. To minimise this situation, lignocellulose plant fibres have been studied extensively in recent years, due to the increasing demand for sustainable, lightweight and environmentally friendly materials. Natural plant fibres are considered as a viable substitute to E-glass fibres owing to their many attractive benefits, such as biodegradable, recyclability, high specific strength and stiffness suitable as reinforcements for many semi-structural and structural composite applications. This new class of lightweight sustainable composites can offer environmental, social and economic benefits as substitute materials for various applications. Through an up-to-date review, this work presents an overview of natural plant fibres as reinforcements of composites for various applications, especially in the context of the South Asian countries.

Keywords: Natural fibre reinforced composites (NFRCs); Fibre morphology; Mechanical properties; Sustainability; Environmental impact; Applications, South Asian countries.

1. Introduction

Composite material can be broadly defined as the resultant of combining two or more materials on a microscopic scale, each of which has their own unique properties, to produce a new material that has properties far superior than either of the base materials. Main constituents of composite materials include matrix and reinforcement (fibres). The matrix acts as a binder. Both constituents enhance the properties of the resultant material (Hull and Clyne, 1996; Dhakal and Ismail, 2020).

Environmental legislation as well as consumers' pressure for adaptation of a "cradle-to-cradle" life cycle thinking for material use throughout the world has triggered a paradigm shift towards using sustainable composite materials, as a substitute to non-renewable man-made fibres such as glass and carbon (Bledzki and Gassan, 1999), among others. Over the last couple of decades, research in the potential use of renewable natural fibres as reinforcements in structural composites has increased significantly, due to their relative cheapness and with their high specific properties when compared with synthetic glass fibres (Dhakal and Ismail, 2020).

2. Natural plant fibres, their origins and potentials for South Asian countries

Dating back to the origin of mankind, natural fibres have been used to make cloths, building materials, such as bricks, ropes and to mention but a few products. Natural fibres have been used as reinforcement materials for over 3000 years (Bledzki and Gassan, 1999). The oldest example of composite material is addition of straw to clay for making bricks for buildings in ancient Egypt. From this application, straws or grass are the reinforcing fibres and clay is the matrix.

The natural fibre-based composites market is expected to grow to $531.3 million US in the year 2019 from $289.3 million in 2010 with 28% market shares by natural fibres. Similarly, this can be compared with the amount of money generated yearly in some South Asian countries, as briefly presented in Table 1.

Table 1: Illustrates key natural fibres, their producing countries, annual production and prices (Syduzzaman et al. 2020)

Fibre types	Main producing countries	Production quantity per year ($x10^3$ ton)	Price (US$/ton)
Hemp	China (80%), Chile, France, Germany, UK	214	1000–2100 (1550)
Jute	India (60%), Bangladesh, Myanmar, Nepal	3450	400–1500 (950)
Flax	Canada, France, Belgium, Netherland, Poland, Russian Federation, China	830	2100–4200 (3150)
Bamboo	Myanmar, Nigeria, Sri Lanka, Philippines, Pakistan	30,000	500
Banana	India (22%), China, Philippines, Ecuador and Brazil	134,000	890
Kenaf	India (45%), China, Malaysia, USA, Mexico, Thailand, Vietnam	970	300–500 (400)
Cotton	China, Brazil, India, Pakistan, USA, Uzbekistan, Turkey	25,000	1500–4200 (2850)
Sisal	Brazil (40%), Kenya, Tanzania, China, Cuba, Haiti, Madagascar, Mexico, Sri Lanka, India	378	600–700 (650)

3. Some key natural fibres available in the South Asian countries

Some key natural fibres that can be found in south Asian countries are presented in Figure 1.

