Tribological Behaviour of Natural Fibre Based Polymer Composites

Rajiv Kumar, Mir Irfan Ul Haq, Ankush Raina, Sanjay Mohan Sharma, Ankush Anand, and Mohd Fadzli Bin Abdollah

Abstract Researchers are continuously working on materials with lower weight, higher strength and lesser in cost. Polymer composites are promising candidate in this category. Natural fibre based polymer composites are being considered for various applications due to environmental concerns and requirement of sustainable environment. Natural fibres are environment friendly, available in abundance, biodegradable, cheap and low in density in comparison to synthetic fibres. Reinforcement of natural fibres have improved mechanical and physical properties of these composites. Researchers are working on various industrial applications of these composites. Study of the tribological aspects of these composites is the new research area. Based on their attractive properties researchers are interested in knowing the feasibility of natural fibres for tribological applications. Developing green friction materials, bearings for automotive applications is the need of the hour. The present chapter highlights the significance of friction and wear behaviour of natural fibre based composites. The work focuses on effect of reinforcement of natural fibres on tribological properties of these composites and also exposes limitations of these fibres. A brief introduction of natural fibres, polymers and tribology is also provided to give the background for the readers. The work will help the enthusiast researchers interested in the tribological study of natural fibre reinforced composites.

Keywords Natural fibres · Bio-composites · Tribology · Wear · Friction · Green composites · Polymers · Green tribology

R. Kumar (✉) · M. I. U. Haq · A. Raina · S. M. Sharma · A. Anand
School of Mechanical Engineering, Shri Mata Vaishno Devi University, Katra, Jammu and Kashmir, India

M. F. B. Abdollah
Fakulti Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

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1 Introduction

The quest for new materials with properties like light in weight, high strength to weight ratio, low cost, environment friendly, etc. will never end (Baba et al. 2019). Designing machine components with these materials involves different aspects like wear, friction and lubrication for the smooth functioning of the system. Therefore, tribology plays a vital role in designing various machine components. The term "tribology' coined by Dr. Peter Jost in England in 1966. He defines it as "The science and technology of interacting surfaces in relative motion, having its origin in the Greek word *tribos* meaning rubbing". He highlighted the huge losses in industry associated with tribological aspects. A saving of 515 million pounds per year can be achieved by the better designing of components from tribological perspective in the industries. Tribology is a multidisciplinary and a complex field involving material science, mechanical engineering, chemistry, fluid dynamics, heat transfer, thermodynamic, etc. (Jost 1990).

During the last decade, polymer composites have emerged as a potential candidate for conventional materials due to their excellent properties like lightweight, easy processing, high strength to weight ratio, low cost, etc. (Vohra et al. 2015; Rajak et al. 2019). These composites mainly involve fibre reinforcement (synthetic or natural) in a polymer matrix. Fibres have higher strength and stiffness, while the matrix material facilitates the transfer of stress to the fibre and also, protect the fibre from direct environmental contact. In the last few years researchers are shifting their focus from synthetic to natural fibres due to strict environmental guidelines and various other benefits of these fibres over synthetic fibres (Nirmal et al. 2015).

Natural fibres are available in abundance throughout the world. Natural fibres include fibres from natural sources (plants, animals, minerals) like jute, flax, hemp, ramie, sisal, banana, cotton, etc. India have abundance availability of natural fibres like jute, bamboo, banana, coir, ramie, sisal, pineapple, etc. composites based on these fibres are good alternatives to wood in housing and construction industries. The motive force behind development of these composites in India mainly is due to two reasons. Firstly, saving of forest resources, and secondly ensuring good economic results to farmers for cultivation of these natural fibres (Kumar et al. 2019).

