# A Comprehensive Review on Mechanical, Electromagnetic Radiation Shielding, and Thermal Conductivity

# of Fibers/ Inorganic Fillers Reinforced Hybrid Polymer Composites

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#### Abstract

Peripheral such as aerospace, armor, sensors, heat exchanger, automobile, storage, and any other electronic equipment are frequently subjected to varying mechanical and thermal stress, which substantially influence their reliability, life cycle, and performance. The aerospace sector, forexample, is in constant research for the decrement in mass to achieve higher fuel efficiency throughlightweighting approach. It is due to the specific parameters that advanced polymer composites exhibit, there are growing research interests in heat management schemes, where both higher thermal characteristics and strength with significantly lower density are simultaneously

essential. In the same manner, nanohybrid particles are commonly utilized as reinforcement fillers to enhance mechanical, electromagnetic shielding efficiency and thermal characteristics of any polymer matrices. This survey discusses the polymer-based nanocomposites incorporated with hybrid nanoparticles for applications in high-performance materials. The subsequent interaction between the selected polymer matrix and hybrid nanofillers, which affects the characteristics of the polymer-based nanocomposites: mechanical, electromagnetic radiation shielding efficiency as well as thermal conductivity have been critically reviewed. The hybrid nanoparticles' synergy facilitates effective dispersion without damaging the structures of the nanofillers tend to optimized electrical properties, thermal conductivity, and higher overall functionality of the fabricated nanocomposites.

Keywords: Dispersion; Electrical conductivity; Electromagnetic radiation shielding; Hybrid nanocomposite; Nano filler; Polymer; Thermal conductivity

1. Introduction

In recent years, the lightweight fillers or fibers reinforced polymer matrix laminates are extensively utilized in aerospace applications that have higher stiffness, strength, reparability, resistance from corrosion, and fatigue <sup>[1, 2]</sup>. The fiber or filler reinforced polymer composites (FiRPC) materials contain both high strength reinforcing fibers and polymer resin. The synergistic influence from polymer resin and high strength fibers outcomes in a reliable and lightweight materials with higher mechanical properties which cannot be attained from either of the constituent alone. FiRPC is the general form of composites fabricated from two more layers of directional fabrics that are arranged or coupled to offer high-performance and engineered characteristic properties <sup>[3]</sup>. These types of materials are broadly utilized in various industries such as vehicles (marine, automobile, and aerospace), medical devices, packaging, electronics,

sports goods, civil engineering (bridges and building), and energy storage devices depend on their wear, and corrosion resistance, thermal stability, and insulation, vibration, high-strength to weight ratio, fatigue/ toughness resistance, and environmental stability <sup>[4]</sup>. The fibers are commercially applied in FiRPC consists of carbon, glass, Kevlar, boron, aramid, natural, and ceramic-based fibers. Among these fibers, carbon and glass fibers are commercially utilized for structural applications <sup>[5]</sup>. Both the thermosetting and thermoplastic polymer resin are being applied as a matrix in FiRPC laminates.

The primary investigator for the selection of polymer resin in FiRPC is mechanical characteristics of the matrix, which containing modulus (affects compression properties), toughness (influences crack development and ply delamination), and tensile strength (regulates intra-ply damage). The thermoplastic polymer is commonly held together with weaker intermolecular forces such as van der Waals force and hydrogen bond. These polymers can be melted, reshaped, and softened by giving an external source of heat. In thermoset resin, the molecules are fixed together with a three-dimensional network structure, tend to cross-link within the matrix. During the process of curing, complete cross-linking has occurred, hence it cannot be re-shaped or melted. The benefits of utilizing thermoplastic resin over thermoset for FiRPC are fracture resistance, strain under failure, and higher impact strength, whereas the benefits of utilization of thermoset resins are higher resistance from a chemical reaction and better thermal stability. These resins also show lower stress relaxation and creep than thermoplastic resin. Conventionally, thermoset resins are preferably utilized as FiRPC other than thermoplastic due to the difficulty of continuous fibers in the matrices <sup>[6]</sup>. The thermoset resin also has lower viscosity at the initial stage due to the lower weight of molecules, which controls better wetting characteristics on reinforcing high strength fibers at the period of fiber

reinforcement without considering both pressure and temperature. It is also observed that the wetting of fibers is an essential parameter to achieve higher interaction between fiber and resin matrix and the essential requirement for higher mechanical properties of FiRPC. These types of polymer-based composites are susceptible to impact damage <sup>[7]</sup>. The risk of destruction owing to impact is well known in aircraft and spacecraft design<sup>[8,9]</sup>. From the destruction record of seventy-one Boeing aircraft, which has a mean life cycle of around 29,500 hours of flying, it has been observed that around 13% of repairs are produced due to the impacts of foreign particles <sup>[8]</sup>. Radar antenna, nacelle, propeller blades, wing or tail, canopy, fuel tanks, and windshield are significant aims of the impact damage during the landing, flight, and takeoff process. There are various causes for this effect; bird strikes and hailstones are being the most important ones, which owes to their higher ability of appearance <sup>[10, 11]</sup>. In the same manner, a piece from a tire can hit the structure of the wing, and the ice produced from the edge of the propeller blade could also affect the aircraft engine nacelle <sup>[12]</sup>. Other kinds of projectiles may also hit the aircraft composite materials, which are fragments or bullet, which tends to the collision. However, the impact of engineering is necessary for the field of spacecraft. Space is occupied with a vast number of debris, where the satellites, international space stations, and space shuttles around the Earth <sup>[13, 14]</sup>. These are very small and owed to be traced independently, as there are many satellites in the orbital region, so the critical impact should not be ignored.

Moreover, the aerospace composite materials could not only collide on the orbit but also during the re-entry process. As an example, the effect of cold foam on the wing structure exhibited catastrophic failure, which is examined from the Columbia space shuttle <sup>[15]</sup>. The investigation of the principle of development of damage during destruction is the initial procedure to recognize the significant parameters which depict the structure characteristics of the composite materials under impact conditions. The failure and destruction of composites

caused by impact have been investigated and documented over several years. From the anisotropic behavior of the composite structure and non-uniform distribution of stresses under the effect of transient loading, the destruction processes of composite materials are complicated <sup>[16]</sup>. In traditional metals, the impact of damage usually is not an essential safety consideration, leading to the ductility of materials and natural energy absorbing mechanisms. In this context, the polymer-based composite materials can absorb energy and naturally brittle in the elastic state, which renders them susceptible to impact destruction <sup>[17]</sup>.

From the recent years, it is observed that engineering plastics has already reported a market share above 19.6 Million tons and pretended to strike more than 29 Million ton by the year 2020<sup>[18, 19]</sup>. Many years ago, McCrum et al. <sup>[20]</sup> provided two reasons for the continuous and unended expansion for the utilization of polymer resins in the engineering application due to their higher performance (resistance from chemical and corrosion, toughness and lightness) and versatility comprised with the shaping process <sup>[19, 21]</sup> at which the raw resin matrix and various other additives are converted into essential hardware products. This process is presently proved in terms of their applications in packaging, automobile <sup>[22]</sup>, aerospace <sup>[23]</sup>, defense <sup>[24]</sup>, sports, marine, control of vibration <sup>[25]</sup>, anti-corrosion <sup>[26]</sup>, many thermomechanical applications <sup>[27]</sup>, and piezoelectric sensor <sup>[28]</sup>. Polymeric composites reinforced with nanoparticles are presently achieving higher interest as they promise engineering materials with varying characteristics improvement courtesy of the various nanofillers reinforced in the polymer resin matrix <sup>[21, 27, 29]</sup>. The nano-based particles have extraordinary higher aspect proportions (surface to volume), which offers the essential engineering characteristics acquired from polymeric based composite materials <sup>[30]</sup>. The characteristics affected on polymer resin these nanoparticles target straightly on the strengthening of electrical, mechanical, thermal, and optical properties as well as barrier characteristics to fluids and temperature <sup>[26, 31]</sup>.

A few years back, the nanoparticles consist of pyrogenic silica, carbon black, and diatomic have been applied in resins as an additive material without observing their real effect <sup>[32]</sup>. Furthermore, the work from the Toyota Research & Development (TRD) group shown definite and limelight effect of nanoclays (general nanoparticle) in polyamide-6 resin<sup>[33]</sup>. Graphene (G), carbon nanoribbon, multiwalled carbon nanotubes (MW-CNT), graphene oxide (GO), and nanoclays consists of nanotubes made from halloysite <sup>[34, 35]</sup>, create the recent document of generally utilized nanoparticles <sup>[21]</sup>. Hence, the industries and scientists are in continuous quest of designing multipurpose, robust, and cost-efficient nanocomposites for developed, especially for various thermomechanical systems such as sensors, aerospace, conductors, automobile, conductors, petroleum processing facilities, aerospace, and any other advanced material applications <sup>[36]</sup>. For example, the aircraft industries need lower-weight nanocomposite components to improve fuel efficiency without compromising the thermal conductivity, stiffness, impact, corrosion resistance, and strength as the system is continuously exploited to fluctuate very harshly environmental condition <sup>[37]</sup>. However, the polymer-based applications shown higher interest in high-energy related fields (storage, medicines, energy transportation, and electronics) emphasis and also prevents from fire safety. One type of heat management is critical in enhancing/ safe-guarding the service life of the system as well as decrement of problems from the quick heat transfer generation, which requires maintenance of practically lower temperatures on the operational service <sup>[38, 39]</sup>.

Consequently, the carbon nanotubes (CNT) promotes to impact improvement in higher electrical <sup>[40]</sup>, thermal, mechanical characteristics <sup>[41]</sup>, and flame retardancy <sup>[42]</sup> when reinforced in polymer resins. The thermal conductivity of 2000-6000 W/mK, higher aspect ratio, and lightweight offer carbon nanotubes its uniqueness. In a solicit toward attaining the polymeric based nanocomposites have high-performance target, hybrid comprises of these two different components, but different nanoparticles are being initiated into polymer

resin to fabricate ternary nanocomposite materials. Thermal conductivities, electrical, optical, lower flammability, corrosion inhibition, and higher protection system while enhancing the mechanical characteristics are targeted <sup>[26, 43]</sup>.

