Epoxy resin based hybrid polymer composites

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Chapter Outline

3.1 Introduction

3.1.1 Reinforcements

Reinforcement in polymer composites include materials either from renewable source such as plant fibers (bast, leaf, core fibers), fibers from recycled wood or waste paper, regenerated cellulose fibers (viscose/rayon), byproducts from food crops, bioagricultural wastes or synthetic/manmade fibers such as aramid, carbon, and glass fibers. In the composites, reinforced fibers provide stiffness and sufficient strength and govern the inherent properties of the final material. Fibers are basically classified in two major types: natural fibers and synthetic fibers, which are then further subclassified depending on their origin (Saba et al., 2014). Broad classification of fibers and their subclassifications are illustrated in Fig. 3.1. Currently, different types of natural fibers (bast, leaf, fruit, and core fibers) have been explored as a potential replacement of

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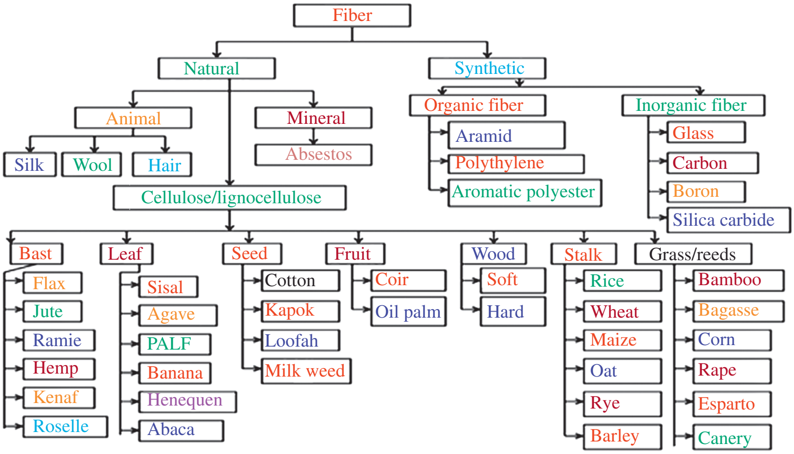

Figure 3.1 Fibers classifications and subclassifications.

synthetic fibers like glass and carbon fibers. These provide benefits to the environment with respect to the degradability and utilization of natural materials. Although natural fibers have relatively lower strength properties compared to the synthetic fibers, the specific modulus and elongation at break signifies the potentiality of these fibers to replace synthetic fibers in engineering polymer composites. Certain modifications by chemical treatments can overcome the limitations of natural fibers such as its hydrophilic tendency and poor compatibility with the matrix. The chemical treatment includes, silane, acetylation, alkaline, benzoylation peroxide, sodium chlorite, isocyanate, permanganate, triazine treatments, and maleated coupling agents are well established to change the fiber structure and surface morphology (Kabir et al., 2012). They also confer improvement in mechanical strength and dimensional stability of the resultant polymer composites.

3.1.1.1 Synthetic fibers

Synthetic fibers are made of polymers that do not occur naturally, and are produced entirely in the laboratory, most generally from petroleum byproducts. Synthetic fibers are made from different chemicals, having their own properties. Fiber produced from these polymers includes nylon, polyesters, acrylics, polyurethanes, etc. Synthetic fibers are more in length and are long lasting. The three most common synthetic fibers used in composites industries are Kevlar (aramid), carbon, and glass fibers, displayed in Fig. 3.2.

3.1.1.2 Kevlar fibers

The combination of para-phenylenediamine and terephthaloyl chloride, results the formation of aromatic polyamide (aramid) threads or Kevlar. Kevlar fibers are

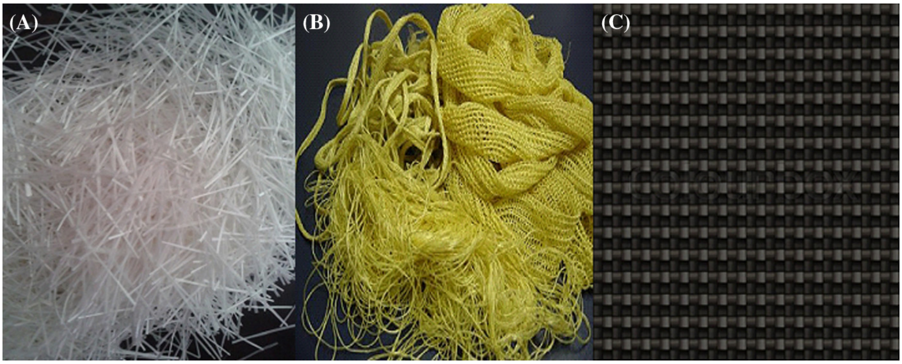

Figure 3.2 Displaying (A) glass fibers, (B) Kevlar fibers, and (C) carbon fibers.

highly expensive due to the costly manufacturing process and costly specific equipment. It exists in three main types as: Kevlar, Kevlar 29, Kevlar 49.

3.1.1.3 Carbon fibers

About 90% of the carbon fibers are prepared from polyacrylonitrile (PAN), while the remaining is from rayon or petroleum pitch. All of these materials are organic polymers, characterized by long strings of molecules bound together by carbon atoms. Currently, three types of precursor are commonly used in manufacturing process including, PAN precursors, rayon precursors, and pitch precursor. Among the three, PAN precursors are the major precursors for commercial carbon fibers, generating about 50% of original fiber mass, followed by pitch precursors yielding high carbon at relatively low cost.