Natural fibre reinforced polymer composites consist of a polymer matrix reinforced with natural fibre. Polymer composites having natural fibres as reinforcement are known as bio-composites (Faruk et al. 2012). Bio-composites based on different types of polymer and natural fibre are shown in Fig. 1. When two or more than two different fibres are mixed with the polymer then that composite is termed as hybrid composite. Hybrid composites have higher mechanical properties as compared to individual fibre based composite (Gupta et al. 2019). The present work highlights the work of various researchers in the field of tribological behaviour of bio-composites during last decade. There are different fabrication methods for these composites. The key features for different fabrication techniques are also tabulated in the current work to give a brief idea for these techniques. Environmental benefits, applications and

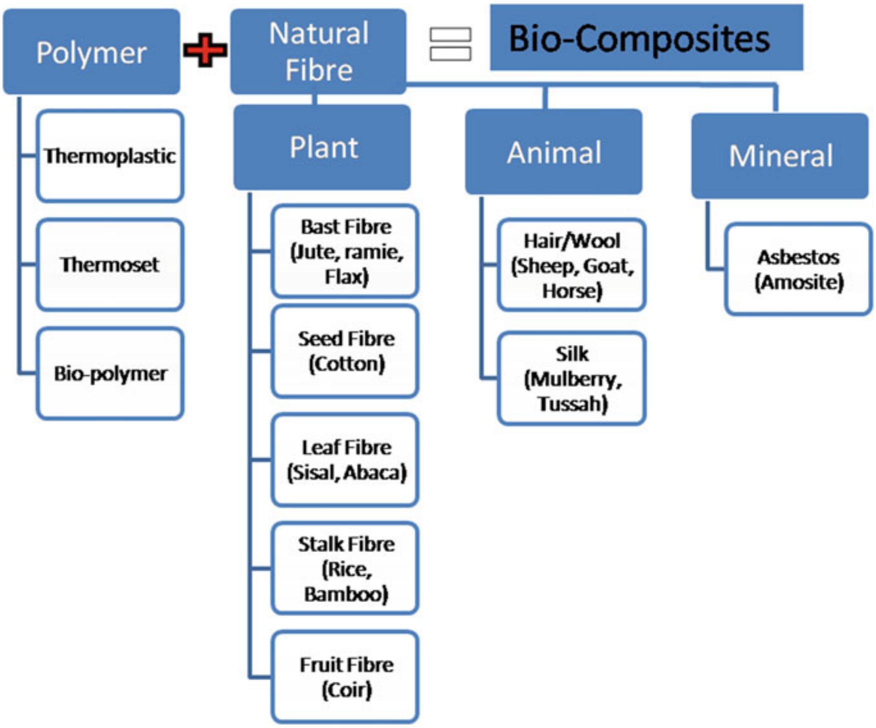

Fig. 1 Bio-composites based on various type of polymers and natural fibres

challenges associated with these composites are also discussed to give an overview to the researchers new to the field.

2 Fabrication Methods of Bio-Composites

All the fabrication methods used to produce synthetic fibre reinforced polymer composites can also be utilized to produce bio-composites with slight modifications. Researchers mainly utilize hand layup technique for fabrication of bio-composites due its easy processing and economical. Figure 2 shows open mold hand layup process. Different fabrication routes for bio-composites are summarized in Table 1.