The nanoparticles play an essential role in the reduction of polymers' failure and to provide more academic novel researches and subsequent consecutive revolutionary industrial requirements for the thermosets, elastomers, and thermoplastic composites <sup>[44, 45]</sup>. A lower amount of nanoparticles significantly modifies the mechanical, physicochemical, optical, electrical, thermal, and magnetic characteristics of the matrix material <sup>[46]</sup>. Many researchers and scientists have performed experiments on the prosperity of reinforcing a single nanofiller type into the polymeric matrix (copolymers, mixed or homopolymer), especially in the field of achieving uniform nanoparticles for enhancing or toughening polymer-based nanocomposites <sup>[27, 47-49]</sup>. Moreover, the active and uniform dispersion with the accumulation of nanoparticles in the resin persists a challenge <sup>[23, 46]</sup>. Another drawback is the incompatibility nature of the reinforcement materials <sup>[50]</sup>.

On the other hand, the property of polymer nanocomposite improvement is straightly related to the formation of interfacial bonding, which exhibits within the matrix and reinforcement material <sup>[22]</sup>. Many investigators in their varying attempts of propounding the solutions applied for the usage of chemicals (either to change the agent or adapted the filler), which are generally costly, damage the structure and surface, environmentally demeaning, and lowering the characteristics predicted from the polymer-based nanocomposites <sup>[51, 52]</sup>. Another alternative of obtaining an effective dispersion is via a higher rate of shear, which de-accumulates the collected nanoparticles, and avoids further accumulations outcome from van der Waals interaction forces. Moreover, the high rate of shear can also damage the nanofibers <sup>[53]</sup>. However, the conducting polymer-based laminates are targeting higher applicability in the

electromagnetic interference (EMI) protection and carbon incorporated conducting polymer laminates, which is commercialized in this area. EMI is generally protected by absorption and reflection processes. Therefore, single carbon reinforcement on conducting polymers provides secondary EMI pollution due to the conductivity obtains from the reflection <sup>[54]</sup>.

The hybridization of nanoparticles in a polymer resin provides an efficient and safe means of establishing the dispersibility of various nanoparticles <sup>[53, 55]</sup>. The combination of nanoparticles could produce synergistic effects within the nanofillers <sup>[56]</sup>, neutralize defects in any of the nanoparticles, and enhance interaction and dispersion of the nanoparticles within the polymeric resin <sup>[57]</sup>. The advantages of the components nanofillers are combined in producing cost-efficient, innovative and advanced materials <sup>[55, 58]</sup>.

Therefore, the review offers the information high-performance polymer nanocomposites developed with the reinforcement of hybrid particles in both thermoplastic and thermoset polymer matrices. The effect of different nanoparticles on the polymers and vice versa was described. The consequent interaction of the hybrid nanofillers in the polymer-based nanocomposites was discussed on each of the bulk characteristics of the nanocomposites like mechanical, electromagnetic, and thermal properties. Finally, a summary of the review of nanofillers hybrid reinforcement on the polymers and other prospects were conferred.

#### 2. Mechanical properties

In recent years, the addition of inorganic particles (metals, ceramics, non-metallic, and metal oxides) in the matrices of polymer improves the efficiency to fabricate high-performance materials, applied in industrial fields <sup>[59]</sup>. Moreover, artificial selection primarily depends on various characteristics like structural, electrical, or electronics <sup>[60]</sup>. With the incorporation of inorganic fillers in polymers, specific properties such as physical, thermal, structural, and rheological behaviors can also be improved significantly <sup>[61]</sup>. The conventional fillers are microscopic and utilized in large quantities. Strength and stiffness also improved from these fillers, but usually, they degrade the structural properties (elongation at break, tensile and impact strength) of polymers. Compared with macroscopic fillers, nanoparticles in lower proportions can significantly improve physicomechanical properties <sup>[62, 63]</sup>. Pradhan et al. <sup>[64]</sup> studied the influence of synergism on 3D MWCNT and graphene nanoparticles to improve the thermal and mechanical characteristics of silicon rubber. Mondal and Khastgir<sup>[65]</sup> observed the elastomer enhances the mechanical and electrical characteristics with the help of hybrid nanoparticles such as G-MWCNT, and G-black carbon. Mowes et al. <sup>[66]</sup> displayed that the Graphene nanoparticles reinforced NBR based nanocomposites have higher mechanical characteristics, which is dissimilar from the conventional NBR laminates consists of black carbon. In the same manner, Zhang et al. <sup>[67]</sup> produced Graphene nanoparticles that reinforced EPDM composites using the in-situ polymerization process and observed that EPDM's mechanical characteristics were noticeably enhanced with the incorporation of nanoparticles up to 50 °C. Scaffaro and Maio, <sup>[68]</sup> investigated the synergism influence of CNT and graphene nanoparticles on the mechanical characteristics of PLA and observed the improvement in elongation at break, and tensile strength up to 36% and 4% respectively. Gong et al. <sup>[69]</sup> studied the synergistic toughening influence of double-walled CNT and reduced graphene oxide in 10,12-pentacosadiyn-1-ol. They exhibited that the toughness and tensile strength of this type of ternary nanocomposites attain up to 10 MJ/m3 and 396.9 MPa, respectively, which is comparably higher than the elegant reduced graphene oxide laminate. The different types of nanofillers reinforcement on polymers and their respective mechanical properties are shown in table 1. Devaraju et al. <sup>[106]</sup> determined the mechanical characteristics of Al2O3 nanofillers and coconut brunch fiber-reinforced polymer laminates and found that the incorporation of nanofillers improves the structural properties. Devaraju and Sivasamy, <sup>[107]</sup> also studied the influence of Zinc oxide nanofillers in sisal fiber laminate and observed that the

addition of 0.5 wt.% of nanofiller improved the mechanical properties than the neat polymer and sisal based polymer composites. Ramdani et al. <sup>[108]</sup> produced polybenzoxazine nanocomposites by incorporating the required amount of treated nano-Si3N-4 varied from 5 and 30 wt% with an increment of 5 wt% in a cylindrical glass container. The addition of silicon nitride particles significantly enhanced the elastic modulus and tensile strength for the P(BA-a). In contrast, elongation for nanocomposites gradually reduced and reached the lower values at 30 wt% of filler loading, because of the higher value of ceramic particles which could not elongate. Enhancements on modulus and stress recommend that nanoparticles toughened the P(BA-a). From this condition, toughness impact may be developed through the production of strong bonding within polymeric matrices and nanofillers and uniform dispersion of silicon nitride nanoparticles into P(BA-a) thermosets <sup>[109]</sup>. The microhardness of the fabricated nanocomposites is observed to gradually rise from 389 MPa to 645 MPa with a nanofiller of 30 wt%. This reason may be assigned to the higher hardness of nanofiller as it correlates with P(BA-a) and uniform dispersion of nanoparticles in the polymer matrix and strong filler thermoset interaction <sup>[60, 110]</sup>. Yan et al. <sup>[111]</sup> fabricated hybrid geopolymer composites reinforced with Cf, SiCf, and Al2O3 and evaluated the influence of heat treatment up to 1200 °C for mechanical characteristics and morphology. After temperature modification, hydration, and free water in the network disappeared, the balance was damaged, and the polycondensation of the geopolymer become lower. The higher temperature treatment also leads to the formation of macro-cracks in geopolymer composites, which is unfavorable to mechanical properties. The flexural strength of the composites under 1000 °C exhibited maximum value (C7S1 sample =  $52.6 \pm 1.3$  MPa), due to the densifying of the geopolymer matrix and production of kalsilite <sup>[112, 113]</sup>. The value of young's modulus also improved at 1000 °C of heat treatment. While comparing the SiCf-Cf/ KGP composites with Al2O3-SiCf-Cf/ KGP composites, Al2O3 reinforced composites have higher young's

modulus [111]. After 800 °C treatment, the many fibers pulling out could be observed on the fracture surface of composites, due to weaker bonding within the geopolymer and fibers <sup>[113, 114]</sup>. After 1000 °C treatment, the pores and pulling out could also be still displayed, but the length of the fibers reduced than the previous one. The amorphous geopolymer fully converted into leucite form after the 1200 °C, the fracture surface of laminates possess horizontal and lower pulling out of fibers, recommends the stronger interfacial bonding within the matrix/ Cf <sup>[112, 115]</sup>. After the heat treatment process, all the fabricated geopolymer hybrid composites incorporated with SiCf and Cf exhibited fracture characteristics with the appearance of nonlinear and plastic regions. The fabrication of eco nanocomposites incorporated with nanoclay (Organo-nano clay Cloisite 30B) & flax fiber (FF) as an addition to fly ash. In this fabrication process, the geopolymer matrix was prepared separately using the alkaline chemical to fly ash (0.75 proportion) and sodium silicate to NaOH solution (2.5 proportion). It is observed that all the fabricated laminates incorporated with flax fiber displayed higher flexural stress value while comparing with nanocomposites and pure polymer specimen. Geopolymer laminates incorporated with flax fiber, enhanced the flexural stress of 4.5 MPa to 23 MPa, comparable to short flax fiber reinforced geopolymer composites <sup>[116]</sup>. This effect can be described by reason that flax fibers combine the damages of polymer matrices developed from bending and prevented failure from frictional deboning in a matrix. The effect also allows the higher stress transfer within FF & matrix, which results in higher flexural strength <sup>[117, 118]</sup>. The highest toughness value of laminates with optimized nanoclay by 58, 39, and 54% for I5, I-failure, and I10 respectively is determined. The reason may be assigned to the influence of fiber pull-out that present more extensively in 0 wt% than 2 wt%. The strong bond within flax fibers & matrix enhanced due to a higher concentration of geopolymer, which provided fiber fractures than the pull out in 2 wt%.