3.1.1.4 Glass fibers

Glass fibers are the most versatile and cheap synthetic fibers compared to Kevlar and carbon, widely used in the polymer composites industries, having high percentage (50%) of silica content, along with different mineral oxides. Glass fibers are lightweight, less brittle, lesser stiff, extremely strong, and robust material. The comparative physical and mechanical properties of different glass fibers types are tabulated in Table 3.1. Glass reinforced polymer composites are used where the higher stiffness of carbon or aramid fibers are not required.

3.1.1.5 Comparison between synthetic fibers

The comparison between glass, carbon, Kevlar, and the most popular thermoset epoxy are tabulated in Table 3.2. Elastic modulus, strength and fatigue strength of Kevlar and carbon fibers are higher than glass fibers. Kevlar (aramid) and carbon fibers has a high strength-to-weight ratio compared to most commonly used E-glass fibers. Kevlar and carbon fibers are resistant to elevated temperatures, but Kevlar

Table 3.1 Different types of glass fibers, physical, and mechanical properties

Glass fibers type	Density (g cm^{-3})	Tensile strength (MPa)	Modulus (GPa)	Elongation at break (%)
A-glass	2.44	3300	72	4.8
C-glass	2.56	3300	69	4.8
D-glass	2.11	2500	55	4.5
E-glass	2.54	3400	72	4.7
R-glass	2.52	4400	86	5.1
S-glass (also S-2 glass)	2.53	4600	89	5.2
ECR-glass	2.72	3400	80	4.3
AR-glass	2.7	1700	72	2.3

Table 3.2 Comparative between synthetic fibers and epoxy

Synthetic fibers	Young's modulus	Strength-to-weight	Fiber strength	Laminate strength
E-glass	30–40	564	3450	1500
Carbon fiber	125–181	1013	4127	1600
Kevlar	70.5–112.4	993	2757	1430
Epoxy	3	28	–	12–40

Source: http://www.christinedemerchant.com/carbon-kevlar-glass-comparison.html.

and glass do not conduct electricity (http://www.christinedemerchant.com/carbon-kevlar-glass-comparison.html).

3.1.1.6 Natural fibers

Natural fibers are the most promising reinforcements, substitute to synthetic fibers for fibers reinforced polymer composites, owing to nontoxic, nonabrasive, higher specific strength, lower density, minimal environmental impact, biodegradability besides desirable mechanical properties compared to synthetic fiber, such as glass, carbon, Kevlar fibers (Rajesh et al., 2016). The natural fibers with high content of lignin exhibit high char yield, high effective heat of combustion (EHC), high activation energy of combustion (E_a) and low CO/CO_2 ratio (Dorez et al., 2014; Saba et al., 2016). The physical and mechanical properties of some important natural fibers are listed in Table 3.3 (Ramamoorthy et al., 2015; Onuaguluchi and Banthia, 2016; Yan et al., 2016b).

Huge varieties of natural fibers have been used as reinforcing agent in thermoplastics and thermosets for the modification or improving the properties, from past

Table 3.3 Tabulated chemical compositions and mechanical properties of natural fibers

Fibers	Compositions (%)	Tensile strength (MPa)	Young Modulus (GPa)	Elongation at break (%)	Density (g cm^{-3})
	Cellulose/hemicellulose/lignin				
Jute	33.4/22.7/28	393–773	26.5	1.5–1.8	1.3
Abaca	56–63/20–25/7–9	400	12	3–10	1.5
Alfa	45.4/38.5/38.5	35	22	5.8	0.89
Flax	71/18.6–20.6/2.2	345–1035	27.6	2.7–3.2	1.5
Bagasse	32–48/19–24/23–32	20–290	19.7–27.1	1.1	1.2
Hemp	68/15/10	690	70	1.6	1.48
Kenaf	72/20.3/9	280	53	1.6	1.2
Ramie	68.6–76.2/13–16/0.6–0.7	560	24.5	2.5	1.5
Bamboo	26–43/30/21–31	140–230	11–17	2.5–3.7	0.6–1.1
Banana	60–65/6–8/5–10	355	33.8	53	1.35
Sisal	73.11/13.33/11.0	511–635	9.4–22	2–2.5	1.5
Pineapple	70–82/18.0/5–12	400–627	1.44	14.5	0.8–1.6
Coir	36–43/0.15–0.25/41–45	175	4–6	30	1.2
Rice	28–36/23–28/12–16	–	–	–	–
OPEFB	65/–/29	248	3.2	25	0.7–1.55
Henequen	60/28/28	430–570	10.1–16.3	3.7–5.9	1.2
Cotton	89/4/0.75	287–800	5.5–12.6	3–10	1.5–1.6
Piassava	–/–/–	134–143	1.07–4.59	7.8–21.9	–

Source: (Ramamoorthy et al., 2015; Onuaguluchi and Banthia, 2016; Yan et al., 2016b).

Figure 3.3 Commonly used natural fibers as reinforcement in thermosets polymer.

decades. Some of the most widely used natural fibers in thermosets polymer composite industries are displayed in Fig. 3.3. Instead of the several advantages, natural fibers confer certain limitations due to physicochemical incompatibility between hydrophilic fibers and hydrophobic matrix, when used as reinforcement in polymeric matrices (Luna et al., 2016).