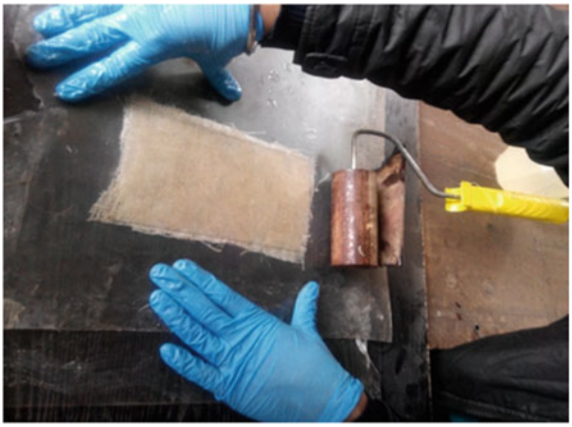

Fig. 2 Hand layup technique

Table 1 Processing methods for bio-composites

Fabrication method	Key features
Hand layup	• Manual procedure to put resin and reinforcement in an open mold • Hand roller removes the entrapped air during the fabrication • Economic, no bar on size of the part. Examples: storage tanks, tubs, boats, etc
Spray layup	• Spray gun is used to spray the mixture of chopped reinforcement and resin in an open mold • Faster than hand layup technique. Examples: storage tanks, tubs, boats, etc
Injection molding	• Reinforcement and resin mixture is pushed into a closed mold by screw extruders through a nozzle • High production. Examples: automobile body panels, bumpers, floor pans, etc
Compression molding	• Resin and reinforcement are placed in a closed mold. Temperature, pressure and time are controlled in the fabrication process • Lesser post processing requirements, better adhesion. Examples: structural components, Automobile components, etc
Resin transfer molding	• High pressurized resin is transferred in the closed mold cavity in which reinforcement is already placed • High fibre content, faster, products with complex geometry, high surface finish, etc
Vaccum bag molding	• Laminates are produced using vacuum bag covers over the mold • Improved mechanical strength, uniformity, no voids
Filament winding	• Continuous reinforcement wounds on to a revolving mandrel, automatic and controllable fibre orientation • High fibre content, hollow cylindrical products. Examples: pressure vessels, chemical storage tanks, etc
Pultrusion method	• Mixture of fibre and resin pulled through heated die • Uniform cross sectional shaped products, high fibre content. Examples: Long rods, beams, channels, etc

3 Tribological Properties of Bio-Composites

Researchers are working on to expedite new sectors of engineering applications for bio-composites. Tribology is one such emerging area. A wide scope is available on tribological behaviour of NFPC. Researchers have worked on the tribological behaviour of bio-composites like kenaf/epoxy (Chin and Yousif 2010), sugarcane/polyester (El-Tayeb 2008), sisal/PLA (Bajpai et al. 2014), cotton/polyester (Hashmi et al. 2007), bamboo/epoxy (Nirmal et al. 2012), betelnut/polyester (Nirmal et al. 2010; Gill and Yousif 2009), hemp/epoxy etc. (Chaudhary et al. 2018). It is also evident from Fig. 3 that during last five years focus of researchers is shifting from synthetic fibres to natural fibres in the area of tribology also. Research work based on tribological characterization of natural fibres reinforced composites has been increased during these years. The detailed review of the work related to tribological behaviour of bio-composites by various researchers is discussed as below.

Sundarakannan et al. (2020) investigated wear and erosion performance of pineapple fibre (40 wt. %) reinforced polyester polymer composites. Redmud an industrial waste was used as filler by wt. % of 10 and 20. The composites were developed by compression moulding machine. Erosive resistance was tested by solid particle erosion test on Ducom tester. It was observed by the authors that redmud fillers enhanced the erosive resistance of the developed composites. The developed composites with 10 wt. % redmud fillers exhibited low erosive wear rate.

Rajesh Kumar (2020) investigated tribological behaviour of Phoenix Sp./epoxy composites. Composites were fabricated by compression molding method based on

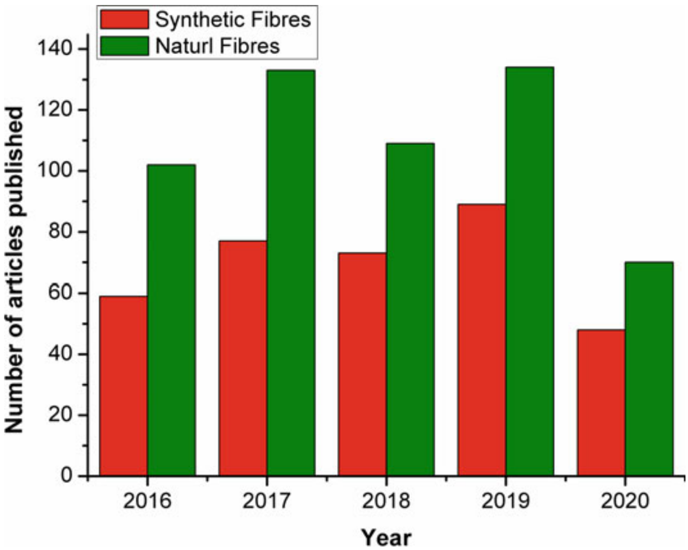

Fig. 3 Articles published on triblogy of synthetic as well as natural fibres in last 5 years (Using keywords—Tribology, synthetic fibres, natural fibres on https://www.sciencedirect.com)

different volume fraction of fibre including 10 to 50%. Fibre length was also varied to check its impact on tribological properties. Pin on disk tribo testing machine was used for three loads including 10, 20 and 30 N. Three Sliding speeds varied in the range of 1–3 m/s and sliding distances varied from 1 to 3 km. The authors observed that reinforcement of Phoenix Sp. Fibre improved the tribological properties of developed composites in comparison to neat polymer.