The micrographs of the fracture surface of FF-reinforced geopolymer nanocomposite after the flexural test are shown in fig. 1. The toughness mechanism, such as fiber pull-out, debonding, rupture, and matrix fracture, are observed. The fracture surface of FF reinforced geopolymer composites displays higher unreacted fly ash and porous structure, which cause poor adhesion within the matrix and fibers (fig. 1 a). Both 1 and 3 wt% of nanoclay reinforced FF geopolymer nanocomposites show relatively denser matrices with a lower amount of unreacted fly ash content (fig. 1 b and d). Furthermore, the geopolymer nanocomposites reinforced with 2 wt% of nanoclay and FF, a higher amount of geopolymer and a smaller quantity of unreacted fly ash particles which offered better adhesion within the matrix and flax fibers. The significant amount of fiber fracture also examined under this improved interfacial fiber-matrix bonding (fig. 1 c).

## 2.1.Impact response

In the impact testing condition, the substantial failure principle can be combined into five key regions that occur in the consequential order <sup>[119, 120]</sup>. The polymer matrix/ filler and matrix damage interfaces debonding damage approach to higher transverse stresses (shear) at the highest layer, transverse flexural crack owed to higher bending stresses at the lowest layer, interlaminar delamination matured to cracks limitations and changed through the interlaminar field, failure of fiber in damage condition under micro-buckling, tension, and compression loading and penetration. There is various interplay damage consisting of polymer matrix/ fiber and resin cracking destruction, whereas interplay destruction like delamination of interlaminar among the two layers is two different dependent destruction conditions under a lower energy impact <sup>[121]</sup>. The breakage in fiber is the dependent failure condition explicitly associated with high energy impact systems <sup>[122, 123]</sup>. The primary characteristic that influences the impact in polymer-based composites is the toughness of the resin matrix. The brittle resin matrix has a lower resistance to fracture propagation and onset. The resistance from the propagation

of the fracture increments due to the enhancement of toughness of the matrix, thus, increasing the laminate resistance to interlaminar delamination onset developed from the resin cracking mechanism. The intraply failure conditions may strengthen the delamination of interlaminar, which is primarily owed to a discrepancy in features among the layers of several types of fillers or fibers or their orientation. When a crack develops, the interface within two adjacent layers, the shear stress, remarkably improves, leading to the quick variations in the properties of the material. The crack is deflected and develops along with the interface as a delamination of interlaminar <sup>[124]</sup>. During the impact loading, the composite materials are capable of dissipating and absorbing a vast amount of impact energy in a wide range of destruction conditions <sup>[125]</sup>. Till the initial damage, most of the impact energy is absorbed from the structure because of its higher elastic behavior, which containing interface, matrix, fiber toughening, using selective interlayers, hybrids, and thickness reinforcements <sup>[126, 127]</sup>. The extensive investigation conducted so far created an understanding of the parameters which affect the propagation and onset of impact damage. The chemical and mechanical features of the fillers, interface, and matrices affect the method in that it laminate fractures and deteriorate <sup>[9]</sup>. The impact strength of the polymer-based composite materials is also concerned by factors such as geometries of component, environmental conditions, and characteristics of the impactor <sup>[8, 9, 16]</sup>.

#### 2.2.Interlaminar shear strength

The interlaminar shear strength of the filler/ inorganic particles reinforced polymer-based laminates depends on the interfacial adhesion within the matrix and filler and strength of the matrix utilized within the system <sup>[128, 129]</sup>. In this context, the addition of various fibers or fillers into the thermoplastic matrix is an efficient method to enhance the mechanical characteristics and other unique properties <sup>[130, 131]</sup>. Due to natural renewability, natural filler, biodegradability, and higher specific strength present the different possibilities in developing

degradable and environmental-friendly composite materials when compared to other fibers consisting of glass and carbon fabrics <sup>[132, 133]</sup>. The characteristics of polymer-based nanocomposites not only straightly corresponds to the single constituent, but also based on the interface behavior, which regulates the efficiency of interfacial load transferring and deriving the reinforcement of fillers or fibers on polymer-based laminates <sup>[134, 135]</sup>. Hence, the optimization of interfacial properties is essential for the practical usage of fillers and the successful production of polymer-based nanocomposites. The inspiration from the tree root's constructive characteristics with a tremendous amount of branch roots comprising tee and nearby soil with each other, the stratified interfacial control has become an efficient method to produce filler –reinforced polymer-based nanocomposites with improved interfacial strength <sup>[136, 137]</sup>. When compared with traditional smooth one, the filler can offer further interfacial friction to restrict the polymer/ filler movement, to promote interfacial load transfer and improve the interfacial interaction within the matrix and filler <sup>[138]</sup>.

Therefore, to enhance the interlaminar shear strength of filler reinforced polymer-based composites, two types of techniques can be utilized. In the same manner, the carbon fiber surface should be treated and Wu et al. prepared the carbon fiber surface with the effect of synergistic modification from electrochemical oxidation process and sizing to improve the activity on the carbon fiber surface, which remarkably improved the interfacial characteristics of the laminate by 158% <sup>[139]</sup>. Qi et al. <sup>[140]</sup> examined that the hybridization of flexural (ethylenediamine) parts and solid (p-phenylenediamine) on the surface of carbon fiber could enhance the interfacial characteristics of the laminates. The plastic parts and stable structures improved the interlaminar shear strength by 38.6% and 44.8%, respectively. The interlaminar shear strength of the epoxy can be improved with the reinforcement of individual nanoparticles like SiO2, CNT, graphene, graphene oxide, and TiO2 <sup>[141]</sup>. Among the above nanofillers reinforcement, the graphene oxide is considered as an ideal nanoparticle

for improving epoxy resins, due to the presence of carboxyl and hydroxyl groups in it. Later it may chemically react with the epoxy polymer resin to attain stronger interfacial adhesion within the graphene oxide and resin <sup>[142, 143]</sup>. Bhanuprakash et al. <sup>[144]</sup> recorded that graphene oxide can efficiently enhance the interfacial characteristics within the epoxy polymer and carbon fiber and increments the interlaminar shear strength of laminates by 47%. Moreover, the uneven structure of the graphene oxide can agglomerate easily when compared with the oriented graphene oxide, which does not help improve the graphene oxide in the laminates <sup>[145]</sup>.

Tamrakar et al. <sup>[146]</sup> produced the root type of glass fiber with horizontally developed CNTs through electrophoretic deposition method, when the mixtures were incorporated into the epoxy polymer, the interfacial shear strength improved by 58% when compared with pure fiber. Qian et al. <sup>[147]</sup> attained the propagating of CNTs on the traditional carbon fiber from chemical vapor deposition technique to improve the interfacial characteristics of the final epoxy laminate with a 60% of enhancement in interfacial strength. Therefore, the systems mentioned above are sometimes conducted at 600 °C, which can degrade the mechanical characteristics of the pure filler and not applicable for the fabrication of the root type of filler due to it has lower thermal degradation temperature and below 500 °C. In past decades, Ehlert and Sodano <sup>[148]</sup> approached a new hydrothermal technique to develop Zinc oxide (ZnO) nanoparticles on the surface of fillers under lower temperature at 90 °C. In this condition, the mechanical characteristics of the fillers were unmodified, and ZnO particles combined the filler ultimately with the polymer resin, from which the efficiency of mechanically interlocking examined the interfacial characteristics, that was controlled by ZnO interphase and filler adhesion. Higher filler interface and ZnO particles is a crucial factor in enhancing the interfacial interaction within the polymer resin and fillers.

Furthermore, the fillers recorded in previous investigations consisting of carbon and aramid fiber are weak bonds and inert with the ZnO not only creates the poor development of ZnO nanoparticles but also tends to massive adhesive failure of the nanoparticles arrangements with the inefficient work of the interlocking mechanism. The molecular dynamics presented that the oxygen groups consisting of carboxylic, hydroxyl, and carbonyl acid groups, can increment interfacial interaction within the polymer substrate and ZnO <sup>[149]</sup>. Patterson accepted atomic force microscopy (AFM) using the tip functionalized from ZnO nanofillers to determine the adhesive force within the functionalized graphite and ZnO and showed that the oxygen functional groups could interact with the ZnO nanoparticles with the addition of Zinc and Oxygen electron, which granted the adhesion of ZnO on the carbon fiber surface <sup>[150]</sup>. The problem of weaker interfacial adhesion within the main filler and nanoparticles can be resolved with the pretreatment on the filler surface is essential to provide the suitable functional groups for the non-movement and development of ZnO nanoparticles. Zheng introduced a dopaminebased functionalization technique to nucleate ZnO nanoparticles on the carbon fiber surface by using a stable chelating capacity of polydopamine with metallic ions, offering higher interlocking within the epoxy matrix. The collected filler-reinforced epoxy composites presented interfacial shear strength is 64% higher than the traditional composites <sup>[151]</sup>. Shen et al. <sup>[145]</sup> signified that the interlaminar shear strength of Fe3O4@GO/CF/ epoxy-based composites produced in a magnetic field, which is comparably higher than the laminates fabricated without the field of magnetism. The reason could be assigned to the ordered structure of Fe3O4@GO, which can resist the significant transverse shear load. It is observed that the interlaminar shear strength of the composites reinforced with non-oriented or oriented reduced with the higher loading of Fe3O4/ GO concentration above the optimum concentration. Moreover, the accumulation

or deficiency of Fe3O4/ GO developed in the epoxy-based composites may also be the reason for the decrement in the laminates' interlaminar shear strength.

3. Electromagnetic radiation shielding properties

The advancement in polymer-based composites reinforced with different nanoparticles represents one of the essential duties of contemporary science. Nanoparticles have a strong influence on polymer characteristics as the nano-sized of such fillers signifies a higher area of surface, which tends to a higher interfacial area with the resin and the production of particulate chain networks under the lower concentration of nanoparticles. The improved characteristics of polymer-based nanocomposites reinforced with various carbon nanofillers (graphite nanoplatelets, CNT, and graphene) create these laminates capable of mechanical piezoresistive deformation transducer or sensor <sup>[152]</sup>, anti-electrostatic coating and electromagnetic interference material <sup>[153, 154]</sup>. In recent decades, the research investigation on microwave absorption composites has shown interest in enhancing the propagation or protection of radiation from the field of electromagnetism. It has been observed that nano-sized MWCNTs possess higher absorption of the functional microwave, because of extraordinary electronic and mechanical characteristics with lightweight structures <sup>[155, 156]</sup>.