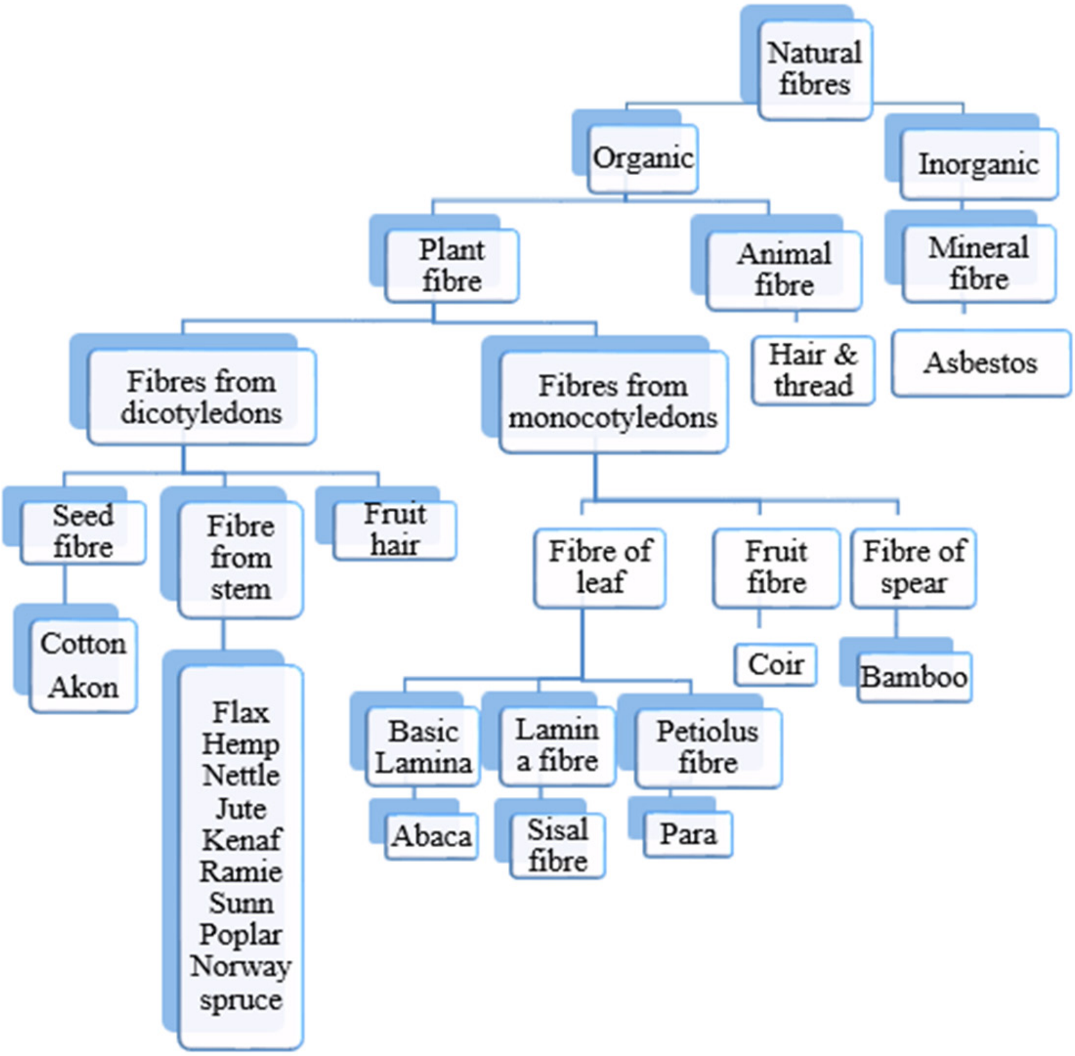

Figure 1. Some natural fibres available in south Asian countries (Müssig, 2010).

4. Natural plant fibres: Advantages and challenges

Despite many attractive attributes of natural fibres, they are not without some challenges, hinder their full structural applications. The main advantages and some drawbacks are summarily illustrated in Table 2.

Table 2. Advantages and some drawbacks of natural fibres as composite reinforcements (Faruk et al. 2012, Dhakal et al.; 2007, Dhakal and Ismail, 2020, Bourmaud et al. 2018).

Advantages	Some drawbacks
▪ High specific strength and stiffness ▪ Low hazardous manufacturing processes ▪ Low processing energy ▪ Renewable sources ▪ Lower cost of manufacturing (reduced tool wear) ▪ Low emission of toxic fumes when ▪ Non abrasive ▪ Lower risk to human health (no skin irritation)	▪ High moisture absorption (due to their polar characteristics) ▪ Lower durability compared to their synthetic fibres composites ▪ Low long-term durability ▪ Lower performance, in particular impact strength compared to synthetic fibres composites ▪ High variability in fibre property (due to their polar characteristics) ▪ Lack of standard, difficult for modelling ▪ Low thermal stability ▪ Lower flame retardance property (additional fire protection required)

5. Important properties of natural fibres

Basically, Table 3(a) shows a comparison of both mechanical and physical properties of some selected metallic, synthetic and natural fibres (bundles). It is evident that natural fibres (hemp and flax) have competitive properties with a few metallic and synthetic fibres, with greater specific strength and specific modulus than both steel and aluminium. This establishes the reason why they are competing with various application of these metals in manufacturing industries. In addition, Table 3(b) presents mechanical and physical properties of natural fibres, as compared among themselves.