Suresh et al. (2020) analyzed wear behaviour of agricultural residues reinforced vinyl ester composites. Agricultural residues included bagasse, rice husk and coconut shell in different weight fractions from 5 to 25% for various type of composites. Composites were developed by compression molding technique. The tribo testing was carried out on pin on disc tribometer. The different experimental parameters included normal load from 20 to 40 N, sliding velocity of 2 and 4 m/s. The sliding distance considered for the experimentation purpose was 500 m. The authors revealed that hybrid composites having 20 wt. % of each natural fibre exhibited lower wear loss and low coefficient of friction.

Pari khand Gohil (2019) developed cotton fibre/polyester composites and analyzed the wear performance. Different weight fractions of fly ash as filler was also used to analyze its impact on wear behaviour. Cotton fibre was used by 18 wt. % and fly ash had two variations of 3 and 5 wt. %. Composites were developed by hand layup compression molding technique. Authors revealed that fly ash as filler had significant impact on wear performance. Authors concluded that composites with 3 wt. % of fly ash filler exhibited highest wear resistance and recommended use of these materials in high wear conditions.

Zhen et al. (2019) examined effect of banana fibre reinforced phenolic based polymer composites on tribological properties. Composites were fabricated using banana and barium sulphate as reinforcements using hot compression technique. Developed composites containing 10 wt. % banana fibre and 45 wt. % barium sulphate exhibited highest coefficient of friction, in comparison to other composites. Authors concluded that the lower banana fibre ($\leq$10 wt. %) loading, enhanced the friction and wear performance of the composites.

Shivamurthy et al. (2019) analyzed sliding wear behaviour of waste tyre rubber reinforced epoxy composites. Composites were developed by open moulding method based on the different weight fractions of reinforcement including 15, 30 and 45 wt. %. Effect of particle size (100, 200, and 300 μm) of the reinforcement was also investigated. It was observed that both the parameters i.e. weight fraction of filler and the particle size has significant impact on wear behaviour of developed composites. The authors concluded that by the reinforcement of waste tyre rubber enhanced the sliding wear behaviour.

Ranganathan et al. (2019) investigated wear and friction behaviour of sisal fibre reinforced composites with cashew nut shell liquid (CNSL) and epoxy resin. Composites were fabricated by hot press technique. Composites were examined for the tribo conditions of varying loads of 10–40 N and sliding distances of 1000 and 2000 m. Graphite and alumina fillers were also added in CNSL composites. Composites having CNSL resin exhibited good wear resistance and frictional properties in comparison to epoxy resin based composites. Lesser wear resistance and frictional coefficient were observed at the load of 40 N and sliding distance of 2000 m.

Kumar and Anand (2018) investigated friction and wear behaviour of Indian ramie reinforced epoxy composites. Composites were developed on the basis of different weight fractions of fibre varying from 0 to 40%. Hand layup technique was used for fabricating the composites. Pin on disc tribometer was used for tribo testing with five different normal loads ranging from 10 to 30 N, sliding speeds of 1, 1.5 and 2 m/s with a constant sliding distance of 1000 m. Composites with 30 wt. % fibre loading offered highest wear resistance and an increment of 75% in wear resistance at 10 N load in comparison to neat epoxy. Frictional coefficient enhanced with the enhancement in fibre content.

Shuhimi et al. (2016) analyzed frictional and wear performance of oil-palm/epoxy (OPF/E) and kenaf/epoxy (KF/E) composites under dry sliding conditions. Composites were developed by hot compaction technique. Tribological testing was performed using POD tribo machine. With the increase in fibre loading of the OPF/E composite observed severe wear. However, in case of the KF/E composite, the same change exhibited higher wear performance. The study revealed that for both the developed composites, wear loss enhanced and frictional coefficient reduced after the temperature increase.

Bajpai et al. (2013) analyzed the tribological behavior of nettle, grewia-optiva and sisal fibre reinforced polypropylene composites using pin-on disc (POD) machine. Significant increase in the specific wear rate of the reinforced composites was observed in comparison to neat polypropylene. Authors also observed that specific wear rate was more sensitive to applied load changes (10–33 N) than the sliding speeds changes (1–3 m/s). Authors observed that 30 wt. % of sisal fibre reinforcement substantially improved wear behaviour of the neat polypropylene.