Furthermore, sometimes, the uniform dispersion of nano-scaled particles is ambiguous because of robust Van der Waals forces between the nanoparticles <sup>[157]</sup>. In the same manner, the conductivity of carbon nanofillers is excellent, which can be utilized as a microwave absorbing composites with reduced impedance. To conquer these significant issues, the dielectric and magnetic materials may be suitable for enhancing the impedance of carbon nanofillers <sup>[158]</sup>. Presently, increasing attention for polymer-based nanocomposites reinforced with hybrid particle systems, for illustration, a carbon nanoparticle comprised of black carbon content <sup>[159]</sup>, different dielectric nanofillers

as MoS2, TiO2, and BaTiO3 <sup>[160-162]</sup>, and metal or other metal oxide particles <sup>[163, 164]</sup>. From these combinations of inorganic nanofillers and carbon nanoparticles develops further enhancement in absorption performance of fillers reinforced polymer composites and also improves the thermal stability and mechanical characteristics. It was examined in <sup>[165]</sup> that 3D chain structure (conductive) produced by CNT/ barium titanate reinforced polyaniline were suitable for the improvement of electromagnetic absorption capacity.

Moreover, these laminates with hybrid nanoparticles may be utilized to produce highly effective microwave absorbing composites with the designation from multi-layer fiber structures. Such multi-layered absorbing materials grants to reduce the electromagnetic reflection at the first boundary region (shield or air) and improves the absorption of electromagnetic radiation's interior of the protective shield due to the production of multi-reflections on the interfaces of multi-layers. The absorption improvement was created from the multilayered composite structure, which should be tuned from nanoparticle concentration variation in every layer <sup>[166]</sup>. There are many research works assigned to the study of dielectric characteristics of polymer-based nanocomposites reinforced with hybrid nanocarbon particles/ dielectric characteristics in the frequency range between 1 Hz and 1 MHz. Therefore, the utilization of higher aspect ratio particles is an assuring method to offer lower dissipation loss under the lower concentration of filler content, and higher dielectric constant, which can be used for electric field grading and capacitors applications. It was observed in <sup>[167]</sup> as a combination of graphene platelets and barium titanate applied in a polydimethylsiloxane polymer matrix provided a higher value of dielectric constant under this frequency range of 1 Hz to 1 MHz. Poly (vinylidene fluoride) (PVDF) polymer-based hybrid nanocomposites reinforced with MWCNT and barium titanate nanoparticles, which exhibited the excellent dispersion of ceramic nanofillers with lower particle accumulation <sup>[168]</sup>. The MWCNT improved the polymer's charge storage capacity by distributing it as a polarized charge transport region for the ferroelectric nanofiller, whereas the utilized MWCNT quantity restricted the production of conductive chain structure. The dielectric characteristics of the polymer-based composite reinforced with hybrid nanoparticles (barium titanate, with and without the addition of MWCNT) were enhanced by upgrading the synergistic influence between the charge transport and storage nature of the conductive and ferroelectric phase. While considering microwave characteristics of polymer-based nanocomposites with coupled dielectric nanoparticles and carbon nanofiller, various investigations and electromagnetic radiation range are restricted up to 18 GHz <sup>[158, 164, 169]</sup>.

In a general polymer-based composite, the conductive nanoparticles are commercially enclosed with different polymer layers and randomly oriented/ dispersed within the polymer resin. The weak link between the nanoparticles, which produces higher electrical percolation and interfacial impedance, decreases the conductivity of the polymer laminates. Hence, nanofillers' higher content is always acquired to attain higher conductivity, which depends on the electron percolation within the nearby nanofillers. For illustration, it has been recorded that reduced graphene oxide (rGO) reinforced epoxy laminates at higher nanofiller content depict an electromagnetic radiation shielding efficiency as 21 dB with an electrical conductivity of 10 S/m <sup>[170]</sup>. The addition of 15 wt.% of carbon nanofiller in polystyrene (PS) foam has an electromagnetic radiation shielding efficiency of 19 dB under the frequency varied between 8.2 and 12.4 GHz <sup>[171]</sup>.

Furthermore, the higher concentration of nanofiller generally tends to easy accumulation, poor distribution, and higher price, which produce the polymer-based composites challenging to process and obtain mechanically brittle (fig. 2) <sup>[170]</sup>. To resolve these issues, polymer-based nanocomposites with arranged conductive nanofillers have been introduced, where the key is to develop a 3D conductive chain structure. The well-known 3D conductive chain is advantageous for lower price fabrication of materials and more comfortable

processability <sup>[89]</sup>. Yousefi et al. <sup>[172]</sup> fabricated a 2 wt.% of graphene reinforced polymer nanocomposites using aqueous casting technique, which showing high-performance electromagnetic radiation shielding effectiveness as 38 dB. It is also observed that ice-templating is an efficient method to prepare ordered 3D solid structure. As an illustration, unidirectional freezing has been used to manufacture anisotropic porous medium waterborne polyurethane (WPU)/ MWCNT hybrid composites with higher electromagnetic shielding efficiency of 20-50 dB based on the particle density of 20-126 mg/cm3 <sup>[173]</sup>. Furthermore, the unidirectional freezing process only permits for conductive particles to arrange in the direction of freezing, whereas the bidirectional freezing method has been introduced to create functional materials with a massive range of arranged lamellar structure (fig. 3) <sup>[174-177]</sup>. The different types of filler or particle hybridization in polymer composites for electromagnetic shielding efficiency and electrical conductivity are presented in tables 2, and 3 respectively, are compared to each other.

The shielding characteristics of ternary polymer composites epoxy/ barium titanate/ graphene nanoplatelets, the electromagnetic radiation transmission, and reflection indices were estimated when electromagnetic waves permeate through the protection material. There are three principles which estimate the efficiency of electromagnetic radiation protection. The part of the energy from incident radiation is reflected from the screen material front portion, and the other section is absorbed in another screen, and the next section is reflected from the screen back surface. The latter section can improve the screening efficiency and weaken based on the phase movement of waves at the material interface of the screen. Biaxially structure under-regulated interlayer spacing and thickness of layer has a colossal aspect ratio and is advantageous for electromagnetic radiation shielding utilization. The graphene has been selected as the conductive particles for polymer-based nanocomposites because of its conductivity, higher mechanical characteristics, lightweight,

higher aspect ratio, and flexibility <sup>[216]</sup>. By arranging graphene into a nacre-mimetic highly aligned 3D chain structure, the PDMS composites show higher mechanical characteristics, anisotropic conductivities, and superior electromagnetic radiation shielding efficiency under the deficient concentration of graphene content. The arranged laminates reinforced with 0.4 wt.% of conductive particles have better electromagnetic radiation shielding efficiency as 42 dB with an electrical conductivity of 32 S/m along the freezing direction, which also reduced up to 15 dB. After the heat treatment of aerogels under 2500 °C, the polymer nanocomposites showed an improvement of 65 dB and 0.5 S/m as the electromagnetic radiation shielding efficiency and electrical conductivity, respectively. Under ultralow concentration of particles as 0.15 wt.% and treated at 800 °C, exhibits an electromagnetic radiation shielding efficiency as 25 dB, which matches the aimed quantity of the electromagnetic radiation shielding efficiency required for general purpose around 20 dB <sup>[227, 228]</sup>. The higher electromagnetic shielding efficiency was obtained in anisotropic graphene/ PDMS laminates by structural regulation under ultralow graphene content <sup>[89]</sup>.

Presently, a new shielding composite materials with higher efficiency was developed from Shahzad research group <sup>[212]</sup>. MXenes are newly developed materials over two-dimensional (2D) transition metal-nitrides, carbide, carbon nitrides, which were first prepared in 2011 from the chemical etching process and MAX layered delamination <sup>[90, 229]</sup>, includes a vast amount of the surface groups developed during the process of exfoliation and chemical etching <sup>[230]</sup>. Hence, protection with specific thickness under constant frequency, the performance of shielding displays stable impedance on the conductivity of the material. It has been observed that Ti3C2Tx with metallic properties exhibits the most magnificent electromagnetic shielding performance because of better electrical conductivity, which came

from the higher electron density of regions around the fermi stage <sup>[212, 231]</sup>. Generally, the Ti3C2Tx thin film is manufactured from the vacuum filtration technique of the element spray or suspension coating process.

Furthermore, MXene is not a unique component for the production of huge-scale area flexible film, due to it has lower mechanical characteristics, weaker intersheet interaction and smaller in size <sup>[196, 232]</sup>. The reinforcement of polymers between the layers of MXene can be applied to modify MXene thin films. For example, MXene is reinforced with poly diallyl dimethylammonium chloride (PDDA), sodium alginate, polyacrylamide (PAM), cellulose fiber, and polyvinyl alcohol (PVA), to fabricate high strength and flexible thin-film <sup>[212, 233-235]</sup>. The electrical conductivity of the laminates, reinforced with 80 wt.% of MXene, was drastically reduced by many orders while comparing with neat MXene film <sup>[233]</sup>. Hence, it is also examined that there is severe degradation of electromagnetic radiation shielding performance of the MXene composites <sup>[236-238]</sup> since the conductivity corresponds to the performance of electromagnetic radiation shielding as per the Simon expression. Similar MXene composite films electromagnetic radiation shielding results are tabulated in Tables 2 and 3. The experimental viewpoint indicates that better mechanical characteristics, flexibility, and adequate thickness are of specific significance for the electromagnetic radiation shielding. The growth attained on the efficient techniques to enhance the shielding efficiency of MXene are Ti3C2Tx/ polymer-based nanocomposites and Ti3C2Tx based foams finding the structurally stable MXene thin films, with identical shielding efficiency which remains a problem.