Table 3(a): Differences in mechanical and physical properties of some selected metallic, synthetic and natural fibres (bundles) (Faruk et al., 2012; Gurunathan et al., 2015; Dhakal and Ismail, 2020).

Fibre types	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	Specific strength (MPa)	Specific modulus (GPa) $\left(\frac{E}{\rho}\right)$
Steel	7.8	1300	200	167	26
Aluminium	2.81	350	73	124	26
Carbon	1.51	2500	151	1656	100
E-glass	2.10	1100	75	524	28
Aramid	1.32	1400	45	1656	100
Hemp	1.4	690	30-70	453	21-50
Flax	1.5	345-1830	27-80	230-1220	18-53

Table 3(b): Selected mechanical and physical properties of some natural plant fibres (Cheung et al., 2009; Pickering et al., 2016).

Fibre	Tensile strength (MPa)	Young's modulus (GPa)	Elongation (%)	Density (g/cm^3)	Diameter (micro meter)	Length (mm)
Date palm fibre	58-230	0.3-7.5	5-50	0.9-1.2	100-1000	20-250
Flax	345-1035	27.6	2.7-3.2	1.5	10-25	10-65
Hemp	690	70	1.6	1.4	25-35	5-55
Jute	393-773	26.5	1.5-1.8	1.3	25-200	0.8-6
Bamboo	140-230	11-17	-	0.6-1.1	14	2.7
Kenaf	930	53	1.6	-	1.14-11	12-36
Cotton	287-800	5.5-12.6	7-8	1.25	10-34	2.7
Sisal	511-635	9.4-22	2-2.5	1.15	7-47	0.8-8
Oil palm (empty fruit)	130-248	3.58	9.7-14	0.7-1.55	191-250	0.8-0.9

6. Natural fibre reinforced composites

Natural fibre reinforced composites (NFRCs) are composite materials produced using natural fibres as reinforcements as opposed to the carbon and glass fibre composites, which use non-renewable synthetic fibres such as glass and carbon fibres as reinforcements. There is a growing trend on use of carbon and glass fibre composites in many industrial sectors including aerospace, marine, automotive and construction. However, after the end of their product life, large quantities of these composites are sent to land field as waste materials. NFRCs are important for environmental sustainability as they are obtained from the renewable sources. These materials can also produce some favourable properties at a lower cost in comparison with synthetic fibre composites. Sustainable use of natural resources are key factors to achieve the sustainable development (SD) goal as described by the 1987 Bruntland Commission Report "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Due to the importance of protecting our environment, concepts and approaches such as sustainability, moving linear economy to circular economy, life cycle thinking, extended producer responsibility (EPR), corporate social responsibility (CSR) and 3R (reduce, reuse and recycle) principles (Dhakal and Ismail, 2020) have become visible in recent years.

Besides, recycling of natural fibres (such as flax, hemp and jute) are far more environmentally beneficial in comparison with other synthetic (glass and carbon) fibres (Figure 2). Ten environmental impact categories were considered by (Pil et al., 2016) to compare between flax and glass fibres (Figure 2). Apart from the land use, flax outperformed glass fibres in all other categories including abiotic depletion, acidification, eutrophication, global warming potential, ozone depletion, among others. When considering the energy required to produce 1 kg of fibres, the reported work by (Pil et al., 2016) further reiterated that scotched flax requires only about 10 MJ/kg whereas for glass fibres, it requires about 50 MJ/kg and for carbon fibres, it requires about 290 MJ/kg. The reported work clearly suggests that when overall environmental performances of natural fibre composites are considered, there are clear advantages against conventional glass fibres.