Yousif et al. (2010) analyzed tribological characteristics of betelnut fibre/polyester composite. To analyze frictional and wear behaviour of developed composites by changing various parameters like sliding distance, sliding speed and load, experiments were carried out on block-on-disc (BOD) machine under dry/wet sliding contact conditions. The study revealed that developed composite exhibited improved wear and frictional behaviour under wet contact condition. Wear and frictional behaviour of developed composites improved by about 50% and 94% respectively.

Many researchers have worked on study of tribological behaviour of bio-composites. Researchers performed the experiments on different tribo testing machines with dry/wet sliding contact conditions using different parameters such as applied load, sliding velocity and, sliding distance. The counterface used was steel or other materials and concluded that bio-composites are a potential alternative for conventional materials. The properties can be improved by adding other filler materials and proper chemical treatment of the fibre.

Wear mechanism of these composites can be analyzed with the help of SEM micrographs of wear our specimen during triobological testing. SEM micrographs presented in Fig. 4 include ramie/epoxy bio-composites with 10% fibre loading (Fig. 4a) and 30% fibre loading (Fig. 4b) at 20 N normal load, 1 m/s sliding speed and 1000 m sliding distance. Fibre fracture, matrix breakage, debonding, ploughing

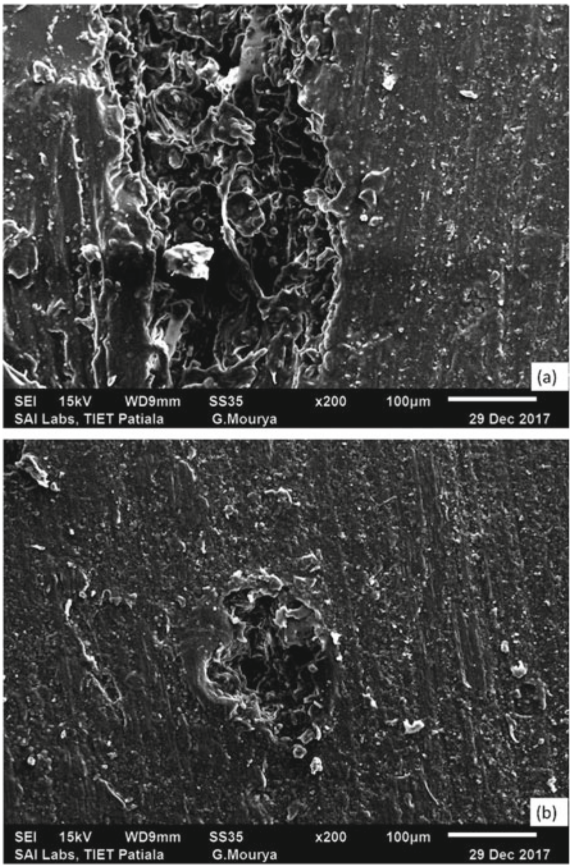

Fig. 4 Wear mechanism of Ramie/epoxy bio-composites with **a** 10% fibre loading and **b** 30% fibre loading at 20 N normal load, 1 m/s sliding speed and 1000 m sliding distance

can be observed in the micrographs. Ploughing and cutting marks indicate abrasive wear mechanism in these composites. Higher matrix breakage, debonding and fibre fracture can be seen in composites with 10% ramie fibre loading. This can be attributed to poor interfacial adhesion between fibre and matrix. As fibre loading increases interfacial adhesion improves and leading to lesser fibre fracture and matrix breakage. That's why composites with 30% ramie fibre loading exhibited better wear performance (Bajpai et al. 2013; Kumar and Anand 2018; Chaudhary et al. 2018).

4 Parameters

Based on the work by different researchers the various parameters in tribological investigation of bio-composites are listed below:

1. Type of fibre
2. Fibre Orientation
3. Fibre loading
4. Type of polymer
5. Applied normal load
6. Sliding speed
7. Sliding distance
8. Sliding direction.