4. Thermal conductivity

The thermal conductivity is commonly the transfer of thermal energy through any material <sup>[239]</sup>. Higher thermal conductivity materials have been applied in heat sinks, whereas materials of lower thermal conductivity are utilized for insulation applications. The dissipation

of thermal energy is essential to regulate the life, reliability, and functioning of the materials. Theoretical and fundamental investigations have been performed to exhibit the principle of thermal conductivity on both quantum and macroscopic scales <sup>[240]</sup>. In polymer-based nanocomposites, thermal conductivity mainly based on the characteristics of the nanoparticle and polymer resin <sup>[241]</sup>. The pure polymers generally have a lower value of thermal conductivity. The various factors affect the heat conduction of materials such as type of polymer matrix (thermosetting/ thermoplastic), polymer/ nanoparticle interface, crystallinity, and miscibility.

Furthermore, the shape of nanoparticle, type of nanoparticle, level of loading, orientation, and distribution of nanofiller have a possible influence on the material's thermal dissipation <sup>[38, 242]</sup>. The thermal conductivity of polymer and their respective composites is generally improved under a lower concentration of nanoparticle loading. In the polymer-based nanocomposites, nanoparticles can produce thermal conduction with uniform nanoparticle dispersion and orientation. The sparse distribution and accumulation of nanoparticles may create thermal protection, restricted to thermal conductivity enhancement. The non-spherical sized nanofillers such as nanorods, nanotubes, or nanoplates can be uniformly oriented and dispersed, which tends to higher thermal conductivity. Various carbon-based nanoparticles, such as graphene, CNT, graphite, nanodiamond, etc. have been utilized to improve the thermal conductivity of the polymer-based nanomaterials<sup>[243]</sup>. The inorganic nanoparticles containing metal oxides, metal nanoparticles, inorganic compounds, etc. have also been applied for the improvement. In the automotive and aerospace structure, the challenges of thermal dissipation have been improved by reinforcing nanocarbon particles in polymer for the fabrication of polymer nanocomposites <sup>[244]</sup>. A newly developed high thermal conductivity materials are also suitable for fuel cells, photovoltaics, and different types of flexible electronics <sup>[245, 246]</sup>. The thermal conductivity value for various polymers is generally lower and ranges between 0.1 and 0.3 W/mK<sup>[247-249]</sup>. Table 4 displays the thermal

conductivity of different types of polymer-based nanocomposites reinforced with nanofiller. The primary reason shows to be bonding strength in a polymeric flexible network. The polymer network chains generally permit which consist of mean free paths that reduce the conductivity.

The heat rejection characteristics of polymer-based nanocomposites can be enhanced; many additives and nanoparticles have been utilized <sup>[303, 304]</sup>. Carbon-based nanoparticle reinforced polymer nanocomposites are granting thermally conducting polymers, as shown in table 4. Among carbon nanoparticles, CNT has exhibited more excellent heat transport characteristics <sup>[305]</sup>. Furthermore, graphite also has higher interior thermal conductivity, whereas the single graphite has more excellent heat conductivity than the ordinary graphite <sup>[306]</sup>. The fullerene and nanodiamond also have significant thermal conductivity value than other types of composites and neat nanofillers. In polymer-based nanocomposites, the value of thermal conductivity mainly based on the nanoparticle dispersion degree within the polymer matrices. The interactions between nanoparticle and polymer matrix may improve the transport of the heat generation process <sup>[307]</sup>.

The carbon black nanofillers can accumulate in polymer resins, so reducing the heat dissipation characteristics. The addition of ordered nanoparticles in resins was found to develop the transfer of phonon <sup>[308]</sup>. It is a challenging task to improve the thermal conductivity of polymer nanocomposites under lower concentrations. The lower concentration of filler may grant uniform orientation and distribution within the resin matrices. Various metallic particles such as nanofillers, whiskers of silver, copper, gold, nickel, aluminum, etc. and metal nanoparticles have been utilized to improve the thermal conductivity characteristics <sup>[309]</sup>. Marconnet et al. <sup>[277]</sup> produced aligned MWCNT and epoxy-based polymer nanocomposites, which grants thermal transfer because of nanofillers' homogeneities, which tend

to be the higher thermal interface. The thermal conductivity was observed to enhance the increment in nanoparticle concentration. The thermal conductivity of the epoxy nanocomposites developed up to 4.87 W/mK with the reinforcement of 16.7 vol.% of MWCNT, which leads to the interface development within the aligned MWCNT and epoxy matrix, mainly responsible for the improvement of heat transport characteristics <sup>[310]</sup>. Pak et al. <sup>[279]</sup> fabricated thermally conductive boron nitride/ MWCNT/ polyphenylene sulfide (PPS) hybrid nanocomposite. The enhancement in thermal conductivity was achieved up to 1.74 W/mK, due to lower interfacial and interaction within the nanoparticles and the matrix material. Bozlar et al. <sup>[280]</sup> investigated the thermal conductivity of epoxy-based nanocomposites under the lower functional CNT concentration and found to be improved up to 0.23 W/mK. The improvement in thermal conduction was assigned to the formation of interaction within the epoxy matrix and alumina functional CNT, which tends to lower thermal resistance. Both electrical and thermal conductivity of these materials also improved with the synergistic interfacial interaction between the matrix and nanofiller. From table 4, it has been that the Py-PGMA graphene/ epoxy-based nanocomposites were highly effective in increasing the property of thermal conductivity. Besides, there was a noticeable increment in thermal conductivity of the Py-PGMA graphene/ epoxy and graphene/ epoxy, when compared with MWCNT/ epoxy material. Araby et al. <sup>[266]</sup> fabricated styrene-butadiene rubber and graphene polymer nanocomposites. The thermal conductivity value was attained as 0.42 W/mK, which is comparably highest at 10.5 vol% of nanoparticle, which was determined as threshold percolation to produce thermal conduction and interface pathways. In this condition, the resistance for the material was observed as lower <sup>[267]</sup>. Kumar et al. <sup>[282]</sup> manufactured graphene reinforced poly(vinylidene fluoride-co-hexafluoropropylene) hybrid nanocomposites. The nanocomposite has displayed higher thermal and electrical conductivity of 19.5 W/mK and 3000 S/m. The remarkable performance of the graphene reinforced polymer-based hybrid nanocomposite was considered to uniform interfacial interaction within the nanofiller and matrix and higher aspect ratio <sup>[311]</sup>. These composite materials have the possibility for commercialization and huge-scale fabrication for advanced thermal applications <sup>[312]</sup>.

Li et al. <sup>[313]</sup> reinforced boron nitride nanosheets in the epoxy polymer to improve the system's heat dissipation characteristics. Yao et al. <sup>[274]</sup> applied silicon carbide nanowire (SiCNW) to strengthen polymeric based nanocomposite. The SiCNW created nanowire chains for heat conduction paths. After the reinforcement, the thermal conductivity leads to 1.67 W/mK, with the addition of 2.17 vol% of SiCNW. Remanan et al. <sup>[314]</sup> reinforced halloysite nanotube (HNT) in PVDF to produce thermally conducting nanocomposite materials. Ouyang et al. <sup>[275]</sup> fabricated phenolic polymer resin reinforced with branched alumina (b-Al2O3) nanocomposite. The nanocomposite exhibited the thermal conductivity as 1.481 W/mK, due to the formation of separate interfaces between the fillers and matrix with the lack of fine miscibility. Zhang et al. <sup>[315]</sup> employed Al2O3 fibers as reinforcement material in high-density polyethylene and found the thermal conductivity as 0.4 W/mK under 50 wt.% of particle loading. This extreme high loading of fillers leads to poor dispersion because of gaps, higher thermal resistance, and a smaller area of contact <sup>[316]</sup>. Shen and Feng, <sup>[317]</sup> investigated the heat transfer characteristics of the nanocellulose/ silver particles reinforced polymer hybrid nanocomposites. They found the thermal conductivity as 6 W/mK, which shows that the silver nanoparticles produce the effective thermal conductivity pathways in the polymer matrix. Zhou et al. [276] fabricated thermal conducting PVDF based nanocomposites reinforced with nickel particles and found the thermal conductivity as 1.5 W/mK, under the lower nanofiller concentrations, which caused lower thermal resistance and higher interfacial interaction. Huang et al. [318] collected the thermal conductivity value as 2.2 W/mK under 50 vol% of Aluminum nitride/ epoxy nanocomposites, which is

comparably 11 times than of the neat epoxy polymer (0.2 W/mK). The epoxy nanocomposite reinforced with 60 wt.% of boron nitride fibers showed the thermal conductivity value as 0.98 W/mK, which is comparably 5 times of neat epoxy polymer <sup>[319]</sup>.

Furthermore, the enhancement of thermal conductivity values is restricted. Investigators selected functionalization of thermally conductive fillers to enhance the epoxy nanocomposites' values for a specific particle concentration <sup>[284, 285, 320]</sup>. Therefore, the increment of thermal conductivity is still insufficient. In this condition, the investigators tried to enhance the thermal conductivity values of the polymers by comprising two or more thermally conductive nanofillers such as SiC nanowires/ graphene, Al/SiC, BN/ SiC, BN/AlN, GNPs/ MWCNTs, AlN/BN/SiC, and Al2O3/AlN. Compared with single thermally conductive nanoparticles, the hybrid nanoparticles of different shapes, sizes, and morphologies are introduced, which can further efficiently improve the probability of producing higher thermal conductive polymers <sup>[321]</sup>.

#### 5. Electrical properties

Levchenko et al. <sup>[53]</sup> selected theoretical and experimental methods to evaluate the effect of clay particles on polypropylene/CNT-based ternary nanocomposites for the enhancement of electrical percolation threshold characteristics. The percolation of electrical threshold decreased by 28.4%, with the addition of CNT content from 0.95 to 0.68 vol.% on the polypropylene nanocomposites. The reason is assigned to avoidance and disengage of CNT accumulations during the mixing and melting processes. Thereby interparticle contacts were augmented to produce conductive chain structure. They collaborated this description from the microstructural examination, which displayed the bundles of CNT or clay content in the marginally reinforced polypropylene/CNT or polypropylene/ clay nanocomposites,

respectively (Fig. 4 a, b) <sup>[19]</sup>. Contrarily, the SEM micrographs of the ternary composites displayed well-established exfoliated CNT at the precedent of clay with the traditional chain structure required for conductivity (fig. 4 c) <sup>[19]</sup>. Some electric properties of different types of fillers reinforcement on polymers based composites are shown in table 4. On the other hand, Khajehpour et al. <sup>[322]</sup> examined an increment of threshold percolation with the reinforcement of clay to PVDF/ CNT and found that there is a degradation of the conductive chain structure influenced from the clay platelets which acts as a protective shield.