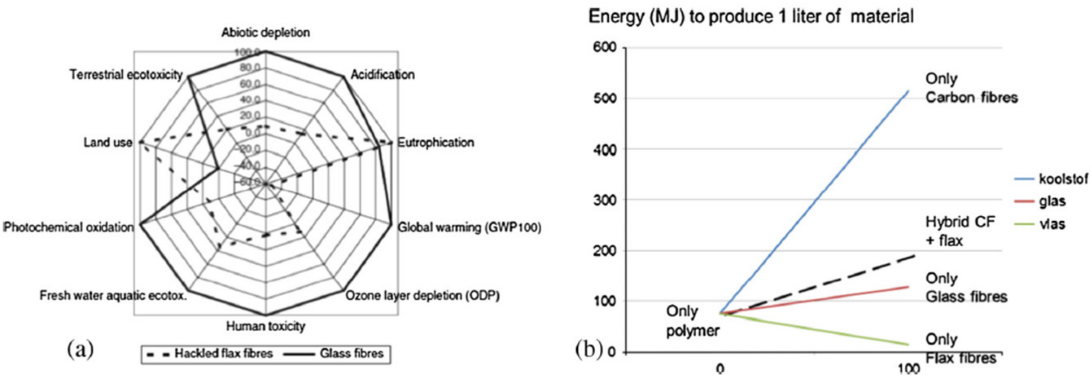

Figure 2: Environmental impact performance, depicting: (a) life cycle analysis/assessment of flax fibres against glass fibres and (b) energy content of flax against glass and carbon fibre reinforced composites (Pil et al., 2016).

Reported work by Sáez-Pérez et al. (2021) also highlights that hemp fibre has an ideal carbon sink, which reduces the CO2 emitted into the atmosphere, due to the absorption effect. For instance, hemp has an outstanding reabsorption capacity equivalent to 1800 kg of CO2 for each tonne cultivated.

7. Potential applications of NFRCs

Natural fibres have long history and their use in Asian countries. For example, jute fibres have been used in India, Bangladesh and Nepal for many years. Asia has one of the fastest growing market in the world. Jute fibres are not only available abundantly in these countries, other natural fibres such as banana, coir, sisal, bagasse, reeds, cotton and silk are also available. This puts the region as a strong powerhouse in terms of exploitation of these natural fibres for industrial applications. Therefore, many multinational companies are outsourcing and offshoring their business in this region. NFRCs are extensively used in automotive sector in Europe and North America (Figure 3).

However, many OEMs have moved their production facilities to Asian countries, specifically to India and China. Major applications of NFRCs include, but are not limited to, building and construction, aerospace and automobile, power and energy, oil and gas, telecommunication and electrical/electronics, games and sports/recreation, biomedical and health, security and military industries (Table 4). Some of the aforementioned sectors are briefly and subsequently elucidated.

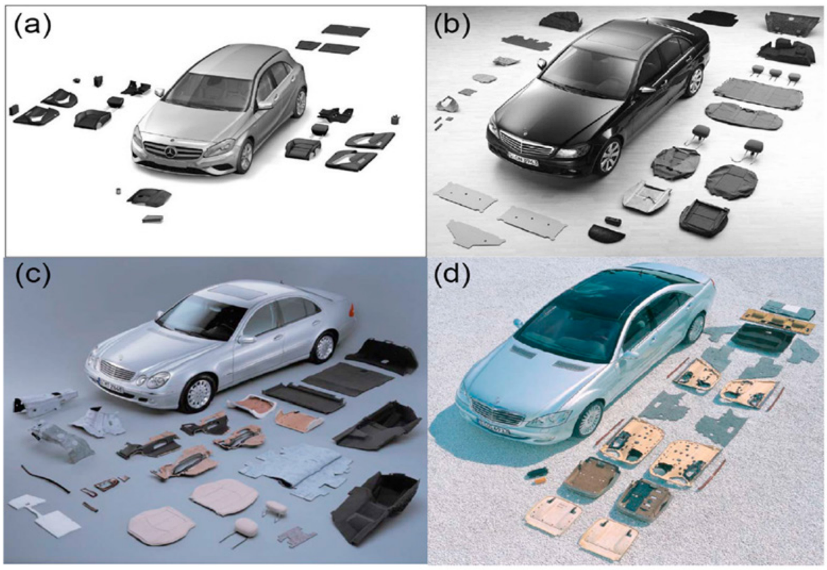

Figure 3: Applications of different natural fibres (flax, hemp, sisal, wool and others) in Mercedes-Benz model (a) A-class, (b) C-class, (c) E-class, and (d) S-class (Li et al., 2020).

Table 4: Industrial applications of key natural fibres (Syduzzaman et al. 2020).

Fibre types	Various industrial applications
Hemp	Textiles, geotextiles, paper and packaging, electrical, furniture, cordage, construction concrete items, 3D printing filaments, manufacturing pipes, auto parts and oil absorbent materials.
Jute	Building panels, door frames, chipboards, geotextiles, door shutters, packaging, transport and roofing sheets.
Flax	Tennis racket, bicycle frames, snowboarding, panels, doors, laptop cases, printed circuit boards and furniture.
Bamboo	Building and construction items, baskets.
Banana	Furniture, building and construction items.
Kenaf	Mobile cases, insulation materials, animal bedding and packaging materials
Cotton	Textiles, cordage, furniture upholstery and goods.
Sisal	Panels, doors, paper and pulp.