These parameters will influence the frictional and wear behaviour of the bio-composites. Figure 5 represents all these parameters in a fish bone diagram that have a significant impact on the tribological behaviour of bio-composites. The effect of above mentioned parameters on tribological properties of bio-composites is discussed as below:

Type of Fibre: Fibre type has a significant impact on the tribological behaviour. It includes fibre length and chemical composition (governs physical and mechanical properties) of the fibre. Type of fibre also includes treated or untreated fibres. Fibre treatment involves surface treatment of fibres for better properties like reducing moisture absorption and enhancing adhesion at fibre-matrix interface. Most commonly

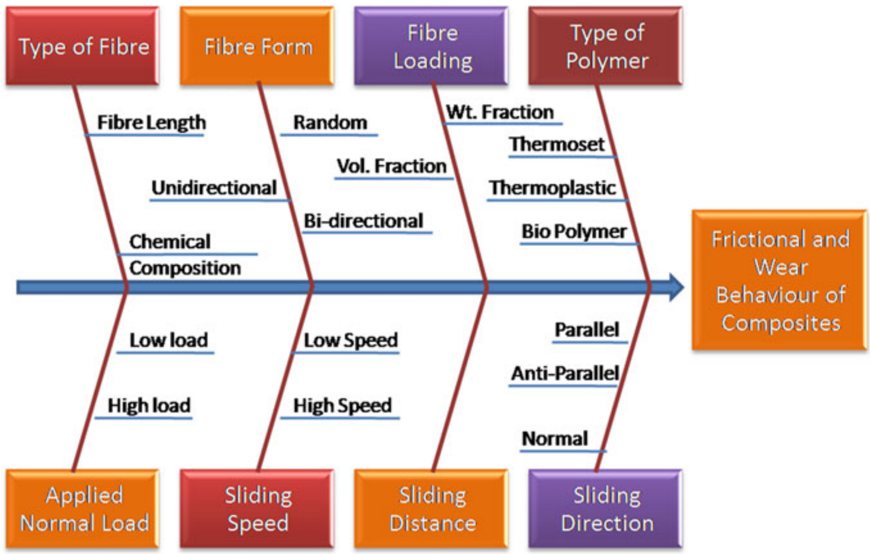

Fig. 5 Fish bone diagram of tribological behavior of polymer composites

used treatments are alkali treatment and acetylation (Omrani et al. 2016). By studying the effect of these components of a fibre one can select the fibre.

Fibre Orientation: Fibre orientation (with respect to applied load) involves random, unidirectional, bidirectional etc. As fibres act as carriers of load and stress under loading conditions, therefore, fibre orientation will have significant effects on tribological behaviour of the composite. Each fibre orientation produces different tribological behaviour as far as various properties are concerned for these composites. By analyzing the requirement, one can finalize the fibre form for reinforcement.

Fibre Loading: Fibre loading means percentage of fibre content in the composite. Researchers normally use fibre loading by weight % or by volume %. With the increase in fibre loading normally wear behaviour of these composites improves and over a specific value it starts decreasing. As the fibre loading increases the adhesion at fibre-matrix interface and proper wetting of fibres by the matrix varies. Therefore, for a particular fibre optimum fibre loading has to be found by experimentation. Coefficient of friction may increase or decrease with the increase in fibre loading depending on the type of fibre.

Type of Polymer: Polymer type includes thermoplastic, thermoset and bio-polymers. Thermoset polymers have good mechanical properties than thermoplastics and have ability to work at higher temperatures. Bio-polymers are produced by biodegradable sources like animal proteins, plants etc. Mechanical properties of bio-polymers are not so good in comparison to other polymers. Composite of bio-polymer and natural fibre is known as green composite. Therefore, by analyzing the application of the composite one can select the polymer type. Each type will exhibit different tribological behaviour.

Applied Normal Load: It is a critical parameter for tribological behaviour of composites. Minimum and maximum loads are finalized based on the load bearing capacity of these composites. As per Archard's wear law with the increase in applied normal load wear loss increases. The reason behind this is the penetration of hard asperities of steel counterface into the softer material of the bio-composite. Also, at higher loads, temperature increases and which softens the polymer, leading to higher material loss. Wear loss is comparatively low in case of reinforced composites in comparison to neat polymer (Kumar and Anand 2018).

Sliding Speed: Sliding speed also, influences the tribological properties of these composites. With the increase in sliding speed, friction and wear performance may increase or decrease depending upon different properties of fibre and polymer. As per literature, different fibre polymer combinations exhibited different behaviour with the change in sliding speed. Temperature also increases at higher speeds and has significant impact on friction and wear properties of the composite at those speeds (Bajpai et al. 2013).