#### 6. Viscoelastic and creep properties

The viscoelastic properties of polymer-based composites are considered as complex modulus, which includes two components as storage and loss modulus. The storage modulus is the energy stored to affect the deformation, which offers useful details about the material stiffness, and it also presents the elastic behavior, whereas the loss modulus explains the loss of energy during the hysteresis. The ratio between the storage and loss modulus is termed as loss parameter or damping factor, which indicates the damping or internal friction <sup>[71]</sup>. The storage modulus of the composites improves with the increment in the content of hybrid particles. This increment in storage modulus represents the elastic behavior of the hybrid particles in the glassy portion, because of the hydrodynamic incorporation effect of both MWCNT and RGO nanoparticles in the polymer matrix, and synergistic influence of these two nanoparticles together enhanced the interfacial adhesion within the matrix and load also transferred within the polymer nanocomposites <sup>[323]</sup>. When the temperature rises, the nanoparticles become in movement and drop their tightly packed structure, which tends to a significant decrement in the storage modulus of the glass transition group. It is also observed that loss modulus attains a higher value when raising the nanoparticles' concentration. This may be because of the synergistic addition of both nanofillers and also increases the heat of friction at the interface of nanofiller and polymer matrix <sup>[324, 325]</sup>. It has been suggested by Nielsen and Landrel that there is a particle to particle interaction which can also develop frictional heat in the polymer hybrid nanocomposites <sup>[326]</sup>. The damping factor provides an essential principle about energy dissipation because of the molecular movement of the nanofiller particles, internal friction, and stress relaxation behavior of composite samples. The decrement in the damping factor of the composites, due to the stronger interfacial interaction between the nanofillers (similar synergistic effect) and polymer matrix.

The viscoelastic characteristics of filled reinforced polymer composites showed an essential problem due to the demand of their strength and dimensional stability, which is reported in many investigations as creep behavior <sup>[327-334]</sup>. This behavior recommends that the viscous relaxation of stress for the cell wall is due to the similar principles as cell-wall crushing, bending, and post-buckling deformation <sup>[335]</sup>. The creep mechanism in polymer-based composites sometimes happens under room temperature and for stresses below strength because of molecular movement in the backbone of the polymeric chain assembly <sup>[336-338]</sup>. Both viscous flow and elastic deformation are impeded with nanofillers' appearance, and substantially, the process of creep is delayed. On the other hand, the matrix/ nanofiller interface is essential, due to the breakage of bonds, and their propagation regulates the displacement of creep <sup>[337, 339]</sup>. The type of fillers are shows to be very necessary, due to Kevlar composites flow higher than the carbon laminates. As observed from the previous literature, carbon fibers showed significant viscoelastic characteristics <sup>[340, 341]</sup>, whereas, for the aramid fibers, there is an increment in creep strain concerning log time <sup>[342]</sup>. Therefore, when the polymer is reinforced with cork filler, the mechanism of creep becomes more complicated. Moreover, the cell wall geometry is modified continuously due to increment in the displacement of creep, and a clash between buckling and bending of the cell walls is predicted <sup>[335, 343, 344]</sup>.

#### 7. Summary and Future Perspectives

This review has offered the recent advancement on high-performance polymer-based nanocomposites mainly prepared from the reinforcement of hybrid nanoparticles. Consistently, the survey reviewed the properties of nanocomposites, such as mechanical, electromagnetic radiation shielding, thermal conductivity, and viscoelastic. The hybrid nanofillers affect the properties, which mainly depend on the dispersion level within the polymer resin. The accumulation of any or more than two nanoparticles substantially decreases or generates a more adverse effect on the results of the polymer nanocomposites. There is a significant improvement in the electromagnetic radiation shielding properties of the composites due to the selection of rigid material, formulation, and other processing parameters. The review well-established the shielding efficiency of nanofillers reinforced polymer composites by considering the dispersion of nanoparticles and lowering the polymer viscosity. This effect may lead to a decrement in nanofillers threshold percolation, which significantly influences the material properties. Substantially, incorporating the production of structure, which facilitates thermal and electrical conductivity, and limits the movement of the polymer chain, hence improves the mechanical and electromagnetic shielding behavior. The other processing parameters, such as shear, residence time, and temperature, which extremely influence the resulting properties of nanocomposites, should be investigated further while ternary fillers in the polymer matrix. New processing techniques also essential to investigate for the fabrication of highly conductive polymer-based nanocomposites containing the higher value of electromagnetic shielding efficiency. Therefore, the development of novel biparticles or triparticle composite materials and manufacturing methods may tend to high-performance generally applicable electromagnetic shielding materials (60-120 dB) under the

lower concentration of nanofillers. Advanced hybrid polymeric based nanocomposites reinforced with three or more fillers have promising future applicability in aerospace/ spacecraft structures and devices, lightweight shielding rooms, smartphones, etc.

Thermal conductivity is also an essential parameter in the development of material for heat management systems, which guarantees and enhances the service life and decrement in hazardous threats. The pure polymer generally has a lower value in interior thermal conductivity. From the review, the thermal conductivity of polymer-based nanocomposites was observed as a formulation of a polymer matrix, type of nanoparticle, interaction between polymer and filler, and microstructure. The higher value of thermal conductivity was attained at a lower concentration of nanoparticle due to the uniform dispersion. The lower viscosity of polymer has been applied to enhance the transport of heat and processability. By regulating the nanoparticle dispersion and orientation may tend to produce higher heat conductive pathways in the matrices of polymers. The present advancement in thermally conducting polymer-based nanocomposites has been examined for light-emitting diode, electronic packaging, photovoltaics, electronics, automotive, and aerospace structures. Acknowledgement

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Table 1 Effect of different types of nano fillers reinforcement on mechanical properties of polymer composites

S. No.	Type of composite	Tensile	Tensile	Compression	Flexural	Flexural	Elongation	Hardness	Ref. No.
		strength	modulus	strength	strength	modulus	at break		
1.	TPI/ HDPE Shape memory	5-8.2					30-60%		[70]
	alloys	MPa	-	-	-	-		-	[/0]
2.	Nano diamond/Gr/ CNT/	39-65	-	-			2.4-4.4%		[70]
	Epoxy	MPa			-	-		-	[/0]
	Polychloropropa/PGO/	9.49-	0.382-	20 16 48 27			500.0	44-55	
3.	MWCNT	16.36	2.519	30.10-40.37 MDo	-	-	1253.1%	(Shore	[71]
	MWCNI	MPa	N/mm	MPa				A)	
4.	Rigidi polyurethane foams/			201 MD <sub>0</sub>					[72]
	MoS2	-	-	291 MPa	-	-	-	-	[/2]

5.	Rigidi polyurethane foams/ Cu2O-MoS2	-	-	333 MPa	-	-	-	_	[72]
6.	Rigidi polyurethane foams/ Cu2O-MoS2-M	-	-	315 MPa	-	-	-	-	[72]
7.	Glass/ carbon/ glass/ polymer	270-360 MPa	5.8-8 GPa	268 MPa	-	-	5.2-5.8%	-	[73]
8.	Ppy/ PEDOT:PSS/ SWCNT	2.5-14 MPa	-	-	-	-	-	-	[74]
9.	PBI/ GO/ MWCNT	2484- 2946 MPa	3.36-4.16 GPa	-	-	-	-	-	[75]
10.	PU/GNP/CNT	34.7 MPa	0.026 GPa	-	-	-	-	-	[76]
11.	PU/GO/CNT	53 MPa	0.034 GPa	-	-	-	-	-	[77]
12.	Polycarbonate/ethylene methyl acrylate/ Graphene/ CNT	98.1 MPa	0.338 GPa	-	-	-	-	-	[78]
13.	Polyimide/ GO/ CNT	95.7-141 MPa	1.74-3.74 GPa	-	-	-	-	-	[79, 80]
14.	Poly (ether sulfone)/ f- graphene/ f-CNT	78.4 MPa	2.69 GPa	-	-	-	-	-	[81]
15.	Poly (vinyl alcohol)/ Graphene/ CNT	81.9 MPa	3.9 GPa	-	-	-	-	-	[82]
16.	Poly (e- caprolactone)/GO/CNT	18.7 MPa	0.363 GPa	-	-	-	-	-	[83]
17.	Nylon-66/f-GO/CNT	40.4 MPa	0.73 GPa	-	-	-	-	-	[84]
18.	UHMWPP/GNP/CNT	39.9 MPa	0.638 GPa	-	-	-	-	-	[85]
19.	Polypropylene/ Ground nut shell/ rice husk	9.12- 15.85 MPa	4.58- 34.54 GPa	-	5.74- 39.48 MPa	3.96- 21.09 GPa	-	-	[86]