3.1.2 Thermoplastics and thermosets

Thermoplastics are linear polymers existing either as semicrystalline or amorphous glasses. On heating beyond the melting point of crystals or beyond the glass transition temperature, thermoplastics loose its structure due to the free segmental movement which consequences more flexible and deformable structure, resulting the possibilities of reshaping and reforming by simply heating and cooling. On the other hand, thermosets are cross-linked polymers and they remain in the solid state as long as the covalent chemical bonds are not destroyed. Thermoset polymers based on petroleum are highly flammable and combustible, such as epoxy, polyester, or vinyl ester resins. Thermoplastic polymers are ductile and tougher (Kabir et al., 2012), but they have lower stiffness and strength compared to thermoset polymers (Saba et al., 2015b). Thermoplastics have poor creep resistance and more susceptible to solvent than thermosets. Commonly used thermosets includes epoxy, polyester, vinyl ester, and phenol formaldehyde to manufactured fibers based composites.

3.1.2.1 Epoxy resin

Epoxy resins have better mechanical properties than polyesters and vinyl esters, and are the principal thermoset polymer used as matrix in aerospace composites. Epoxy resins describe a broad class of molecular structures having at least two oxirane groups as epoxide functional groups (shown in Fig. 3.4) in the polymer chain (Saba et al., 2015b), being first synthesized as early as 1891. The epoxide group is planar, with a three-membered ring composed of one oxygen and two carbon atoms, where the carbon atoms of the ring are electrophilic and highly reactive.

The most popular epoxy monomers are derived from the reaction of bis(4-hydroxy phenylene)-2,2 propane (bisphenol A) and 1-chloroprene,2-oxide (called epichlorohydrin), in the presence of base (sodium hydroxide). Some typical epoxy monomers are represented in Fig. 3.5. The reaction of epichlorohydrin with an aromatic amine, results other typical epoxy resins, such as tetraglycidylmethylenedianiline (TGMDA), that are extensively used in aerospace composites (Vidil et al., 2016). Polyglycidyl derivatives of phenolic prepolymers (phenolic resin) are also common epoxy resins with high glass transition temperature (T_g) and thermal stability. Additionally, cycloaliphatic resins also shows considerable interest as they have better weather

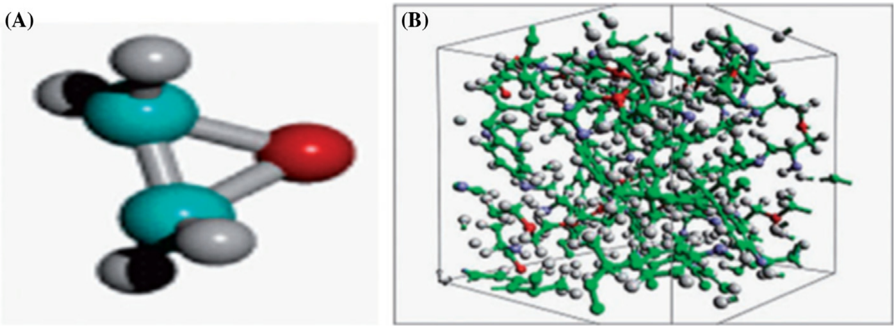

Figure 3.4 (A) Epoxy oxirane ring and (B) cross-linked structure of cured epoxy.

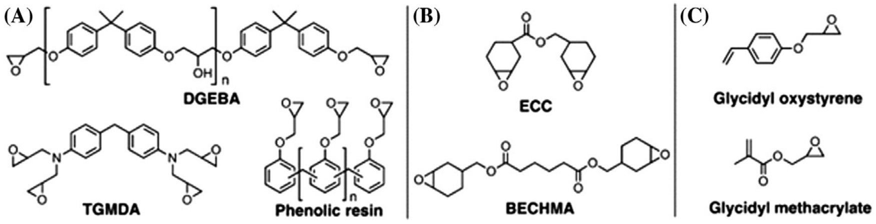

Figure 3.5 Typical epoxy monomers, (A), (B) and (C).

resistance and lesser tendency to get yellow compared to aromatic resins (Vidil et al., 2016). Epoxy monomers containing vinyl groups, like glycidyl (meth) acrylate, or glycidyl oxystyrene, can be used for the synthesis of functional oligomers.

Cured epoxies with tight three-dimensional molecular network structures have relatively high thermal stability and T_g. Cured epoxy exhibit inherent brittle fracture behavior and poor crack growth resistance that restrained its mechanical applications. The brittleness of epoxy resins can be reduced by the process of rubber toughening, involving the addition of a liquid rubber, such as butadiene−acrylonitrile, to the uncured resin. Toughened epoxy polymer composites are extensively applied for load-bearing applications (Gong et al., 2015). Epoxies possess higher curing time and are highly combustible and expensive with respect to phenolic. Epoxies on exposing to high temperatures (300−400°C), decomposes releasing smoke, heat, toxic volatiles, and soot from the organic matrix of the cured epoxy laminate. However by incorporating flame retardants (FRs) additives or by copolymerization with reactive FRs, its flame retardancy can be improved (Saba et al., 2015b). FR epoxies are widely used in printed wiring boards, electrical and electronics, construction materials, automobile, aerospace, marine, painting, coating, adhesive and in advanced engineered composites fabrication for high end applications on a large scale worldwide (Saba et al., 2015a).

3.2 Polymer composites

Composite materials composed of at least two constituents of different phase, in order to achieve combined properties that cannot be met by a single-phase material, and it can be classified in three subclasses, including particles, fibers, and structural based composites (Fig. 3.6) (http://textilelearner.blogspot.my/2012/09/glass-fiber-composites-properties-of.html).

The polymer composites have at least one phase as a polymer or matrix as binder and second phase includes reinforcing fibers or particles in a matrix to

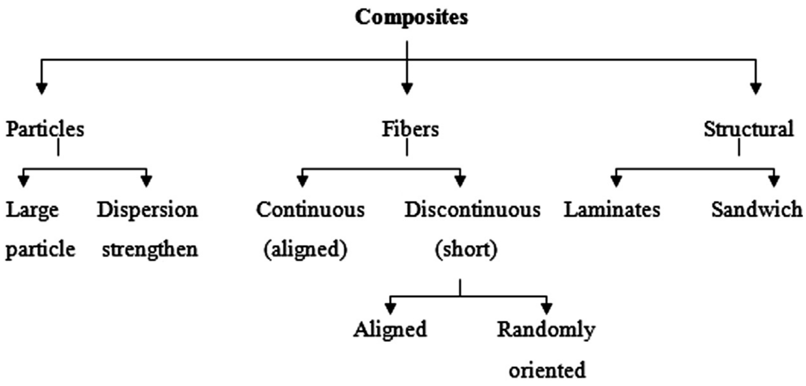

Figure 3.6 Classification of polymer composites.

improve dimensional and thermal stability, stiffness, toughness, and tensile strength. Polymer composites are able to meet diverse design requirements with significant weight savings as well as high strength-to-weight ratio.

3.3 Natural fibers polymer composites

Currently natural fibers are reinforced in a variety of thermoplastic and thermosets polymers for modification of their properties. Among thermosets such as polyester and phenolic, epoxy polymer is the most common polymer that is reinforced by natural fibers. Natural fibers reinforced polymer composites are of great interest due to the ease of fabrication, cost effectiveness, and remarkable structural rigidity. These composites show extensive applications, including constructional, aerospace, and automotive industries because they represent an ecological and inexpensive alternative to conventional petroleum derived materials (Väisänen et al., 2016).

3.4 Hybrid composites

Hybridization is the approach to meet competing and diverse design requirements in a more cost-effective way compared to traditional engineering materials. The term “hybrid composites” represents a composite having at least two different types of fibers reinforced in the single matrix, or blends of polymer reinforced with single fibers, in order to provide a synergistic effect such as enhanced mechanical properties (Kalantari et al., 2016). Hybrid composites offered balanced thermal stability, reduced weight/cost, balanced strength and stiffness, better fatigue resistance, impact resistance, fracture toughness besides reduced notch sensitivity (Ferrante et al., 2015). Several studies have been reported on the hybridization of epoxy reinforced with natural/synthetic fibers, fabricated by variety of techniques such as hand lay-up, compression molding, resin transfer molding (RTM), illustrate marked increase in mechanical, thermal, physical, and flame retardancy properties.

3.5 Epoxy based hybrid polymer composites

Huge varieties of epoxy hybrid composites have been fabricated from synthetic fibers, natural fibers, and a combination of both synthetic/natural fibers, and with natural fibers/natural fibers to widen the epoxy industrial applications.

3.5.1 Natural fibers/synthetic fibers based epoxy hybrid polymer composites

Some of the important and recent studies on the hybridization of epoxy with natural/synthetic fibers, along with characteristics improvement in properties are tabulated in Table 3.4. The advantages of hybridization are fully utilized to reduce the

Table 3.4 **Reported study on the natural/synthetic fibers based epoxy hybrid polymer composites**

Natural/synthetic fibers reinforced epoxy hybrid polymer composites			
Polymer	**Reinforcements**	**Hybridization effects**	**References**
Epoxy	Basalt/carbon fibers	The hybridization modifies the failure mechanisms depending on the stacking sequence	Ferrante et al. (2015)
Epoxy	Flax/carbon fibers	Hybridization improved the mechanical properties and reduced the vibration damping of the composites	Flynn et al. (2016)
Epoxy	Microsized red mud/glass fibers	Considerable improvements in mechanical properties, erosion wear performances and density are observed by the addition of red mud to the glass/epoxy composites	Biswas and Satapathy (2009)
Epoxy	Jute/E-glass fibers	Hybridization results improved mechanical properties.	Johnson et al. (2016)
Epoxy	Core–shell particles (CSP)/glass fibers	Hybridization of glass fibers with CSP particles results less structural defects with significant improvement in impact properties	Zhong and Joshi (2016)
Epoxy	Rice husk particulates/glass fibers	Hardness, tensile modulus, impact energy and erosion resistance of hybrid composites improved by the hybridization. Small declines in tensile and flexural properties are also observed	Rout and Satapathy (2012)
Epoxy	Basalt/carbon fibers	Mechanical analysis indicate that hybrid laminates with intercalated configuration have better impact energy absorption capability, while hybrid laminates with sandwich-like configuration displayed higher flexural behavior, fabricated by RTM	(Sarasini et al., 2014)
Epoxy	*Pennisetum purpureum*/E-glass	Higher tensile and flexural strengths were recorded for the hybrid composites with the 5% alkali-treated *Pennisetum purpureum* fibers, fabricated by vacuum infusion process	Ridzuan et al. (2016b)
Epoxy	Jute/glass fibers	Hybridization of jute fibers with glass fibers/epoxy composites results considerable increase in impact energy, density, tensile and flexural strength along with noticeable decrease in water absorption properties	Braga and Magalhaes (2015)

Epoxy	Coir pith/Nylon fabric	Durability, chemical and flame retardancy get improved on hybridization in moist conditions	Narendar et al. (2014)
Epoxy	NaOH treated woven kenaf/aramid fibers	Tensile and flexural properties of treated hybrid composites are better than nontreated hybrid composites. Hybrid composites with Kevlar as outer layers possess better mechanical properties among the rest	Yahaya et al. (2015)
Epoxy	Kenaf/glass fibers	Hybridization results enhancement in mechanical properties to use for car bumper beams as automotive structural components fabricated by modified SMC	Davoodi et al. (2010)
Epoxy	Banana/hemp/glass fibers	Banana/hemp/glass fibers reinforced hybrid epoxy composites exhibited superior properties and can use as potential material to replace synthetic fibers reinforced composites.	Bhoopathi et al. (2014)
Epoxy	Pennisetum purpureum/glass fibers	The incorporation of the glass fibers into the P. purpureum/epoxy composites enhanced the tensile, flexural strength, as well as their modulus, fabricated by vacuum infusion method	Ridzuan et al. (2016a)
Epoxy	Basalt woven fabric/glass fibers	Hybridization improves the impact energy absorption and damage tolerance tendency with respect to glass laminates fabricated by RTM	Sarasini et al. (2013)
Epoxy	Basalt/glass fibers	Increase in tensile and flexural properties are observed by the hybridization, compared to those of GFRP laminates	Fiore et al. (2011)
Epoxy	Sisal/jute/glass fibers	Hybridization of sisal fiber with glass improved the tensile properties. While Hybridization of jute fibers with glass fibers improves the flexural properties fabricated by hand lay-up	Ramesh et al. (2013)
Epoxy	Kenaf/aramid fibers	Hybridization of woven kenaf mat with aramid fibers yield composite material with high tensile strength and impact resistance properties	Yahaya et al. (2016)

Notes: Resin transfer molding (RTM), sheet molding compound (SMC).

use of synthetic fibers which are generally nonenvironmentally friendly (Yahaya et al., 2016).

3.5.2 Natural fibers/natural fibers based epoxy hybrid polymer composites

Incorporation of natural/natural fibers also results improved properties by the hybridization effects. Some of the reported findings are listed in Table 3.5.

3.5.3 Synthetic/synthetic fibers based epoxy hybrid polymer composites

Huge varieties of hybridized epoxy composites are fabricated by different techniques by the reinforcements of synthetic/synthetic fibers, resulting considerable improvement in thermal, mechanical, and flame retardancy properties of epoxy composites. Hybrid composites involving carbon and glass fibers allow to combine the advantages of both groups of fibers including, low price of glass fibers, low weight, high tensile strength and stiffness of carbon fibers, and to minimize their limitations including, high costs and low compressive strength of carbon fibers (Dai and Mishnaevsky, 2015). The hybridization involving synthetic/synthetic fibers reinforced in epoxy and its effects are tabulated in Table 3.6.

3.5.4 Epoxy based hybrid polymer nanocomposites

Currently, incorporation of nanosized fillers such as carbon nanotubes (CNTs), graphite, nanoclay has been extensively used along with natural fibers such as kenaf, jute or with synthetic fibers such as carbon and glass fibers. Some exclusive study on epoxy based hybrid nanocomposites with different nanofillers/synthetic or nanofillers/natural fibers are listed in Table 3.7. Hybrid epoxy nanocomposites possess marked enhanced properties compared with epoxy composites, at relatively lower concentrations.

3.6 Applications

3.6.1 Applications of epoxy based polymer composites

Epoxy based composites are extensively been used in making automobiles components including radiator supports, bumper beams, fenders, hoods, roof panels, deck lids, and a number other exterior and interior body components. Synthetic fibers reinforced epoxy polymer composites are being increasingly used for aircraft structures owing to their superior structural performance, such as long fatigue life, high stiffness, high strength, and low density (Chowdhury et al., 2016).

Table 3.5 Reported study on the natural/natural fibers based epoxy hybrid polymer composites

Natural fibers reinforced hybrid polymer composites			
Polymer	**Reinforcements**	**Properties improvement**	**References**
Epoxy	Jute/Sansevieria cylindrica fibers	Hybrid composites showed higher strength than untreated composites fabricated through hand lay-up technique	Kumar and Reddy (2014)
Epoxy	Plain woven/ Rib-knitted flax preforms	Thermal stability and tensile strength of flax hybrid preforms composites get improved fabricated by hand lay-up	Muralidhar (2013)
Epoxy	Jute/oil palm fibers	Hybridization increases the tensile and dynamic mechanical properties of the oil palm/epoxy composites manufactured by hand lay-up	Jawaid et al. (2013)
Epoxy	Flax/glass fibers	Flax/glass hybridization fabricated by compression molding, shows positive effect in a wet environment at low temperatures (~20°C) for Young's modulus and tensile strength. While negative effect on the tensile strength and on the specific tensile strength are observed on hybridization	Saidane et al. (2016)
Epoxy	OPEFB fibers/ woven jute fibers	Hybridization increases the tensile and flexural properties, compared to independent composites	Jawaid et al. (2011)
Epoxy	Sisal/Jute fibers	The hybrid composites fabricated by hand lay-up technique followed by light compression molding technique, displayed higher storage and loss modulus values and lower value of damping parameter and water absorption properties	Gupta and Srivastava (2015)
Epoxy	Luffa fibers/ groundnut	The mechanical properties of hybridized luffa fibers/groundnut/ epoxy composites fabricated by hand lay-up get enhanced compared to luffa fibers/epoxy composites	Panneerdhass et al. (2014)
Epoxy	OPEFB/jute fibers	The flexural properties of hybrid composites are higher than that of pure OPEFB composites	Jawaid et al. (2010)
Epoxy	Jute/banana fibers	Hybridization of banana fibers in jute/ epoxy composites fabricated by Hand lay-up technique results in	Boopalan et al. (2013)

(*Continued*)

Table 3.5 **(Continued)**

Natural fibers reinforced hybrid polymer composites			
Polymer	**Reinforcements**	**Properties improvement**	**References**
		increasing the mechanical and thermal properties, along with a marked decrease in the moisture absorption properties	
Epoxy	Abaca/jute fibers	The abaca/jute/epoxy hybrid composites displayed better tensile and shear properties compared with single fiber composites. Hybridization also improves the ductility than the single type composites	Ramnath et al. (2013)
Epoxy	Flax/basalt fibers	Storage modulus of hybrid composites decreases after 15 days of aging. T_g increment is also higher for hybrid composites	Fiore et al. (2016)
Epoxy	Basalt/hemp fibers	The hybridization in a sandwich configuration markedly improved both post-impact residual properties and damage tolerance tendency, fabricated by combination of hand lay-up and compression molding techniques	Dhakal et al. (2015)

Note: Oil palm empty fruit bunch (OPEFB).

3.6.2 Applications of epoxy based hybrid polymer composites

Most promising applications of epoxy hybrid polymer composites are in making the components of coal dust carrying pipes, desert structures, industrial fans, low cost housing, false ceiling, partition boards and fishing boats/water-sports equipment (Chowdhury et al., 2016).

Currently, epoxy based hybrid polymer composites and epoxy based hybrid polymer nanocomposites are being extensively utilized in electrical and electronic components, automotive and military applications. Research study also illustrates the promising applications of epoxy hybrid composites in drug delivery, dentary fills, artificial limbs and in orthopedic trauma applications (Ramakrishna et al., 2001). Hybrid composites made of natural/natural fibers offer the opportunity for extensive applications in the fields of low cost construction and civil structures, domestic, and toilets accessories and in many other common applications where the prohibitive cost of reinforcements restricts the use of conventional lightweight reinforced plastics (Harish et al., 2009).

Table 3.6 **Reported study on synthetic/synthetic fibers based epoxy hybrid polymer composites**

Synthetic/synthetic fibers reinforced hybrid polymer composites			
Polymer	**Reinforcements**	**Hybridization effects**	**References**
Epoxy	Glass/kevlar fabrics	Kevlar/glass hybrid structure fabricated by hand lay-up, showed improvement in specific mechanical strength as well as bending and impact energy properties	Valença et al. (2015)
Epoxy	SiC/pitch-based carbon fibers	Thermal conductivity of SiC/pitch-CF/epoxy composites increases 18.8 times to that of epoxy resin	Mun et al. (2015)
Epoxy	Unidirectional glass/carbon fibers	Unidirectional glass/carbon fibers/epoxy hybrid composites possess maximum flexural strength and robustness under flexural loading	Kalantari et al. (2016)
Epoxy	Glass/carbon fibers	Hybridization increases the tensile strength and modulus of hybrid composites	Naresh et al. (2016)
Epoxy	E-glass/T700S carbon fibers	Hybridization potentially improves the flexural strength	Dong and Davies (2015)
Epoxy	Glass/ceramic whisker/solid lubricant filler	Incorporation of solid lubricant results in the improvement of both mechanical and tribological properties of composites, fabricated by the hand lay-up procedure followed by vacuum bagging technique	Sudheer et al. (2014)

Furthermore, the epoxy hybrid composites reinforced by natural/synthetic fibers are widely used in making the components of desert structures, low cost housing, fishing boats/water-sports equipment, false ceiling, partition boards, automotive (tails, wings, propellers), bicycle frames, boat hulls, fishing rods, storage tanks, baseball bats, ice skating boards, shelters, clothes, door panels, and in weapons construction (Sanjay et al., 2015). Carbon fibers based epoxy hybrid composites shows extensive applications in load-bearing structural materials in aerospace and automotive sectors along with sports and consumer goods, owing to an interesting combination of low weight, high strength, and excellent corrosion resistance (Yan et al., 2016a).