Sliding Distance: Sliding distance is also an vital parameter and has significant impact on tribological properties of bio-composites. Generally, with the increase in sliding distance coefficient of friction attains a steady state. As far as wear loss is concerned with the increase in sliding distance generally, wear loss increased for bio-composites. Effect of sliding distance is generally predictable, therefore, many researchers use constant sliding distance in their work.

Sliding Direction: Sliding direction plays an important role in determining tribological performance of the composites. Based on the direction rotating disc with respect to fibres, there are three orientations. These include parallel, anti-parallel and normal orientation. Anti-parallel orientation exhibits better wear performance in comparison to other orientations since, more resistance is provided by fibres in this case (Chaudhary et al. 2018). These orientations are normally used for composites having unidirectional and bidirectional form normally.

5 Environmental Benefits

Natural fibres have emerged to be more environmental friendly as compared to synthetic fibres for the following reasons:

(1) Production of natural fibres consume less energy than synthetic fibre.
(2) Natural fibres have higher volume fraction than synthetic fibres for equivalent performance. That will reduce volume and weight of synthetic matrix, therefore, reduction in emissions and energy use for the production of polymers.
(3) Natural fibre composites when incinerated, lead to positive carbon credit and lesser air emissions due to lower mass in comparison to synthetic fibre composites.
(4) Natural fibre possess lower weight (around 20–30 by wt. %) and more volume in comparison to synthetic fibres. Therefore, higher fuel efficiency and lesser emission during the working stage in auto applications.
(5) Natural fibres have lower cost (200–1000 $/ton) and energy (4 GJ/ton) to produce in comparison to glass fibre (1200–1800 $/ton; 30 GJ/ton) and carbon fibre (12,500 $/ton; 130 GJ/ton) (Shalwan and Yousif 2013).

These advantages are the driving forces for the increased use of natural fibre composites in various applications. Environmental benefits of natural fibres are also summarized in Fig. 6.

6 Applications

The use of natural fibre composites has shown significant applications in the automotive industry throughout the world. Natural fibres are being preferred in this sector due to their low density and increasing environmental concerns. These composites are being utilized in various applications where, load carrying capacity and dimensional stability in moist environment are not significant. Flax/polyolefins composites are extensively used in automotive sector for non-structural interior panels (Holbery and Houston 2006). Various other automotive parts produced using natural fibres are dashboards, glove box, trunk panel, door panels, seat coverings, trunk floor, spare

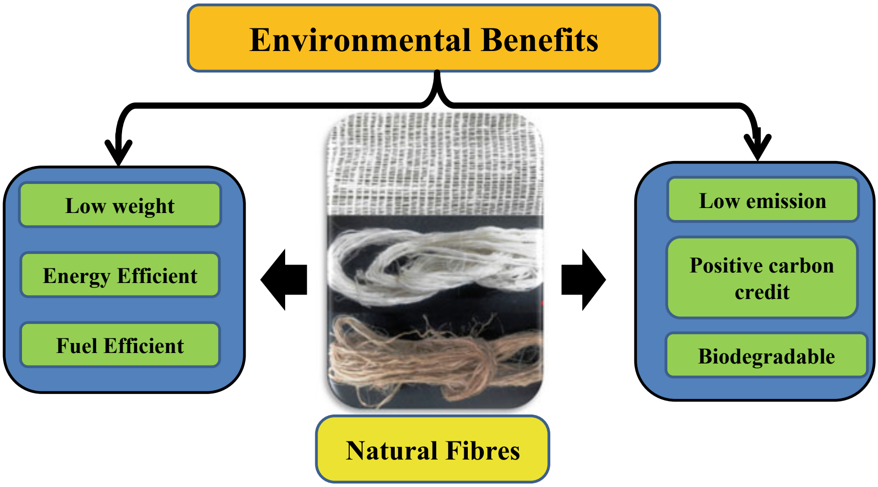

Fig. 6 Environmental benefits of natural fibres

tyre covers, floor panels, headliners etc. (Pandey et al. 2010; Das 2009; Nakamura et al. 2009).