20.	Epoxy/ Jute/ Glass fiber	50.64- 280.25 MPa	-	-	165.92- 359.14 MPa	-	-	-	[87]
21.	Epoxy/jute/ sisal/ tungsten carbide	50.26 – 222.7 MPa	-	-	31.38 – 149 MPa	-	-	-	[88]
22.	Graphene/ PDMS	0.1-0.3 MPa	-	-	-	-	63-146%	-	[89]
23.	Mxene/ Polymer	41.4 MPa	_	_	-	-	0.325%	-	[90]
24.	EPDM/NBR/Zinc Oxide/ CBS/ Sulfur/ GO	3 to 5 MPa	1.5 - 3 GPa	-	-	-	370-320%	50-58 kgf/mm <sup>2</sup>	[91]
25.	EPDM/NBR/Zinc Oxide/ CBS/ Sulfur/ Graphene	3 to 4.5 MPa	1.8 - 3.5 GPa	-	-	-	360-310%	52-57 kgf/mm <sup>2</sup>	[91]
26.	EPDM/NBR/Zinc Oxide/ CBS/ Sulfur/ GO/ Graphene	6.25 MPa	4.89 GPa	-	-	-	325%	59 kgf/mm <sup>2</sup>	[91]
27.	PAA/GO	186 MPa	2.02 GPa	-	-	-	0.91%	-	[92]
28.	PEG/GO	270 MPa	3.86 GPa	_	_	-	0.42%	-	[92]
29.	PVA/ GO	241 MPa	3.29 GPa	_	_	-	0.63 %	-	[92]
30.	Epoxy/ Copper Nano wire/ thermally annealed graphene	-	4.69 GPa	-	-	-	-	0.33 GPa	[93]
31.	Epoxy/ Flax/ Carbon Fiber	778 MPa	19 GPa	-	-	-	3.7 %	-	[94]
32.	carboxylated butadiene nitrile rubber/ CNT	0.32-0.68 MPa		-	-	-	-	-	[95]
33.	WPU/ Fe3O4/ rGO/ MWCNT	4.5-8 MPa	8 to 22 GPa	-	-	-	-	-	[96]
34.	Epoxy/ block polymer/ core shell rubber	34.39- 103.58 MPa	2838- 3658 MPa	114 MPa	-	-	1.33-5.83 %	-	[97]
35.	PVDF/ Ni	42 MPa		-	-	-	-	-	[98]
36.	Epoxy/ Jute/ CNT	23-36 MPa	-	-	14-22 MPa	-	-	-	[99]

37.	Epoxy/ZnS/ glass/ jute fiber	-	-	-	7006- 7440 MPa	-	-	-	[100]
38.	Epoxy/ Palm kernel shell fiber/ casava peel	10 - 25MPa	330-430 MPa	-	50-75 MPa	-	-	-	[101]
39.	Epoxy/ oil palm EFB/ Kenaf fiber	38-85 MPa	2500- 3700 MPa	-	58-110 MPa	3500- 7800 MPa	-	-	[102]
40.	PLA/ NIO/ Carbon	52-58 MPa	1944- 2037 MPa	-	-	-	-	-	[103]
41.	Polypropylene/ Wheat straw fiber/ nano TiO2	6-14.1 MPa	-	-	16-31.8 MPa	790-1550 MPa	-	-	[104]
42.	Epoxy/ SNCF/ Al-SiC	21.23-28 MPa	1.36 - 1.5 GPa	94.37-113 MPa	80.4-97 MPa	4-4.7 GPa	-	85-99 kgf/mm <sup>2</sup>	[105]

	Type of Composite	Reflection loss, dB	Respective frequency of reflection loss	Shielding efficiency in dB	respective frequency for shielding efficiency	Ref No.
1	Nano cabron/ BaTiO3 epoxy composites	-12 to -37	16 to 38 GHz	4-22%	25.5-37.5 GHz	[178]
2	15 wt.% of GNP/ epoxy	-14.5	18.9 GHz	-	-	[179]
3	2.6 vol.% of r- GO/PEO	-40	16.4 GHz	-	-	[180]
4	15 wt.% of BT/ epoxy	-12 to -6	11-12.5 GHz)	-	-	[181]
5	70 wt.% of (BT@Ni)- PVDF+PANI	-22.6	12.7 GHz	-	-	[182, 183]
6	20 wt.% CNT @BT-PANI/ wax	-28.9	10.7 GHz	-	-	[184]
7	1 wt.% of MWNT + 2 vol.% of (BT- GO)/ PVDF/ ABS	-44.9	15.9 GHz	26	8-18 GHz	[185]
8	GNP/ PBAT	-	-	5 to 13	8-12 GHz	[186]
9	15 wt% of r-GO/ PS	-	-	21.4	18 GHz	[187]
10	GNP/ PP/ PE	-	-	5	8-12 GHz	[188]
11	GNP/ CNT/ PP/ PE	-	-	13	8-12 GHz	[188]
12	GNP/ CNT/ PU	-	-	47	12.4-18	[189]
13	GNP/ CF/ Epoxy	-	-	25	26.5-40	[190]
14	BT/ PEK	-	-	7.5	8.2-12.4	[191]
15	BaTiO3/ Ag/ PVDF	-	-	26	8-12 GHz	[192]
16	Graphene-Fe3O4- BaTiO3/ Silicone Rubber	-	-	35	1-20 GHz	[193]
17	Polychloroprene/ RGO/ MWCNT	4 to -6	2.5-3.5 GHz	11.87	2.5-3.5 GHz	[71]
18	Fluroinated rubber/ SWCNT	-	-	20	6-10 GHz	[194]
19	Natural rubber/ Fe3O4/ rGO	-	-	26	8.2-12.4 GHz	[195]

Table 2 Different types of nano fillers reinforcement on electromagnetic radiation shielding properties of polymer composites

20	Styrene butadiene rubber/ graphene	-	-	45	8-12 GHz	[196, 197]
21	Ground tire rubber/ MWCNT	-	-	66	8-12 GHz	[198]
22	Styrene butadiene riubber/ ionic liquid modified MWCNT	-	-	72	18 GHz	[199]
23	Acrylonitrile butadiene rubber	-	-	77	8-12 GHz	[200, 201]
24	Ppy/ PEDOT:PSS/ SWCNT	-	-	29-35	8.2-12.4 GHz	[74]
25	Graphene/ PDMS	-	-	31-62	8.2-12.4 GHz	[89]
26	Mxene/ Polymer	-	-	40.5	8.2-12.5 GHz	[90]
27	PVDF/ SiC/ Graphene	8.6 to 12.4	8.2-12.4 GHz	15-32.5	8.2-12.4 GHz	[202]
28	Epoxy/ Copper Nano wire/ thermally annealed graphene	40.2	8-12.5 GHz	47	8-12.5 GHz	[93]
29	PVA/Mxene	3867-9343	8.2-12.4 GHz	21-44.4	8.2-12.4 GHz	[203, 204]
30	WPU/ RGO	34	8.2-12.4 GHz	338	8.2-12.4 GHz	[205]
31	PVC/RGO/Fe3O4	13	8.2-12.4 GHz	49.5	8.2-12.4 GHz	[206]
32	PVA/RGO- gamma-Fe3O4	20.3	8.2-12.4 GHz	416.7	8.2-12.4 GHz	[207]
33	PANI/ RGO	34.2	8.2-12.4 GHz	118.75	8.2-12.4 GHz	[208]
34	PANI/ SWCNTs	31.5	8.2-12.4 GHz	100.8	8.2-12.4 GHz	[208]
35	Epoxy/ MWCNTs	40	8.2-12.4 GHz	100.5	8.2-12.4 GHz	[38, 209]
36	PC/ CNTs	25	8.2-12.4 GHz	112.6	8.2-12.4 GHz	[210]
37	PP/ CNTs	35	8.2-12.4 GHz	372	8.2-12.4 GHz	[211]
38	SA/ Mxene	57	8.2-12.4 GHz	30830	8.2-12.4 GHz	[212]
39	PU/Cotton fabric/ rGO	48.1	8.2-12.4 GHz	48.1	8.2-12.4 GHz	[213]

40	PCL/ Cu hollow	110.7	8.2-12.4 GHz	110.7	8.2-12.4 GHz	[214]
41	PA/ EG/ CNT	50	8.2-12.4 GHz	38.5	8.2-12.4 GHz	[215]
42	Epoxy/ Ag/ Carbon Fiber	35-38	8.2-12.4 GHz	14-15.2	8.2-12.4 GHz	[216, 217]
43	SEBS-PHDDT/ rGO/ BN	37.92	8.2-12.4 GHz	9.5	8.2-12.4 GHz	[218]
44	Epoxy/ rGO/ Fe3O4	13.45	8.2-12.4 GHz	13.45	8.2-12.4 GHz	[219]
45	Cyanate ester/ Graphene nanoparticles/ Carbonyl ion-NI	48	8.2-12.4 GHz	13.7	8.2-12.4 GHz	[34, 220]
46	PVDF/ CNTs/ Ni	57.3	8.2-12.4 GHz	95.5	8.2-12.4 GHz	[54]
47	PVDF/ Graphene nanoparticles/ Ni	55.8	8.2-12.4 GHz	93	8.2-12.4 GHz	[54]
48	PVDF/ CNTs/ Co	35.3	8.2-12.4 GHz	117.7	8.2-12.4 GHz	[221]
49	Epoxy/ CNT/ Fe3O4/ Ag	35	8.2-12.4 GHz	17.5	8.2-12.4 GHz	[222]
50	PVDF/ rGO/ Fe3O4	35.6	8.2-12.4 GHz	32.4	8.2-12.4 GHz	[223]
51	PVDF/ CNT/ Fe3O4	32.7	8.2-12.4 GHz	29.7	8.2-12.4 GHz	[223]
52	WPU/ Fe3O4/ rGO/ MWCNT	34.4	8.2-12.4 GHz	28.4-35.9	8.2-12.4 GHz	[96]
53	PVDF/ Ni	127.62	8.2-12.4 GHz	26.8	8.2-12.4 GHz	[98]

Table 3 Different types of nano fillers reinforcement on electrical properties of polymer composites

	Type of Composite	Conductivity, S/m	Volume resistivity, Ohm.cm	Breakdown voltage, mV	Ref. No.
1	Nano cabron/ BaTiO3 epoxy composites	1.30 x 10 <sup>-2</sup> – 2 x 10 <sup>-11</sup>	-	-	[178]
2	Polychloroprene/ RGO/ MWCNT	0.1-1.2 x 10 <sup>-4</sup>	-	-	[71]
3	Ppy/ PEDOT:PSS/ SWCNT	10-950	-	-	[74]