Currently, epoxy based hybrid polymer nanocomposites signify as most encouraging materials hence are receiving higher attention in the field of cosmetics, construction, food packaging, medical sciences, and other composite based industries, owing to distinctive features of incorporated nanofiller in enhancing the mechanical and barrier properties of epoxy polymer composites (Saba et al., 2014). Some of

Table 3.7 Exclusive research study on epoxy based hybrid polymer nanocomposites

Epoxy hybrid polymer nanocomposites			
Polymer	**Reinforcements**	**Hybridization effects**	**References**
Epoxy	Banana fiber/silica powder/	Hybridization of banana fibers with silica powder improves the bending strength	Singh et al. (2012)
Green Epoxy	Alkali-treated jute/nanojute fibers	Hybrid composites fabricated by hand lay-up method and compression molding technique display higher storage modulus and T_g values. Marked reduction in delta peak height also been realized	Jabbar et al. (2016)
Epoxy	Kevlar/nanoclay	The hybrid laminates manufactured by hand lay-up with epoxy resin/ 6 wt% of nanoclays display higher elastic recuperation and penetration threshold	Reis et al. (2013)
Epoxy	CNTs/GO	Hybrid composites fabricated by ultra-sonication followed hand lay-up technique with 0.5 phr MWCNTs and 0.1 phr GO, results increase in the friction coefficient and a reduction in the specific wear rate are observed	Reis et al. (2013)
Epoxy	Fe_2O_3/RGO nanoplatelets	TGA analysis revealed improvement in the thermal stability of Epoxy/RGO–Fe_2O_3 nanocomposites. Hybrid composites also possess improved dielectric and microwave properties, through in situ polymerization	Sharmila et al. (2016)
Epoxy	Kevlar fibers/CNT	The hybrid composites shows improved tendency to absorb mechanical shocks and effectively shield from electromagnetic interferences by the impact of metallic bullets fired at about 400 m s^{-1} and 1000 m s^{-1}	Micheli et al. (2016)
Epoxy	Silica coated with hybrid particles of MWCNTs	The rheology and electrical conductivity (conductivity $\sim 10^{-4}$ S m^{-1}) of epoxy resin	Wilkinson et al. (2016)

(*Continued*)

Table 3.7 **(Continued)**

Epoxy hybrid polymer nanocomposites			
Polymer	**Reinforcements**	**Hybridization effects**	**References**
		suspensions of particles found comparable to the neat resin	
Epoxy	CNT–Al_2O_3	The flexural strength, flexural modulus and dielectric constant of CNTs–Al_2O_3/epoxy hybrid composites shows significant improvement up to 30%, 35%, and 20%, respectively, compared to the epoxy composites	Zakaria et al. (2015)
Epoxy	MWCNTs/MnZn ferrite	3MWNCTs/1MnZn ferrite/epoxy hybrid nanocomposites fabricated by ultra-sonication followed by hand lay-up, displayed the highest effective electromagnetic-interference (EMI) and shielding effectiveness (SE). The EMISE of the hybrid composites are better than epoxy composites filled with single conductive filler and are comparable with that of commercial EMI absorber	Phan et al. (2016)
Epoxy	Nanosilica/ AgNWs	Epoxy/SNP/AgNWs hybrid nanocomposites displayed distinct improvements in thermal conductivity without degrading mechanical properties	Chen et al. (2016)
Epoxy	CNTs/NDs	Hybrid nanocomposites manufactured by ultra-sonication followed by hand lay-up having 0.2 wt% MWCNTs/0.2 wt% NDs showed 50% increase in hardness while tensile strength and modulus enhanced to 70% and 84%, respectively. Flexural strength and modulus also increases by 104% and 56%, respectively. Fracture strain also increased in both the tensile and flexural testing. The impact resistance or toughness of hybrid nanocomposites also get increased to 161%	Subhani et al. (2015)

(*Continued*)

Table 3.7 **(Continued)**

Epoxy hybrid polymer nanocomposites			
Polymer	**Reinforcements**	**Hybridization effects**	**References**
Epoxy	Al_2O_3/GNPs/ magnesium hydroxide	Hybridization by the incorporation of layered GNPs efficiently increases the thermal conductivity of epoxy/Al_2O_3 composites with considerable flame retardancy	Guan et al. (2016)
Epoxy	CTBN-rubber/ GNPs	Hybridization enhanced the fracture toughness and thermal conductivity of the epoxy composites with the addition of 5 μm (GNP-5) to the CTBN/ epoxy composites	Wang et al. (2016)
Epoxy	Graphene-functionalized with POSS	Hybridization results reduce in the dielectric constant of epoxy composite materials with ultra-low filler content	Yu et al. (2014)
Epoxy	GNPs/carbon fiber	Hybridization results an increment in the overall mechanical properties by the addition of GNPs to the carbon fiber/epoxy composites	Hadden et al. (2015)
Epoxy	CNTs/Al_2O_3 particles	Addition of CNT–Al_2O_3 hybrid compound to the epoxy composites exhibit an enhancement of 117% and 148% in compressive strength and compressive modulus respectively. Thermal stability also improved for the CNT–Al_2O_3 hybrid compound/ epoxy composites	Zakaria et al. (2016)
Epoxy	Reactive liquid rubber/Silica nanoparticles	Improvement in mechanical properties by the addition of surface-modified silica nanoparticles of 20 nm size to epoxy was perceived	Sprenger et al. (2014)
Epoxy	Nano-SiO_2/short carbon fiber	The hybrid composites with 4 wt% nano-SiO_2/6 wt% carbon fiber/ epoxy hybrid nanocomposites delivered the highest improvement of the tribological performance	Guo et al. (2009)

(*Continued*)

Table 3.7 **(Continued)**

Epoxy hybrid polymer nanocomposites			
Polymer	**Reinforcements**	**Hybridization effects**	**References**
Epoxy	Nanocopper particles/ MWCNTs	Heat transfer performance as a thermal interface material (TIM) of hybrid nanocomposites gets improved by the incorporation of MWCNTs and nanocopper particles into epoxy	Zhang et al. (2014)
Epoxy	CNTs/carbon fibers	Hybridization of CNTs and carbon fibers to the epoxy shows positive effect on erosive wear response	Papadopoulos et al. (2016)
Epoxy	Bentonites/silica modified with POSS	Hybridization results an improvement in mechanical properties with particular increase in tensile strength by 44%, and Charpy impact strength by 93% for hybrid nanocomposites	Oleksy et al. (2014)
Epoxy	Kenaf/silica nanoparticles	Inclusion of hydrophobic silica nanoparticles had a detrimental effect on the mechanical properties of hybrid nanocomposites including flexural modulus, flexural strength, compressive strength and compressive modulus, fabricated by vacuum infusion	Bajuri et al. (2016)
Rubbery epoxy	Carbon nanofiber/ BN	The developed hybrid nanocomposites are thermally conducting and electrically insulating TIMs	Raza et al. (2015)

Notes: Polyhedral oligomeric silsesquioxane (POSS), Multiwall carbon nanotubes (MWCNTs), Iron oxide (Fe_2O_3), Reduced graphene oxide nanoplatelets (RGO), Manganese zinc ferrite (MnZn ferrite), Carboxyl terminated butadiene acrylonitrile (CTBN), Carbon nanotube (CNTs), Silicon carbide (SiC), Oil palm empty fruit bunches (OPEFB), Thermal interface materials (TIMs), Alumina (Al_2O_3), Graphene nanoplatelet (GNPs), Nanodiamonds (NDs), Graphene oxide (GO), Boron nitride (BN).

the most important and exclusive applications of epoxy hybrid polymer composites and epoxy hybrid nanocomposites are listed in Table 3.8.

3.7 Conclusion

Epoxy delivers diverse applications from adhesives to coatings; however its pervasive applications in advanced engineering are restricted due to its delamination, low

Table 3.8 Applications of epoxy based hybrid polymer composites and hybrid nanocomposites in different sectors

Epoxy hybrid polymer composites	Fields of applications	References
Epoxy/CNT/coated silica particles	As electrically conductive composites	Wilkinson et al. (2016)
Epoxy/carbon/glass fibers	As advanced pseudoductile unidirectional thin-ply	Czél et al. (2016)
Epoxy/Kevlar fibers/CNT	In aerospace structures for low energy range of potential mechanical shocks	Micheli et al. (2016)
Epoxy/PDMS-OH	As protective agents for stone surface	Xu et al. (2015)
Epoxy/basalt/glass mat fibers	In real ship component and marine applications	Fiore et al. (2011)
Epoxy/flax fiber/carbon fibers	In controlling vibration damping applications	Flynn et al. (2016)
Epoxy/Al_2O_3, GNPs/magnesium hydroxide	As thermal conductive hybrid epoxy nanocomposites with satisfactory flame retardancy	Guan et al. (2016)
Rubbery epoxy/carbon nanofibers/BN	As interfacial thermal transport at thick bond lines	Raza et al. (2015)
Epoxy/graphene/POSS	Applications in low-dielectric epoxy composites	Yu et al. (2014)
Epoxy/carbon/glass fibers	As hybrid laminate reinforcement and in the repairing of aeronautic structures	Guermazi et al. (2014)
Epoxy/kenaf/aramid fibers	Military vehicle's spall-liner applications	Yahaya et al. (2016)
Epoxy/nanosilica/AgNWs	As electronic packaging hybrid materials with thermally conductive and electrically insulating properties	Chen et al. (2016)
Epoxy/carbon/basalt, glass fibers	As components in wind turbine blades and wind energy generation	Chikhradze et al. (2015)
Epoxy/carbon/flax fibers	In long bone fracture fixation for replacing clinically used metal plates	Bagheri et al. (2013)
Epoxy/graphene/graphite oxide	As electrically conductive composites in electrical and electronic industries	Pokharel and Truong (2014)
Epoxy/CNTs/carbon/glass fibers	Wind energy applications	Dai and Mishnaevsky (2015)
Epoxy/carbon fiber/flax fibers	As bone fracture plate in orthopedic trauma	Bagheri et al. (2015)
Epoxy/unidirectional glass/carbon fibers	Robust designing	Kalantari et al. (2016)

impact resistance, low fracture toughness behavior, inherent brittleness, and inferior thermal stability. Modification of epoxy by reinforcing natural fibers and synthetic fibers or combination of both (natural/synthetic fibers) results superior physical, mechanical, thermal, wear, flame retardancy, and electrical properties. Currently reinforcing of nanofiller at relatively lower concentration in epoxy are receiving more responses in the fabrication of high performance engineering materials.

The present review provides the valuable research and analysis that has been carried out in the area of the epoxy based hybrid polymer composites reinforced with natural fibers, synthetic fibers and nanofillers, for further investigations. From the literature it seemed that a wide variety of research studies have been conducted focusing on improving the physical, mechanical (tensile, flexural, impact strength), thermal, and electrical properties of cured epoxy through hybridization. The developed epoxy hybrid composites displayed extensive and wide applications in areas such as aircraft, automotive components, sporting goods, building industry, and biomedical science.

The future research study will be the hybridization of epoxy by the introduction of nanofillers exclusively derived from agriculture wastes such as coconut pith, groundnut husk, wheat straw, flax straw, sunflower leaves, used tea leaves, and newspapers which are still underutilized along with natural fibers to modify and enhance the properties of cured epoxies, would be the keen interests areas for researchers to yield epoxy bionanocomposites.

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