Many materials used in building and construction sector currently are not so environmentally friendly. For example, cement has been used for many years as structural material, but cement is one of the high energy consumption materials when considered its lifecycle performance. During the production process, it consumes high amount of energy. One of the solutions put forward to improve this sector is the use of sustainable materials to replace high energy consuming materials. There are several reported works that suggested the benefits of using natural fibre compounds, such as hemp and other natural fibres in building materials. There are many examples where biocomposites are successfully used in building and construction materials. The lower production costs with an improved environmental performance makes these materials sustainable and cost effective, as reported (Sáez-Pérez et al., 2021). They studied on influence of the state of preservation on different formulations of geopolymer hempcrete and hydraulic lime hempcrete (Figure 5). Industrial hemp fibres have been extensively sought to be used in building and construction industry.

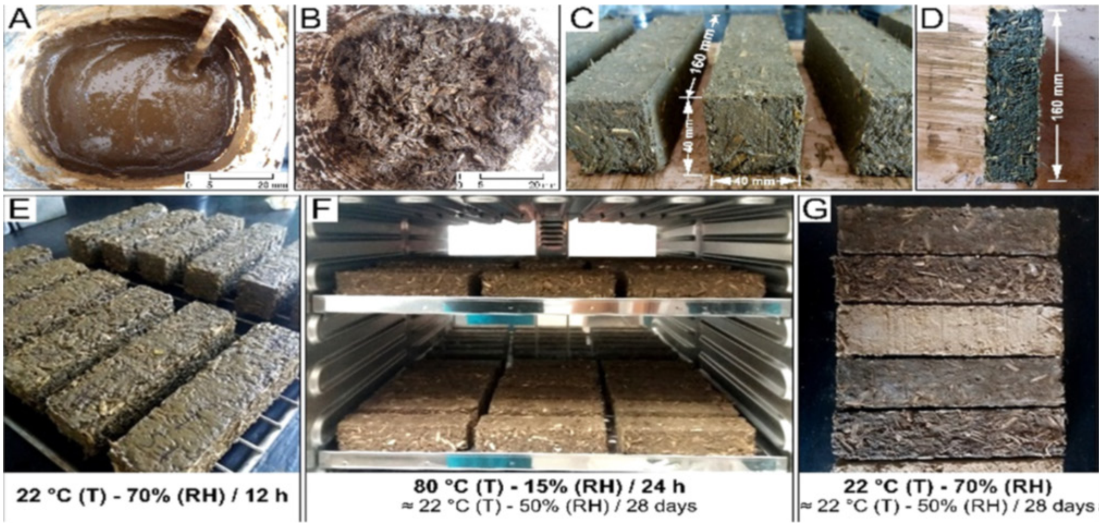

Figure 5: Process used for the preparation of geopolymer hempcrete samples and hydraulic lime hempcrete (Sáez-Pérez et al., 2021).

Moreover, NFRCs have been widely used in automobile companies to manufacture several components. Comprehensive applications of NFCs in automobile (such as Toyota, Fiat, Audi, Peugeot, Volvo, Ford, Mitsubishi, and others) and other sectors have been extensively reported (Mohammed et al., 2015; Dhakal and Ismail, 2020).

8. Conclusions and future perspective

Natural fibres offer several sustainable, low-cost, recycling, abundant resource, and environmental benefits as reinforcements in NFRCs, when compared with their synthetic counterparts such as glass and carbon fibres. Natural plant fibres are eco-friendly and sustainable and the global demand for these plant fibres is predicted to grow faster. Similarly, key research and development work in this field is expected to grow significantly in the coming years. NFRCs provide several advantages, including but not limited to, biodegradability, non-abrasive processing, high specific strength and stiffness. The findings of this review present that for the sustainable materials, these lightweight composites provide a strong alternative. Although, NFRCs provide multiple benefits, some inherent drawbacks (inherent hydrophilic polar and their limited long-term stability) of these fibres place some challenges that can limit their full potential for semi-structural and structural lightweight applications. However, the benefits of NFRCs outweigh their associated challenges. Therefore, it is evident that South Asian countries have inexhaustible natural resources of plant fibres to increase their opportunities and become global leading suppliers of natural fibres and their composites to multi-national manufacturing companies, hence increasing/improving their economy substantially.

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