Natural fibres being non-abrasive to the mixing and moulding equipments also, lower material cost make them an exciting prospect for household appliances and other applications. As these composites based on these fibres are low cost materials, they can play a vital role in application for various building and construction areas (e.g. partition, ceiling, walls, door and window frames, etc.). Bamboo-poplar/epoxy laminate, an attractive material developed for wind turbine rotor blades (Debnath et al. 2013). Some other application areas can be storage devices (e.g., bio-gas container, post boxes, etc.), electronic devices (outer casting of mobile phones), furniture (e.g., table, chair, tools, etc.), toys and other miscellaneous applications (e.g. suitcases, helmets, etc.). Jute/polyester composites are being used in buildings, elevators, panels and pipes (Oksman et al. 2003). Natural fibres and their composites have a great future in applications like fibre cement, foundations and interface elements (Smith and Walcott 2006). Figure 7 shows the various application areas of natural fibres and their composites.

7 Challenges

Usage of bio-composites is limited due to the challenges associated with these composites. Degradation of properties takes place, when exposed to external environment. The major challenges are mainly due to the presence of natural fibres, which include water absorption tendency, weak interfacial adhesion with the synthetic polymer, poor wettability and durability. Also, during the processing poor thermal

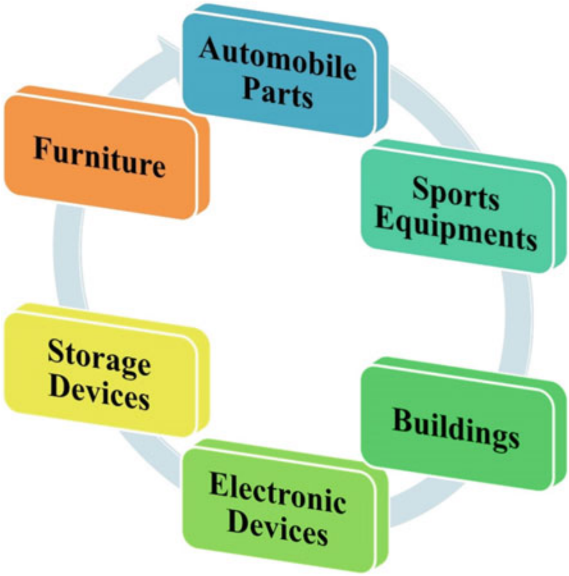

Fig. 7 Applications of natural fibre reinforced polymers

stability issue comes into picture with these composites (Gassan and Gutowski 2000; Debnath et al. 2013). Water absorption is the major challenge associated with these composites. Absorbed water bonds with fibre's hydroxyl group, weakens the bonding strength at the interface, eventually leading to reduced mechanical strength. As tribological properties are influenced by mechanical properties, therefore, decrement in wear performance is also observed. The moisture absorption behavior of natural fibres restricts the outdoor applications of bio-composites. There are various techniques like chemical treatment and coupling agents which are being used to avoid moisture absorption (Ahmad et al. 2015). Percentage moisture absorption by natural fibres lie in the range of 5 to 20% by wt. Moisture absorption by prominent fibres is as follows: Jute (10–13%), hemp (6–12%), flax (7–12%), ramie (7.5–17%), sisal (10–22), cotton (7.5–20%), abaca (5–10%), coir (0.2–10%), etc. (Kumar et al. 2019). Moisture content diminishes the physical and mechanical properties of the fibres and the composites.

8 Conclusions and Future Scope

Based on the work by various researchers, it can be concluded that bio-composites are potential candidates for tribological applications. Natural fibres like sisal, jute, ramie, flax, hemp, banana, pineapple etc. are being used by researchers as reinforcement for bio-composites in tribological investigations. Wear behaviour of bio-composites improved in comparison to neat polymer. This can be attributed to improved hardness and stiffness of bio-composites by reinforcing natural fibres. Coefficient of friction for these composites may increase or decrease depending on the type of fibre and other parameters. Therefore, these composites can act as friction and anti-friction materials depending upon the frictional behaviour of that particular bio-composite. Researchers are mainly working on general tribological behaviour of these composites. Now, there is a need to focus the research work on specific tribo based applications for those bio-composites, whose tribo-potential is known.

As far as future scope is concerned, there are still numerous natural fibres available which are still unexplored in this area. Work on hybrid bio-composites is still not explored much in tribological investigations. There are many fabrication techniques whose impact on tribological behaviour is not known. That can be an area where researchers have to focus. Researchers can also shift towards bio-polymers, making it a green composite. That will be a next step towards sustainable development.

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