4	Graphene/ PDMS	0.32-0.39	-	-	[89]
5	Mxene/ Polymer	102622	_	_	[90]
6	EPDM/NBR/Zinc Oxide/ CBS/ Sulfur/ GO/ Graphene	1.05 x 10 <sup>-5</sup>	-	-	[91]
7	PVDF/ SiC/ Graphene	0.015	-	-	[202]
8	Epoxy/ Copper Nano wire/ thermally annealed graphene	120.8	-	-	[93]
9	PVA/Mxene	716	_	_	[203, 204]
10	PVDF/ EG/ Ionic liquid	8.9 x 10 <sup>-9</sup>	-	-	[224]
11	WPU/ Fe3O4/ rGO/ MWCNT	6 x 10 <sup>-5</sup> to 1145.8	-	-	[96]
12	PVDF/ Ni	0.01			[98]
13	BNNS/ PDMS	-	7.5 x $10^{13}$ to 6.2 x $10^{12}$	33-40	[225]
14	S-BN/PDMS	-	$\begin{array}{c} 2.3 \text{ x } 10^{13} \text{ to} \\ 4.7 \text{ x } 10^{13} \end{array}$	28-33	[225]
15	Elastomer/	-	$3.25 \times 10^6$ to 3.26 x $10^{15}$	_	[226]

Table 4 Different types of nano fillers reinforcement on thermal conductivity of polymer composites

	Type of composites	Thermal conductivity, W/mK	Ref. No.
1	BNNS/ PDMS	0.21-1.16	[225]
2	S-BN/PDMS	0.21-0.77	[225]
3	P/EG	0.74-2.08	[249, 250]
4	P/LDPE/EG	1.02-1.278	[251, 252]
5	P/HDPE/EG	0.85-1.55	[114, 253-255]
6	Stearyl alcohol/HDPE/EG	0.6698	[256]
7	P/EP/CNT	0.285	[257]
8	MPCM/HPDE/EG	0.94	[254, 255]
9	P/EP/MWCNT	0.516	[67, 258]
10	MPCM/HPDE/Graphite	0.65	[254, 255]
11	P/MWCNT	0.34	[259]
12	P/CNF	0.31	[260]
13	P/GNP	0.7	[260]
14	P/EVA/EG/CF	2.03	[261]
15	P/HDPE/EG	0.575	[262]

16	P/HDPE/SBS/EG/MWCNT	0.673	[262]
17	P/MWCNT/Graphene	0.87	[263]
18	PEG/GO/BN	0.85-3	[260]
19	P/HDPE/EG/MWCNT	1.09-1.36	[264]
20	P/HDPE/EG/CNF	1.03	[264]
21	PU/p-MWCNT	0.23-0.31	[265]
22	Elastomer/ Graphene	0.23-0.42	[266, 267]
23	Epoxy/ MWCNTs	0.2-0.4	[268]
24	Epoxy/ Graphene	0.2-1.5	[268]
25	Epoxy/ Py-PGMA-graphene	0.2-2	[268]
26	Epoxy/ ex-foliated graphene	0.2-0.3	[245, 268]
27	Epoxy/ EBN	0.15-0.4	[269]
28	Epoxy/ NDEBN	0.15-0.5	[270]
29	PDMS/ BN nanowire	7.46	[271]
30	PVDF/ BN	1.8	[272, 273]
31	PVDF/ SiCNW	1.67	[274]
32	PR/AI2O3	1.481	[275]
33	PVDF/ Ni	1.5	[276]
34	Epoxy/ CNT	4.87	[277]
35	PU/CNT	0.47	[278]
36	Polyphenylene sulfide/ BN/	1 74	[279]
50	MWCNT	1.7 1	
37	Epoxy/ Functional carbon	0.16-0.23	[280]
	nano tube	0.10 0.20	[200]
38	Polyamide 6/ Graphene	0.416	[281]
•	Poly(vinylidene fluoride-		
39	cohexafluoropropylene)/	19.5	[282]
	Graphene		
40	Poly(vinylidene fluoride)/	0.66	[283]
	Nanodiamond		
41	Poly(dimethylsiloxane)/ BN	7.46	[271]
42	Poly(vinylidene fluoride)/ BN	1.8	[284, 285]
43	Epoxy/ SiC	1.67	[274]
44	Poly(vinylidene fluoride)/ Ni	1.5	[270]
45	Epoxy/ hBN	0.3-1.3	286]
46	Epoxy/ hBN/ rGO	0.3-2	[286]
47	Polypropylene/ Ground nut	0.16-0.29	[86]
	shell/ rice husk		[~~]
48	Epoxy/ Alumina/ Graphene	2 to 35	[287]
49	PVDF/ SiC/ Graphene	2.13	[74]
50	PVDF/Graphene	0.679	[288]
51	PVDF/ SiC/ Titanate	1.68	[54]
52	Polyamide/ Graphene/ Boron Nitride	1.76	[289]
53	PVDF/ CNT/ GO	1.56	[290]

51	PVDF/ Graphene	0.562	[201]
34	Nanoparticles	0.362	[291]
55	PVDF/ CNT/ Co	1.39	[34, 220]
56	PVDF/ Graphene	0.66	[202]
50	Nanoparticles/ Nickel	0:00	
57	Epoxy/ Graphene	1.2	[293]
58	Epoxy/ SiC/ BNNS	0.3-0.77	[77]
59	Polysiloxane/ Graphene	0.092-0.35	[294]
60	PVA/ Mxene	2.31-4.57	[203]
61	PU/Cotton fabric/ rGO	2.31	[213]
62	PCL/ Cu hollow bead	7	[214]
63	PA/ EG/ CNT	2.06	[215]
64	Epoxy/ Ag/ Carbon Fiber	2.33	[216, 217]
65	SEBS-PHDDT/ rGO/ BN	12.62	[218]
66	Epoxy/ rGO/ Fe3O4	1.213	[219]
	Cyanate ester/ Graphene		
67	nanoparticles/ Carbonyl ion-	4.13	[34, 220]
	NI		
68	PVDF/ CNTs/ Ni	0.65	[54]
60	PVDF/ Graphene	0.66	[54]
09	nanoparticles/ Ni	0:00	[54]
70	PVDF/ CNTs/ Co	1.39	[221]
71	Epoxy/ CNT/ Fe3O4/ Ag	0.46	[222]
72	PVDF/ rGO/ Fe3O4	0.68	[223]
73	PVDF/ CNT/ Fe3O4	0.62	[223]
74	PVDF/ EG/ Ionic liquid	0.18-0.82	[224]
75	PP/ BN	1.38	[269, 270]
76	PA/ BN	1.46	[295]
77	Si-Rubber/ ZnO	0.26	[117]
78	Si-Rubber/ Al2O3	0.25	[118]
79	Si- Rubber/ BN	0.8-2.1	[296]
80	Epoxy/BN	2.9-9	[183, 184, 297]
81	Epoxy/ CNT	0.195-250.4	[298, 299]
82	Epoxy/ Graphene	12.4	[297]
83	PDVB/ Fullerene	0.164	[300]
84	PDMS/ Ag-nano wire	6	[301]
85	PVB/ BN	0.5194	[302]
86	PVB/ZnO	0.2995	[302]
87	PVB/ SiC	0.2865	[302]

# Abbreviations used in tables

ABS - Acrylonitrile Butadiene Styrene, Ag – Silver, Al2O3 - Alumina, AlSiC - Aluminum Silicon Carbide, BaTiO3 - Barium titanate, BN - Boron Nitride, BNNS - Boron Nitride Nano Sheets, BT - Barium Titanate, CBS - Chloroprene Butadiene Rubber, CF - Carbon Fiber, CNT - Carbon Nano Tube, Co - Cobalt, Cu2O - Copper Oxide, EBN - Ethylidene nobornene, EFB - Empty Fruit Bunch, EG - Expanded Graphite, EPDM - Ethylene Propylene Diene Monomer, EVA - Ethylene-vinyl acetate, Fe3O4 - Iron (III) oxide, GNP - Graphene nanoplatelets, GO - Graphene Oxide, Gr -Graphene, hBN - Hexagonal Boron Nitride, HDPE - High Density Poly Ethylene, LDPE - Liner Density Polyethylene, MoS2 - Molybdenum Sulphide, MPCM - Modified Phase Change Material, MWCNT - Multi Walled Carbon Nano Tube, NBR - Nitrile Butadiene Rubber, NDEBN -Nanodiamond exfoliated hexagonal boron nitride nanoplatelets, Ni - Nickel, NIO - Nickel oxide, PA - Polyamide, PAA - Polyacrylic acid, PANI - Polyaniline, PBAT - polybutylene adipate terephthalate, PBI - polybenzimidazole, PC - Polycarbonate, PDMS - Polydimethylsiloxane, PDVB - Porous polydivinylbenzene, PE - Polyethylene, PEDOT:PSS - poly(3,4ethylenedioxythiophene) polystyrene sulfonate, PEG - Polyethylne Glycol, PEK - Poly Ether Ketone, PHDDT - partial hydrolyzed-deflavored and depigmented turmeric, PLA - Poly(lactic acid), PP - Polypropylene, PPy - Polypyrrole, PU - Polyureathane, PVA - Poly(vinyl alcohol), PVB - Polyvinyl butyral, PVDF - Poly (vinylidene fluoride), Py-PGMA - Pyrene-end poly(glycidyl methacrylate), RGO - Reduced Graphene Oxide, SA - Stearyl alcohol, S-BN -Spherical Boron Nitride, SBS - Styrene Butadiene Styrene, SEBS - Styrene-ethylene-butylenestyrene, SiC - Silicon Carbide, SiCNW - Silicon Carbide Nano Wires, SNCF - Sugarcane Nanocellulose Fiber, SWCNT - Single Walled Carbon Nano Tube, TiO2 - Titanium dioxide, UHWMPP - Ultra High Weight Molecular Polypropylene, WPU - Waterborne polyurethane, ZnO - Zinc oxide, ZnS - Zinc Sulphide

Figure Captions

Fig. 1. SEM micrographs of fractureed surfaces of flax fiber incorporated composites (a) GPFNC-0,

(b) GPFNC-1, (c) GPFNC-2 and (d) GPFNC-3 [116].

Fig. 2. SEM images of cross-section of graphene/ epoxy composites with two different magnifications [170]

Fig. 3. Boron nitride nanosheet reinforced epoxy composites with different types of filler network (a) randomly distributed network, (b) uniaxially aligned network and (c) long-range lamellar network [174]

Fig. 4. SEM images of (a) polypropylene/clay, (b) polypropylene/CNT, and

(c) polypropylene/CNT/clay [19]



Figure 1:



Figure 2:





(a)





**(b)** 





# (c)

Figure 3:



Figure 4: