

A review on the mechanical, electrical and EMI shielding properties of carbon nanotubes and graphene reinforced polycarbonate nanocomposites

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Recently, it has been found that carbon nanotubes (CNTs) and graphene could prove to be the most promising carbonaceous fillers in polymers nanocomposites field because of their better structural and functional properties. Their uniform dispersion in polymer matrix leads to significant improvements in their several properties. This paper reviews the effect of nanofillers, ie, CNTs, derivatized CNTs, and graphene on the polycarbonate nanocomposite and its application in aerospace, automobile, sports, electronic sectors, and various industries. The comparative analysis of carbon-based fillers on the different properties of polycarbonate nanocomposites is also included.

KEYWORDS

carbon nanotubes, EMI shielding, graphene, mechanical properties, polycarbonate

1 | INTRODUCTION

Polycarbonate (PC) is a strong, tough, and unbreakable thermoplastic, which can be conventionally used for industrial skylights, window shades, walkways, safety eye glasses, commercial greenhouses, office partitions, curtain walls, sidelites, shatter-proof or bullet-resistant windows, sliding doors, CDs and DVDs, etc. However, recently, commercial application of PC has been extended, but still, there is more scope in further extending PC properties and applications by incorporating carbon nanotubes (CNTs) and graphene as nanofiller. Polycarbonate is a nonconducting polymer; however, its conductivity can be increased by incorporating conducting filler such as carbon nanofiller in PC matrix. Previously, carbon nanofillers, ie, carbon black, carbon nanofibers, graphite fibers, and glass fibers, have been used as filler in PC nanocomposites.^{1–8} These nanocomposites are lightweight and high strength having electrical- and thermal-conducting materials. In fact, nowadays, the most promising fillers used are CNTs and graphene

to improve the ultimate mechanical and electrical properties.^{9–11} Their properties are much better than those of other carbon fillers.

1.1 | Lifecycle of PC

1.1.1 | Global production of PC

Polycarbonates are one of the fastest growing engineering plastics as new applications are being increasingly devised. Traditionally, the global PC market has served a wide range of application in different areas and has observed huge global demand. A significant increase in PC demand was from the Asia-Pacific region, which constituted 62.6% of the global demand of PC during 2010. Current global market demand for PC is 1.5 million tons, and its use is projected to increase up to 6.09 million tons at least 2020 (Figure 1). About 72.6% of global demand of PC is expected by the Asia-Pacific region in 2020.¹³ Figure 2 presents the world consumption of PC resin in 2015. Polycarbonate can be recycled; therefore, its market would continue to

Abbreviations: G, nanoparticles decorated graphene nanosheets; Ni, nickel; ABS, poly(acrylonitrile-butadiene-styrene); a-MWCNTs, acid-functionalized MWCNTs; BPA, bisphenol A; CBT, cyclic butylene terephthalate; CFs, carbon fibers; CNTs, carbon nanotubes; CO₂, carbon dioxide; dB, decibel; EC, electrical conductivity; EG, ethylene glycol; EGr, expanded graphite; EMI SE, electromagnetic interference shielding effectiveness; FGS, functionalized graphene sheet; FLG, few layer graphene; f-MWCNT, functionalized MWCNT; GNP, graphene nanoplate; GO, graphene oxide; GO-PPD, *p*-phenylenediamine-functionalized graphene oxide; GSs, graphene sheets; HNT, halloysite nanotubes; IS, impact strength; LA-g-MWCNT, lactic acid-grafted multiwall carbon nanotube; Mg, magnesium; m-SEBS, maleated styrene/ethylene butylene/styrene; MWCNT, multiwalled carbon nanotube; Ni, nickel; NMP, *N*-methylpyrrolidone; OGNP, oxygen-plasma treated graphene nanoplatelet; P3HT, poly(3-hexylthiophene); P3HT-g-PCLs, poly(3-hexylthiophene)-*g*-polycaprolactones; PBT, polybutylene terephthalate; PC, polycarbonate; PEDOT/PSS, poly(3,4-ethylenedioxythiophene)/poly(styrenesulfonate); PLA, poly(lactic acid); PVA, polyvinylalcohol; SAN, styrene acrylonitrile; SAN-g-MAH, poly(styrene-co-acrylonitrile)-*g*-maleic anhydride; SAN-g-MWCNT, styrene acrylonitrile-grafted MWCNT; scCO₂, supercritical carbon dioxide; s-MWCNT, synthesized MWCNT; SWCNT, single-walled carbon nanotube; THF, tetrahydrofuran; Zn, zinc

Global Polycarbonate Market Revenue, 2014-2020

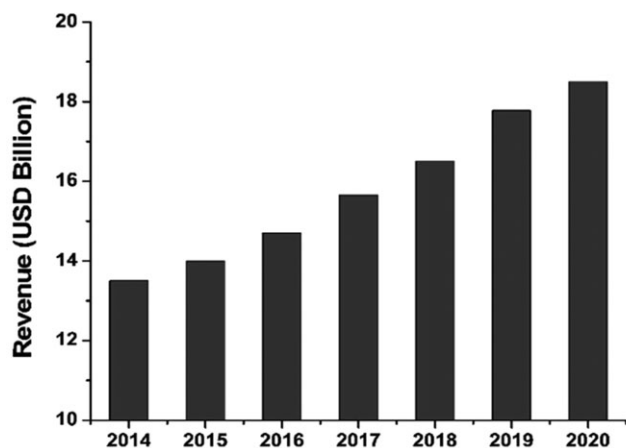


FIGURE 1 Global polycarbonate market revenue, 2014-2020 (Zion Research Analysis 2016)¹²

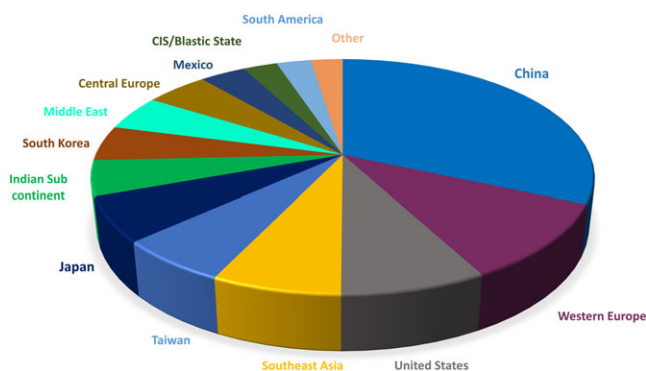


FIGURE 2 World consumption of polycarbonate resin, 2015 (IHS report 2016)¹⁴

increase, since researchers have used to develop PC using ecofriendly approach as it can solve the problem of global warming. In fact, if the uses of PC are expanded, then more of the CO₂ can be permanently stored to take care of the climate change problem. In fact, the use of CNTs and graphene fillers would increase the scope of the utilization of PC.

1.2 | Effect of PC on environment

Polycarbonate is commonly used in the production of CDs, DVDs, and automotive components and also used in the manufacture of baby bottles and water bottles.¹⁵ However, because of the presence of bisphenol A (BPA), many manufacturers have stopped using PC for applications related to human intake, and its use in landfills is definitely an environmental nightmare. It never biodegrades since it is a biorefractory material, and microorganisms cannot easily attack this. The nonbiodegradable PC results in serious pollution and disposal issues. However, a part of this polymer degrades though very slowly. The degraded chemicals produced leach into the environment causing significant harm. Many of these chemicals are consumed by marine organisms¹⁶ and other animals resulting in a lot of damage. It is of concern that the accidental dumping of plastics into oceans has resulted in mammals and birds starving to death and fish ingesting toxins that may

make them dangerous to eat. Annually, large amounts of CDs are discarded worldwide. Although there are methods being devised to recycle CDs, these are not very effective, and novel methods are being tried out.

1.3 | Recycling of PC

Polycarbonate is coded 7 implying that it is difficult to recycle. However, a lot of research has been done in this regard, and PC bottles and CDs are being extensively recycled. One method of recycling PC is by chemical recycling. Polycarbonate is made to react with phenol in the presence of a catalyst to form BPA and diphenyl carbonate monomers. After purification, both these monomers are used to produce the polymer. The CD includes at least 95% PC with the dye and reflective layers on the surface. The dye layer has organic dyes such as the metal azo and cyanine, while the reflective layer contains metals such as aluminum for laser reflection. A novel recycling method was recently devised and that has been discussed below.

The CD surface is burnished, and the reflective and the dye layers are burnished into powders that are collected for further treatment. The burnished disc body includes mainly PC with minimal amount of impurities like metals and dyes. The burnished CDs are then subjected to washing with ethanol that acts as a solvent for dissolving the dyes. The dyes that get dissolved in ethanol are treated with Fenton reagent. NaOH is added for iron ion precipitation or for any other metal ions in the solution. The remaining solution will contain very few impurities. Finally, the remains are made to react with concentrated nitric acid. By electrolysis, the metals are recovered, while PC is left as it is.¹⁷

1.4 | Applications of recycled PC

Recycled PC may show lesser resilience and has reduced impact resistance when compared with newly manufactured PC. Addition of fillers and pigments may reduce the resilience of the plastic. Chemicals can be used to improve impact resistance in recycled PC, and they could be used for most of the applications that virgin PC is used. Recycled PC finds applications in manufacture of plastic profiles. They have good stiffness, impact resistance, toughness, and are transparent. These profiles have a high colorability with a lovely gloss finish that can imitate metal and glass.

2 | ADVANTAGES OF CNT AS NANOFILLER OVER THE OTHER CARBON FILLER

Carbon nanotubes (Figure 3) have extremely high elastic modulus as compared with carbon fibers (CFs),^{18,19} and its strength is found to be 2 times higher than that of CF.¹⁹⁻²² Their density is lower than that of the CF.²³ The significant increase in strength indicates that the polymer/CNTs nanocomposite parts can be used in aerospace and different high performance applications having low volume and density commercial CF. Carbon nanotubes also have both elastic and plastic distortion behavior to relieve stresses. This effect makes them soft for lower loading but stiff for higher loading, accommodating large deformations without breaking, resulting in the fracture strains between 10% and 30%, which is better than most CFs, which have

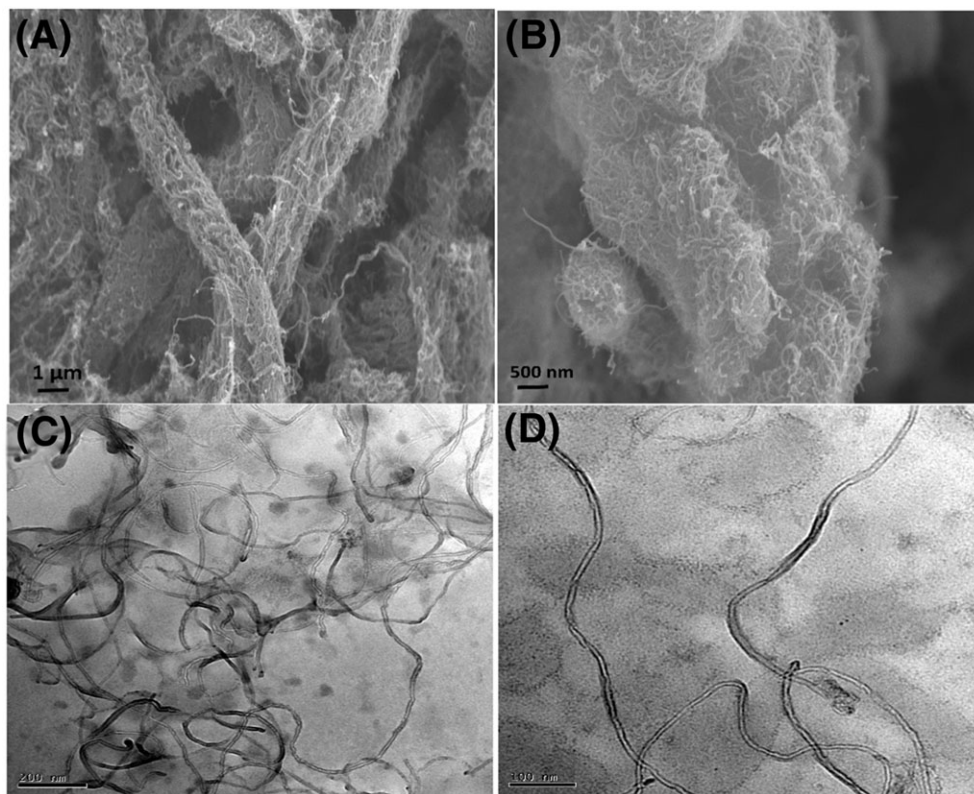


FIGURE 3 (A, B) Scanning electron microscopy micrograph and (C, D) transmission electron microscopy micrographs of a multiwalled carbon nanotube

values between 0.1% and 2%.²⁴ Thus, it is apparent that the combination of elastic and plastic behavior of CNTs makes it outstanding candidates as toughening nanofillers for polymer/nanocomposite that behavior is absent in graphite fibers. Their aspect ratios are approximately 10 000, which is higher than those of the other carbon fillers, which can be a benefit for electrical conductivity (EC) and mechanical strength of a nanocomposite system. Therefore, the combination of size, topology, and structure provides the CNTs with outstanding mechanical properties.

In addition, the electrical current carrying capacity of CNTs is also 1000 times greater than that of the copper wires, the thermal conductivity is about twice as compare with diamond, and the thermal stability of CNTs is found to be up to 2800°C in vacuum or inert atmosphere. Both single-walled CNT (SWCNT) and multiwalled CNT (MWCNT) have been used for PC nanocomposite production. The high aspect ratio of CNTs helps in the better interaction between polymers and CNTs because of the high surface area of interaction than that of CF. Therefore, the lower loading of CNTs can significantly increase the mechanical strength and EC of polymer nanocomposite.²⁴⁻²⁶

3 | PROPERTIES OF GRAPHENE AND THEIR APPLICATION

Graphene is considered as the basic structural unit of all graphitic materials like fullerenes, graphite, and CNTs. Graphene is the world's stiffest, thinnest, and strongest nanomaterial, as well as it also acts as an excellent conductor of both electricity and heat. These properties

enable graphene to make records in terms of strength, electricity, and heat conduction. Graphene has potential applications in different fields, ie, nanoelectronics, supercapacitors, batteries, solar cells, hydrogen storage, sensors, and flexible displays, due to its various fascinating properties.²⁷

Graphene has incredible properties as the lightest and strongest nanomaterial, compared with its ability to conduct heat and electricity better than other nanomaterials. Because of their excellent properties, it can be included into a large number of applications.²⁸⁻³⁴ Graphene has low mass density as compared with the classical fillers and also have high electrical and thermal conductivity, due to the sp^2 hybridized carbon atoms in the monolayer graphenes (Figure 4). The graphene have superior mechanical properties. Graphene is estimated to be 200 times stronger than steel, is as flexible as rubber, and conducts heat and electricity extremely efficiently. Besides, unlike other graphitic carbon nanofillers, such as CNTs and CF, which usually require costly and complex apparatus for the production, as well as high energy consumption methods such as chemical vapor decomposition, arc discharging, and laser ablation, high-purity graphene can also be produced from the natural graphite using relatively suitable methods.³¹ Graphene sheets show almost all extraordinary properties of CNTs while they are significantly cheaper than CNTs.³⁵ Combination of extraordinary mechanical, chemical, electrical, and thermal properties of graphene sheets³⁶⁻³⁸ and their relatively low production cost methods differentiate them from other nanomaterials.³⁹ The thermal conductivity of a single layer graphene (SLG) sheet has been measured to be extremely high, in the range of 4.84 to 5.3 W/mK, considerably outperforming CNTs in heat conduction.⁴⁰ Their

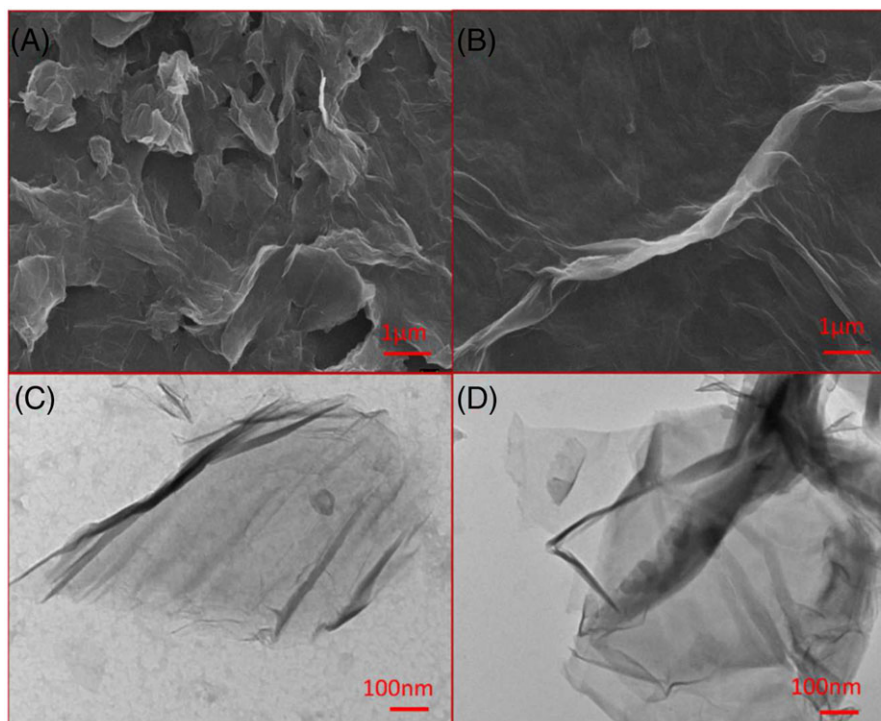


FIGURE 4 (A, B) Scanning electron microscopy images and (C, D) transmission electron microscopy image of graphene

mechanical stiffness is about 1.06 TPa, similar to CNTs. Recently, graphene is used for improving the performance and efficiency of current materials and substances.

4 | UTILIZATION OF CARBON DIOXIDE FOR PRODUCTION OF PC, CNTS, AND GRAPHENE

Permanent storage of carbon dioxide is very important. The usual geological storage systems are prone to leakages, and thus, the stored carbon dioxide finds its way to atmosphere in shorter times. Even utilization of CO₂ through soft drinks or biofuels production etc is a short-term storage of CO₂. However, chemical utilization of CO₂ is a very attractive subject not only from carbon source utilization point of view but also from the increasing environmental concerns (greenhouse effect) provided the storage is for a fairly longer time if not forever. CO₂ is one of the main greenhouse gas and also an inexpensive carbon feedstock. Recently, the consumption of abundant, non-flammable and nontoxic, CO₂ has gained attention because of the effective approach to reduce the release of the greenhouse gases.⁴¹ Moreover, interest in the use of CO₂ as a raw material in the synthesis of organic molecules and carbon materials has also increased over the last decades.^{42,43} One of the most promising approach of CO₂ utilization is its application as a direct material in polymer synthesis, and this could afford a longer time storage of this gas.

Mainly, PC has been manufactured using the phosgene process where chlorine and CO₂ are combined to form phosgene gas (a toxic gas). However, the phosgene-based process has a number of disadvantages as environmental concern. Polycarbonate can be prepared by the copolymerization of epoxides with CO₂. Copolymerization of CO₂ and

epoxides, which was first described by Inoue and coworkers in 1960s, has been considered as one of the most effective process for the production of variety of aliphatic PC⁴⁴ as shown below:

Asahi Kasei's researchers have developed nonphosgene process for the production of aromatic PC. They developed an innovative nonphosgene process for production of PC from BPA and CO₂ as starting materials.⁴⁵ However, there is a need to expand the market of the PC or modified PC products so that more and more of CO₂ can be used and removed from the atmosphere. Therefore, there is a need to develop more products such as nanocomposites from the PC so that its uses could be expanded (Figure 5). The use of CNTs in the preparation of PC/CNT composites can result in incorporating several interesting properties in the PC/CNT composites, and a detailed discussion on this has been included in the present paper later in the text. However, interestingly, even CNTs can be produced by using the CO₂.

In fact, the recent improvements in the production of CNTs have been reviewed^{46,47} with an emphasis on the use of CO₂ as carbon source. Compared with the other widely used carbon precursors such as graphite, methane, toluene, acetylene, ethanol, ethylene, and coal-derived hydrocarbons, CO₂ is competitively cheaper with relatively high carbon yield content. Motiei et al⁴⁶ reported the production of CNT and nested fullerenes from the reaction of CO₂ with Mg in a closed chamber for 3 hours at 1000°C. The MgO is also produced in this reaction, which is removed by washing reaction products with diluted HCl. The total yield of carbonaceous materials is about 15.5% (CNT of 10% and nested fullerenes of 1%-2%). Lou et al⁴⁷ used metallic Li as a reductant at an operating temperature of 550°C for 10 hours. X-ray diffraction analysis was used for the characterization of CNTs. Even the use of CO₂ can be made for the production of graphene. Various experimental methods for scalable production of graphene have been

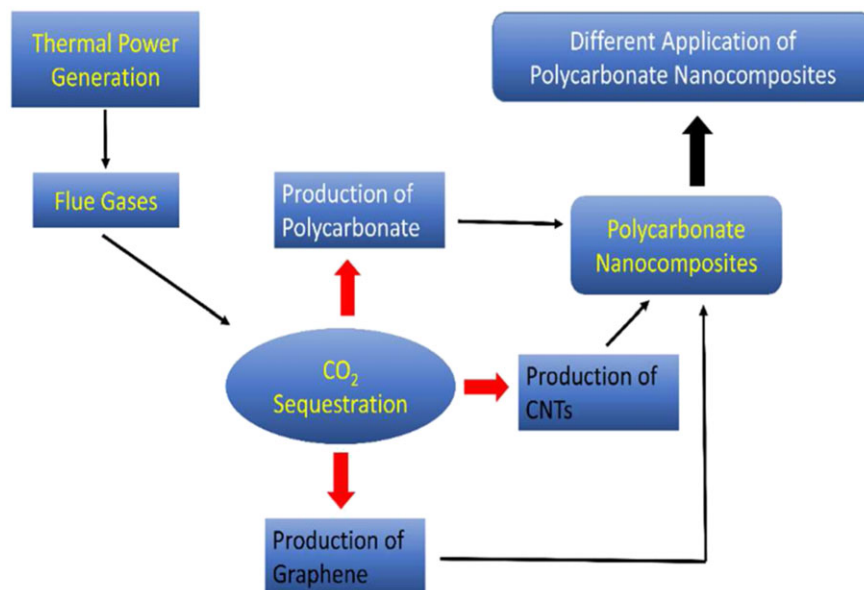


FIGURE 5 Flow chart showing utilization of CO₂. CNT, carbon nanotube

developed in recent years.⁴⁸ There are several methods available for production of graphene including chemical reduction of exfoliated graphite oxide (graphene oxide [GO]), electrochemical exfoliation of graphite, chemical vapor deposition, and chemical reduction in metal flames. However, they use expensive feedstocks for the production of graphene. Nowadays, graphene is also produced by using CO₂. Pu et al⁴⁸ demonstrated a method for production of few layer graphene (FLG) by using supercritical CO₂ (scCO₂) for exfoliation of natural graphite. One major advantage of this method over other methods is that the high-purity graphene is obtained by simply depressurizing the scCO₂, which returns to gas phase by evaporation, leaving no solvent residue in graphene material. Chakrabarti et al⁴⁹ synthesized FLG by combustion of magnesium (Mg) metal in CO₂ (dry ice). In this method, the black product containing graphene and MgO was formed, and this product can be cleaned by using dilute HCl. Zhang et al⁵⁰ also reported the synthesis of graphene by reducing CO₂ in magnesium and calcium flames and used the graphene formed for supercapacitor applications. Graphene was also produced in the author's laboratory by burning the Mg metal with Ni and Zn metal separately, in CO₂ (dry ice).⁵¹

5 | PC/CNT NANOCOMPOSITES

In many of the PC/CNT nanocomposite studies, the conventional polymer processing methods have been used. Polycarbonate has an amorphous structure, which helps in easy melt blending through softening by heating. Polycarbonate also shows good solubility in common organic solvents such as chloroform and dichloromethane. Most of the studies on PC/CNT nanocomposites have been focused on improving the dispersion of CNT in matrix and load transfer efficiency. The interaction between the polymer matrix and CNTs has been increased through chemical functionalization of CNT surface during nanocomposites processing, which showed improved mechanical and electrical properties of composites. These have been discussed in details in the present review. The PC/CNT nanocomposites are processed by 2 methods, ie, melt and solution processing. In most of the studies, melt

blending is the preferred method of nanocomposite fabrication. Presently, the mechanical and electrical properties and electromagnetic interference (EMI) shielding effectiveness (SE) of PC/CNT nanocomposites have also been discussed.

Earlier, PC/CNT nanocomposites were used for industrial applications such as in automobiles' exteriors because of their good mechanical and thermal resistance properties.⁵² Firstly, Covas et al⁵³ studied on the continuous, laboratory scale, production of PC/CNT nanocomposites by using microextruder (melt blending), and its parameter was comparable with industrial extruder. MWCNTs produced by chemical vapor deposition of acetylene on alumina-supported transition metal catalysts were used in this study. Further, PC/SWCNT nanocomposites were prepared by using microcompounder, and their electrical properties were studied.⁵⁴ In this study, SWCNTs were synthesized by arc discharge method, and then melt mixing method was used for production of PC/SWCNTs nanocomposites. Pötschke et al^{55,56} further elaborated melt blending method for dispersion state of MWCNTs in PC matrix and also studied electrical and mechanical properties of PC/MWCNT nanocomposites. Suhr et al⁵⁷ used solution mixing technique for dispersion of oxidized SWCNTs in PC matrix to investigate the effect of mechanical prestrain on interfacial friction damping in PC/SWCNTs nanocomposites. For good dispersion of MWCNTs in PC matrix, ultrasonic waves were used by ultrasonication method with mechanical stirring.⁵⁸ Chin et al⁵⁹ developed a method to fabricate transparent MWCNT-toughened PC films and designed PC/MWCNT-laminated structure for practical applications. Mainly, they used solution blending method for dispersion of MWCNTs in PC matrix. Chloroform was used for solution blending because PC is soluble in chloroform and this can be easily evaporated. Crystallization was observed in PC/MWCNT film because the solution cools down rapidly. Some researchers solved this problem by moving the petri dish gently side-to-side until the chloroform evaporated completely, and thus, they achieved uniform evaporation throughout the evaporation process. By this method, transparent PC/MWCNT nanocomposite film was fabricated, which has high toughness (11% increase in tensile strength) than neat PC film.

The effects of injection molding parameters on the electrical conductivities of PC/CNT nanocomposites were also studied during melt blending process.⁶⁰ High electrical conductivities were observed at high melt temperature. However, high injection speeds resulted in the nonuniform distribution of conductivities across the specimen width. Exfoliation of CNT from bundle and dispersion of nanotubes throughout the polymer matrix is the most critical challenge during the preparation of polymer/CNT nanocomposites. This problem is solved by using a new process (foaming process). Supercritical CO₂ foaming process was used to improve the dispersion of SWCNTs in PC.⁶¹ A mechanism of exfoliating SWCNT bundles by scCO₂ bubble nucleation and growth during foaming process was proposed by the researchers. Authors feel that solution blending method is suitable for laboratory scale purpose. However, for industrial level processing, melt blending is the most appropriate method for production of polymer CNT nanocomposites. Ultrasonication method with mechanical stirring and scCO₂ foaming process is the most efficient method for proper dispersion of CNTs in PC matrix.

5.1 | Functionalization of CNTs

Functionalization of CNTs is required to avoid the agglomeration of CNTs, and this also helps in enhancing the chemical reactivity of CNTs to make them more effective and improve the properties of the CNT-based nanocomposites. There are other reasons for the functionalization of CNTs, and these have also been discussed in the text. Therefore, several workers had worked on the functionalization of CNT for the preparation of PC/CNT nanocomposites. Virgin CNTs are insoluble in many solvents such as water and most of the common solvents.⁶² In fact, the outer wall of CNT is chemically inert. Thus, it is difficult to disperse CNTs evenly in a liquid matrix such as epoxides and other polymers. The outer walls of CNT are chemically inert because of the aromatic nature of the bond. Thus, the incorporated CNTs are inert and interact with the polymer matrix through van der Waals interactions, which unable to provide an efficient load transfer across the polymer matrix/CNT interface. For easy and uniform dispersion of CNTs in solvents, it is required that certain molecules or functional groups attach to the smooth sidewalls of CNTs by physical or chemical interaction without significant change in the desirable properties of CNTs.

In many applications, it is required to chemically tailor the CNTs to take benefit of their exclusive properties. Functionalization of CNTs has attracted substantial attention in the fields of material science, physics, chemistry, and biology. The functionalization approaches could be divided into 2 types: (1) the covalent connection of functional groups and (2) the noncovalent adsorption of functional groups onto the CNT surface. Hornbostel et al⁶² functionalized SWCNTs with the carboxyl groups and used those SWCNTs for improvement in electrical and mechanical properties of PC/SWCNT nanocomposites. Multiwalled CNTs were also functionalized by treatment with H₂O₂⁶³ and used for the preparation of PC/MWCNT composites by solution blending method. These H₂O₂-treated MWCNT/PC nanocomposites showed good electrical properties at very low loading of MWCNTs (2 wt%) than untreated PC/MWCNT nanocomposites. The electrical properties of PC/MWCNT nanocomposites are affected by

the MWCNT-MWCNT network structure, such as the degree of aggregation and aspect ratio of the MWCNTs. Mormann et al⁶⁴ studied modification and grafting of MWCNTs by BPA-PC. Multiwalled CNTs were oxidized with nitric acid, and then the carboxy group formed was transformed into amino group with diamine under microwave irradiation. Compatibilizers were also used for homogeneous dispersion of CNTs in PC matrix.⁶⁵ Poly(3-hexylthiophene)-g-polycaprolactones (P3HT-g-PCLs) with poly(3-hexylthiophene), ie, P3HT backbone, was used as a compatibilizer for PC/MWCNT nanocomposites.⁶⁵ It was interpreted that P3HT-g-PCL with lower degree of polymerization in P3HT backbone is more effective for homogeneous dispersion of MWCNTs in PC matrix than that with higher degree of polymerization in P3HT because of the stronger π - π interaction between P3HT-g-PCLs and MWCNTs. Single-walled CNTs were functionalized with -COOH, -OH group, *meso*-tritolylcorrole, UV-ozone, etc for their better and homogeneous dispersion in PC matrix.⁶⁶⁻⁷⁰ Plasma-modified CNTs were also used for PC/CNT nanocomposite production because these modified CNTs show better macrodispersion and good adhesion with PC matrix.^{71,72} Compatibilizers such as Zn⁺⁺ ion-coated nanosilica and cloisite 6A have been used for the study of PC/MWCNT nanocomposite properties.⁷³ Multiwalled CNTs have been functionalized with -COOH, -OH, and amino group, and these functionalized MWCNTs (f-MWCNTs) were used for preparation of PC/MWCNT composites with better dispersion of CNTs in matrix, which improve the different properties of nanocomposites.⁷⁴⁻⁸¹ Ozone and UV-ozone were also used for functionalization of MWCNTs (ie, mainly through the oxidation reactions), and these functionalized CNTs were further used in PC/MWCNT nanocomposites.^{82,83} Some grafted MWCNTs such as styrene acrylonitrile (SAN), glass fiber, and lactic acid-grafted MWCNTs (LA-g-MWCNTs) have been used by the researchers for fabrication of PC/MWCNT nanocomposites because these grafting materials help in interfacial interaction between MWCNTs and PC matrix.⁸⁴⁻⁸⁶ Thus, the functionalized CNTs exhibit improved properties, which are allowing the fabrication of novel nanomaterials and nanodevices. It seems there is still a wide scope of further functionalizing the CNTs and using these for preparing PC/CNT nanocomposites. Polycarbonate is very strong mechanically; however, the mechanical properties of PC could be further improved by using CNTs as well as functionalized CNTs.

5.2 | Mechanical properties of PC/CNT nanocomposites

Recent studies on improvement in mechanical properties of PC/CNT nanocomposites have been discussed in this section. Direct comparison between the different studies is not possible because different processing methods have been used in different studies. Here, the efforts have been made to compare the different studies on the basis of the type of CNTs used, loading amount of CNTs, and state of dispersion in matrix. Carbon nanotubes are known as the ultimate mechanical filler, which is used for the production of new generation of high-performance structural nanocomposites. The main aim of most of the studies for using CNTs is improvement in tensile strength, elastic modulus, and fracture strength of composite materials. Significant

data of recent studies on CNT/PC nanocomposites have been summarized in Table 1. Both SWCNTs and MWCNTs have been used by researchers for the production of PC/CNT nanocomposites. In the past, several automobile and other industries had used CNT-filled PC nanocomposites for manufacturing the molded products such as casings and trays for electronic devices, office automation devices, precision machines, and automobiles,^{52,87} because of the reason that these PC/CNT nanocomposites show excellent mechanical properties.

Noncovalently functionalized SWCNTs were fabricated with PC, and a dramatic improvement in tensile strength was reported at low loading of SWCNTs.⁸⁸ The PC/SWCNT nanocomposites were produced by coagulation method (solution mixing); however, these have been reported to show very less increase in tensile strength⁶² (Table 1). Khan et al prepared PC/SWCNT nanocomposite film produced by solution blending using ultrasonic waves, and this film showed 53% increase in tensile strength than that of PC film only at 2 wt% loading of SWCNTs.⁸⁹ Magnetically aligned SWCNTs were also used for PC nanocomposites, and magnetically treated nanocomposites had better tensile strength than of untreated nanocomposites.⁹⁰ Researchers also used UV-ozone-pretreated SWCNTs for PC/SWCNT nanocomposite film production. These nanocomposites showed low percolation threshold for mechanical properties⁶⁹ (Table 1). In fact, for the last 9 to 10 years, MWCNTs have been used as nanofiller for the production of PC nanocomposites. In a study, polyvinylalcohol (PVA) was used as a surface modifier of MWCNT, and these f-MWCNTs were further used for production of PC/MWCNT nanocomposites.⁹¹ These nanocomposites showed 81% tensile elongation with 5% loading of PVA-coated MWCNT, and without PVA-coated sample showed only 25% tensile elongation. Thus, the addition of PVA enhanced mechanical durability of nanocomposites and also helps in the homogeneous dispersion of MWCNTs. Pardo et al⁹² studied the relationship between mechanical, electrical, and morphology of PC/MWCNT nanocomposites (Table 1). In this work, they used cyclic butylene terephthalate (CBT) modifier with MWCNTs. PC/MWCNT nanocomposites thus prepared showed 40% increase in tensile modulus with 5 wt% loading of MWCNT and 5 wt% CBT than that of PC. Acid-functionalized MWCNTs (a-MWCNTs) were also used for the study of mechanical property of PC/a-MWCNT nanocomposites.⁹³ PC/a-MWCNT nanocomposites showed 22% and 14.4% improvement in tensile strength and elastic modulus, respectively. Two-step dispersion method has also been used for production of PC/MWCNT nanocomposites by the researchers^{71,94} (Table 1). In the first step, a masterbatch of PC/MWCNT was prepared by extrusion, and in the second step, nanocomposites of PC/MWCNT with different loadings of MWCNTs were produced by using of masterbatch, PC pellets, and MWCNT powder. Wang et al⁹⁴ used this method for PC/MWCNT nanocomposite production. They observed only 7% increase in tensile strength of nanocomposites with 5 wt% loading of MWCNT and 35% decrease in tensile strength at 10 wt% loading. Thus, these above results show that this method is not much effective for maintaining tensile strength of PC at higher loading of MWCNTs. Pötschke et al⁷¹ performed an important study on PC/MWCNT nanocomposites by using plasma-modified MWCNT bucky paper. The nanocomposites showed 14.5% enhancement in tensile strength at lower (0.5 wt%) loading of MWCNT. The plasma modification induced the formation

of some carboxylic and ester groups on MWCNTs surface, which help in better phase adhesion of CNT with matrix.

Pande et al⁹⁵ studied the mechanical behavior of PC/as-synthesized MWCNT (s-MWCNT) and PC/f-MWCNT nanocomposites. The elastic modulus of PC/s-MWCNT nanocomposites increased by 29 and 43% with s-MWCNT content of 10 and 20 wt%, respectively. Improvement in elastic modulus with increase in CNT content may be due to the uniform dispersion of CNTs in polymer matrix, which restricts the polymer mobility. Tensile strength of PC/s-MWCNT nanocomposites does not show much variation with the loading of s-MWCNTs. The elastic modulus was increased by only 5% at 2 wt% loading of f-MWCNTs in PC/f-MWCNT nanocomposites. The average tensile strength was increased by 35% at 0.6 and 5 wt% loading of f-MWCNTs and 12% at 2 wt% loading of f-MWCNTs. The increase in tensile strength suggests that the load transfer from PC to MWCNT is improved by the use of f-MWCNTs. Rejisha et al⁹⁶ studied the effect of MWCNTs on the mechanical properties of polybutylene terephthalate (PBT)/PC blends (Table 1). The ultimate tensile strength of the nanocomposites was increased from 54 to 85 MPa with addition of MWCNT up to 0.3% in PBT/PC blend (80/20). The values of tensile modulus and flexural modulus were also increased to about 60% and the more than about 80%, respectively, at the same loading of MWCNTs. The impact strength of PBT/PC blend (80/20) was improved about 60%, and PBT/PC nanocomposites with 0.15% MWCNT showed about 50% increment. Choi et al⁸⁴ performed study on PC/SAN-grafted MWCNT nanocomposites. PC/SAN-g-MWCNT nanocomposites showed better mechanical properties as compared with PC/MWCNT nanocomposites. Authors feel there is still lot of scope to further improve the mechanical properties of PC/CNT nanocomposites by using different functionalizations such as alkylation, nitration, sulfonation, and metalation. In fact, PC itself can be modified to impart different properties in this material, and then the same may also be used for the preparation of nanocomposites having improved mechanical strengths. In fact, authors have introduced rubber (ethylene methyl acrylate [EMA]) in PC for enhancement of notch impact strength of PC.⁹⁷ The impact strength of toughened PC prepared by blending PC with 5 wt% of EMA copolymer having impact strength 318 J/m, ie, 381% improvement as compared with neat PC, was further increased to 19% (378 J/m) after 1 phr addition of MWCNTs.⁷ Maximum tensile strength and modulus of PC/EMA-MWCNT composites (about 39 and 60% increase, respectively, as compared with PC/EMA blend) was achieved at the loading of 10 phr MWCNT.

5.3 | Electrical properties of PC/CNT nanocomposites

In fact, the electrical properties such as surface conductivity can also be improved by the addition of CNTs to the PCs, which are otherwise nonconducting but strong. This would afford the production of stronger conducting materials. A lot of studies have been reported on electrical properties of PC/CNT nanocomposites. The results indicate that the fabrication of CNT into PC propose attractive ways to introduce electrical properties into insulating polymer. Recent improvement in electrical properties of PC/CNT composites is discussed in the present

TABLE 1 Mechanical properties of different PC/CNT nanocomposites

Sr.	Matrix	Type of CNT	Method of Processing	CNT Content	Result	Ref.
1	PC	SWCNT	Melt extrusion and solution mixing	0.5-7 wt%	TS- 27 MPa & YM- 1250 MPa at 5 wt% SWCNT (melt-extruded sample) TS- 50 MPa & YM- 1305 MPa at 5 wt% SWCNT (solution-blended sample)	Hornbostel et al ⁶²
2	PC	SWCNT	Solution blending	0.5-5 wt%	TS- 85 MPa at 2 wt% loading of SWCNT TS- 55 MPa (neat PC)	Khan et al ⁶⁹
3	PC	SWCNT	Solvent casting	0.1 wt%	TS- 22 MPa (without field) TS- 26 MPa (with magnetic field)	Sharma et al ⁷⁰
4	PC	UV-functionalized SWCNT	Solution blending	0.4, 0.8, and 1 wt%	Storage modulus increases up to 44% as the weight fraction of SWCNTs increases up to 1 wt%	Ayesh ⁶⁹
5	PC	MWCNT-coated PVA	Melt blending	5 wt%	TE- 81% at 5 wt% of CNT	Jung et al ⁷¹
6	PC	MWCNTs	Melt blending	2.5 wt%	YM- 1448, 1591, and 1888 MPa at 2 and 5 wt% MWNT & 5 wt% MWNT+5 wt% CBT respectively. TS- 30.9, 15.2 & 28 MPa at 2, 5 wt% MWNT & 5 wt% MWNT+5 wt% CBT respectively.	Pardo et al ⁹²
7	PC	MWCNTs, a-MWCNTs	Melt mixing	2 wt%	1. YM- 1574 MPa (MWCNTs/PC) and 1581 MPa (a-MWCNTs/PC) at 2 wt% MWCNTs 2. UTS- 79.6 MPa (MWCNTs/PC) and 81.3 MPa (a-MWCNTs/PCa) at 2 wt% MWCNTs 3. FS- 110 MPa (MWCNTs/PC) and 113 MPa (a-MWCNTs/PC), at 2 wt% MWCNTs	Babal et al ⁹³
8	PC	MWCNTs (average diameter of 10-15 nm and a mean length of 3 μm)	Melt blending	0, 1, 2.5, 5, or 10 wt%	TS- above 55 MPa for MWCNTs < 5 wt%.	Pötschke et al ⁷¹
9	PC	MWCNTs, plasma-treated bucky paper MWCNTs	Melt blending	0.25, 0.5, 0.75, and 1 wt%	TS- 55 MPa (PC), 58 MPa (0.5% MWCNTs + PC) & 64 MPa (0.5% plasma-MWCNTs+PC)	Wang et al ⁹⁴
10	PC	As-synthesized MWCNTs and acid-functionalized MWCNTs	Solvent casting	0.1-23 wt% (s-MWCNTs) and 0.1-5 wt% (f-MWCNTs)	YM- 1650 MPa at 20 wt% and 1480 MPa at 10 wt% s-MWNT UTS- 15 MPa at 20 wt% s-MWNT YM- 1205 MPa at 2 wt% f-MWNT UTS- 23 MPa at 5 wt% f-MWNT	Pande et al ⁹⁵
11	Poly(butylene terephthalate)/ polycarbonate blends	MWCNTs	Melt processing	0.15, 0.3, and 0.45 wt%	UTS- 85 MPa & YM- 4 GPa at 0.3 wt%	Rejisha et al ⁹⁶
12	Polyethylene terephthalate/ polycarbonate/maleic anhydride Grafted styrene-ethylene-butylene-styrene	Halloysite nanotubes	Melt blending	2 phr	TS- 49 MPa at 2phr HNT/5 phr MA-g-SEBS IS- 58 J/m at 2phr HNT/10 phr MA-g-SEBS	Choi and Ryu ⁶⁴
13	PC/EMA	MWCNT	Melt blending	0.25-10 phr	TS- 84 MPa at 10 phr MWCNT IS- 378 J/m at 1 phr MWCNT	Bagotia et al ⁷

Abbreviations: a-MWCNT, acid-functionalized carbon nanotube; CBT, cyclic butylene terephthalate; CNT, carbon nanotube; EMA, ethylene methyl acrylate; f-MWCNT, functionalized multiwalled carbon nanotube; FS, flexural strength; MWCNT, multiwalled carbon nanotube; PC, polycarbonate; PVA, polyvinylalcohol; s-MWCNT, as-synthesized multiwalled carbon nanotube; SWCNT, single-walled carbon nanotube; TS, tensile strength; UTS, ultimate tensile; YM, Young modulus.

review paper, and some significant data from those studies are presented in Table 2. The studies on electrical properties of PC/CNT nanocomposites show that EC of these nanocomposites follows the classical percolating behavior with percolation threshold varying between 1 to 5 wt%.^{85,96,98,99} Interestingly, because of the high aspect ratio and small diameter of CNTs, the values of percolation threshold of CNT-based nanocomposites are much less compared with carbon black and CF-based nanocomposites whose percolation thresholds are usually up to 15 to 20 wt% and 9 to 18 wt%, respectively.¹⁰⁰⁻¹⁰²

Jung et al.⁹¹ studied the electrical properties of PC/MWCNT nanocomposites by using surface-modified MWCNTs. The EC of about 2×10^{-2} S/cm of nanocomposites was observed at 5 wt% loading of MWCNTs (Table 2). Pardo et al.⁹² performed studies on PC/MWCNT nanocomposites modified with CBT. The highest ionic conductivity of about 10^8 pS/cm was obtained at loading of 3 wt% of MWCNTs and 5 wt% of CBT. Pande et al.⁹⁵ also studied the EC of PC/s-MWCNT and PC/f-MWCNT nanocomposites. Highest conductivity (3 S/cm) was achieved at 10 wt% loading of MWCNT, and percolation threshold was observed at 2 to 3 wt% MWCNT loading. Supercritical CO₂-aided melt mixing method was used for the generation of PC/MWCNT nanocomposites with high EC and improved dispersion.¹⁰³ The electrical percolation threshold was reduced from 1.53% to 0.83% because of the scCO₂ processing method. The scCO₂ processing reduces the bulk density of CNTs agglomerates and helps in proper dispersion of CNTs in matrix. In another work, Krause et al.¹⁰⁴ used ball-milled MWCNTs (5 and 10 h) for PC nanocomposites. These nanocomposites had maximum conductivity in the range of 0.01 to 0.02 S/cm, and percolation threshold at 0.33 and 0.38 wt% for 5 and 10 h ball milled MWCNTs, respectively. Yan et al.¹⁰⁵ studied conductivity and percolation threshold of PC/MWCNT nanocomposites by use of positron annihilation coincidence Doppler broadening measurements. The electrical percolation threshold was achieved at 2.9 wt% of MWCNTs, and maximum EC (10^{-3} S/cm) was obtained at 7 wt% MWCNTs loading. Maiti et al.¹⁰⁶ demonstrated a method of preparation of highly conductive PC/MWCNT composites in the presence of PBT. The electrical percolation was obtained at 0.21 wt% loading of MWCNTs with EC approximately 10^{-9} S/cm. Maximum conductivity of about 7×10^{-2} S/cm of nanocomposites was achieved at only 1.4 wt% loading of CNTs. So PBT in PC helps in dispersion of MWCNTs in matrix PC. In another study, researchers used maleated styrene/ethylene butylene/styrene (m-SEBS) rubber for toughening of PC/MWCNT nanocomposites.¹⁰⁷ Multiwalled CNTs were found only in PC phase and not in m-SEBS phase and were homogeneously dispersed in PC matrix. The conductivity of nanocomposites was increased by more than 7 decades on addition of 0.5 wt% MWCNTs, indicating the percolation threshold. Zhou et al.¹⁰⁸ performed a study on conductivity of PC/composites using highly conductive poly(3,4-ethylenedioxythiophene) (PEDOT)/poly(styrenesulfonate) (PSS)-coated MWCNTs. These nanocomposites showed percolation threshold at 0.3 wt% loading of CNTs with conductivity of about 0.23×10^{-9} S/cm. A polar solvent such as ethylene glycol (EG) has also been used in this study for enhancement of conductivity of PEDOT/PSS polymer. Incorporation of EG-PEDOT/PSS into MWCNT/PC composites is an effective way to lower the percolation threshold (0.3 wt%) and increase in the EC (approximately 0.30×10^{-7} S/cm). The

abovementioned results demonstrated that EG solvent-treated PEDOT/PSS plays a dominant role in the conducting mechanisms.

A systematic study related to the effect of processing methods on the morphology, mechanical properties, the electrical properties, and the SE of PC/MWCNT composites was performed by Pardo et al.¹⁰⁹ The electrical percolation threshold for PC/MWCNT nanocomposites was found at 1 wt% MWCNT content, and the highest conductivity (around 0.7 S/cm) was achieved at 5 wt% MWCNT loading for compression-molded samples. These results showed that the compression-molded composite samples have the higher conductivity than injection-molded samples. During the compression molding, the shear forces applied to the melt are lower, and the melt does not suffer orientation in a preferential direction. All this encourages the formation of a CNT network with more tube-tube contacts, and for this, the conductivity of compression-molded samples is higher than injection-molded samples. In another study, Han et al.¹¹⁰ investigated the influence of MWCNT dispersion and compatibilizer on the rheological and electrical properties of PC/poly(acrylonitrile-butadiene-styrene)/MWCNT nanocomposites. The EC of the PC/acrylonitrile butadiene styrene (ABS)/MWCNT nanocomposites with the compatibilizer was higher than those of the nanocomposite without compatibilizer. For the PC/ABS/MWCNT nanocomposites with the compatibilizer (SAN-g-MAH, 5 phr), the electrical conductivities were found to be 4.3×10^{-3} , 9.8×10^{-2} , and 2.0×10^{-1} S/cm at the MWCNT content of 1, 3, and 5 phr, respectively. This behavior possibly may be due to the reason that the conductive path can be made more easily when the domain size is decreased and, as a result, the MWCNT can be dispersed more evenly. A strategy to achieve high EMI shielding and ultralow percolation in PC/MWCNT nanocomposites through selective localization of CNTs was presented by Maiti et al.¹¹¹ The PC/MWCNT nanocomposites were prepared through solution blending of PC and MWCNT in the presence of commercial PC beads. The variation in EC of nanocomposites with different amounts (0%-70%) of PC beads at constant MWCNT loading (0.05 and 0.10 wt%) was observed. The value of EC of the nanocomposite was approximately 8.27×10^{-4} S/cm when the nanocomposites were prepared without any PC bead at 0.10 wt% MWCNT loading. However, the value of EC of the nanocomposites was increased with the addition of PC bead during solution blending of PC and MWCNT, and EC of approximately 2.15×10^{-3} S/cm was achieved when the nanocomposites were prepared with 60 wt% of PC bead at a similar MWCNT loading. The presence of PC beads in the PC matrix phase increased the effective concentration of the MWCNT in the solvent-blended continuous PC region. The PC beads in the continuous phase of PC/MWCNT composites can be regarded as "excluded volume," in which the MWCNT cannot penetrate, resulting a high effective concentration of the MWCNT in the solution-blended PC/MWCNT phase. Thus, the high effective concentration of the MWCNT in the solution-blended and solvent-dried PC phase plays a key role for achieving high EC of the composites at an extremely low loading (0.05 wt%) of MWCNT. Thus, high EC of the PC/MWCNT composites was achieved with increasing the content of PC beads in the composites.

Monnereau et al.^{112,113} studied the effect of foaming on the electrical properties of PC/MWCNT nanocomposites. In the first study, the maximum value of EC of about 2.25×10^{-2} S/cm of

TABLE 2 Electrical properties of PC/CNT nanocomposites

Sr.	Matrix	Type of CNT	Method of Processing	CNT Content	Result	Ref.
1	PC	MWCNTs-coated PVA	Melt blending	5 wt%	EC- 2×10^{-2} S/cm	Jung et al ⁹¹
2	PC	MWCNTs	Melt mixing	2, 5 wt%	Ionic conductivity = 10^8 pS/cm	Pardo et al ⁹²
3	PC	As-synthesized MWCNTs & acid-functionalized MWCNTs	Solvent casting	0.1-23 wt% (s-MWCNTs) & 0.1-5 wt% (f-MWCNTs)	EC- 3 S/cm at 10 wt%	Pande et al ⁹⁵
3	PC	MWCNTs	Supercritical carbon dioxide-aided melt blending method	0.5-7 wt%	Surface conductivity- 8×10^{-2} S/cm at 7 wt% CNT samples prepared with the scCO ₂ -aided melt blending at 10X scCO ₂ processing	Quigley et al ¹⁰³
4	PC	Ball-milled MWCNTs	Melt blending	0.25 (MWCNTs), 0.33 (5 h), 0.38 (10 h) wt%	As received, 5 and 10 h ball-milled MWCNTs shows maximum conductivity in the range of 0.01-0.02 S/cm	Krause et al ¹⁰⁴
5	PC	MWCNTs	Solution mixing	1-7 wt%	EC- 10^{-3} S/cm at 7 wt%	Yan et al ¹⁰⁵
6	PC/PBT	MWCNTs	Melt mixing	0.2-1.42 wt%	EC- 6.87×10^{-7} S/cm at 0.35 wt%	Maiti et al ¹⁰⁶
7	PC/styrene/ethylene-butylene/styrene (m-SEBS)	15% MWCNTs masterbatch	Melt mixing	0.25-2.5%	EC- 8.6×10^{-5} S/cm at 0.5 wt%	Gonzalez et al ¹⁰⁷
8	PC	PEDOT/PSS & (EG-PEDOT/PSS) coated MWCNTs	Solvent casting	0.1-2 wt%	EC- 9×10^{-8} S/cm at 0.3 wt% MWCNTs/(EG-PEDOT/PSS)/PC	Zhou and Lubineau ¹⁰⁸
9	PC	15 wt% MWCNTs masterbatch	Melt mixing	2 & 5 wt%	EC- 0.7 S/cm at 5 wt%	Pardo et al ¹⁰⁹
10	PC/ABS/SAN-g-MAH	MWCNTs	Melt mixing	0.99, 1.96, & 4.76 wt%	EC- 2.0×10^{-1} S/cm at 4.76 wt%	Han et al ¹¹⁰
11	PC	MWCNTs	Solvent casting with addition of PC beads	0.05, 0.08, 0.10, and 0.12 wt%	EC- 2.15×10^{-3} S/cm at 0.1 wt%	Maiti et al ¹¹¹
12	PC	MWCNTs	Melt blending and foam processing	0.25, 0.5, 1, & 2 wt%	EC- 2.25×10^{-2} S/cm at 2 wt% EC- 2.3×10^{-2} S/cm at 0.5 wt% (foamed sample)	Monnereau et al ¹¹²
13	PC	MWCNTs	Melt blending and gradient foam processing	0.5, 0.75, 1 & 2 wt%	EC- 5.5×10^{-2} S/cm at 2 wt% (20 min CO ₂ impregnation time)	Monnereau et al ¹¹³
14	PC/SAN [poly(styrene-co-acrylonitrile)] blend	MWNT-grafted Fe ₃ O ₄ nanoparticles	Two step- 1st solution blending & then melt blending	1-3 wt%	EC- 8×10^{-2} S/cm at 3 wt% of MWCNTs-g-Fe ₃ O ₄	Pawar et al ¹¹⁴
15	PC	MWCNTs	Melt mixing and then foaming	1, 3, & 5 wt%	EC- 7.7 and 7.0 S/m for the composite foams with porosities of 24% and 33%, ¹ at 5 wt%	Zhi et al ¹¹⁵
16	PC/ABS blend	MWCNTs	Melt mixing	0.5, 1, & 1.5 wt%	EC- 0.93×10^{-3} S/cm at 1.5 wt%	Rostami et al ¹¹⁶
17	PC/PLA blend	Lactic acid-grafted MWCNTs	Melt mixing	0.1 to 4.76 wt%	EC- 0.095 S/cm at 1 wt%	Jang et al ⁸⁶

Abbreviations: ABS, poly(acrylonitrile-butadiene-styrene); CNT, carbon nanotube; EC, electrical conductivity; EG, ethylene glycol; MWCNT, multiwalled carbon nanotube; PBT, polybutylene terephthalate; PC, polycarbonate; PEDOT/PSS, poly(3,4-ethylenedioxythiophene)/poly(styrenesulfonate); PLA, poly(lactic acid); PVA, polyvinylalcohol; SAN-g-MAH, poly(styrene-co-acrylonitrile)-g-maleic anhydride.

unfoamed samples was observed at 2 wt% MWCNT loading, and for foamed sample, the highest EC of around 2.3×10^{-2} S/cm was observed at only 0.5 wt% loading. In another study, the gradient foaming of nanocomposites was attained by the scCO₂ by limiting the time of impregnation of the foaming agent (CO₂) inside the polymer material. The maximum value of EC of about 5.5×10^{-2} S/cm was obtained at 2 wt% loading of MWCNTs with 20-minute CO₂ impregnation time. This might be attributed to the formation of conducting CNT pathways during the foaming process. Because of the foaming action, the microcellular structure growth would induce the nanotubes enriching and orientating around cells, resulting in the distribution of MWCNTs along the cell wall. Thus increased the chance of interconnectivity between MWCNTs, resulting in the improvement of the EC. Pawar et al¹¹⁴ designed conductive material from PC/poly(styrene-co-acrylonitrile) (SAN) and MWNT-grafted Fe₃O₄ nanoparticles. The highest value of EC of nanocomposites of around 8×10^{-2} S/cm was achieved at 3 wt% of MWCNTs-g-Fe₃O₄(PC/SAN:50/50). Zhi et al¹¹⁵ prepared PC/MWCNT nanocomposites by melt blending of PC matrix with CNTs, and the foams of these nanocomposites were prepared by foaming with scCO₂ as the foaming agent. Highest electrical conductivities around 7.7 and 7.0 S/m were obtained for the nanocomposite foams with porosities of 24% and 33%, respectively. Rostami et al¹¹⁶ studied the effect of MWCNTs on the thermal and electrical properties of PC/ABS blend prepared using simultaneous melt compounding. The rapid decrease (approximately 10⁹ orders) in the electrical resistivity at 0.5 wt% MWCNTs loading indicated the formation of an interconnected structure of the MWCNTs in the PC matrix. PC/ABS/MWCNT nanocomposites were showed EC about 9.3×10^{-2} S/cm at 1.5 wt% loading of MWCNTs. In another study, Jang et al⁸⁶ studied the influence of LA-g-MWCNT on the electrical properties of PC/poly(lactic acid) (PLA)/LA-g-MWCNT nanocomposites. The electrical conductivities of the PC/PLA/MWCNT and PC/PLA/LA-g-MWCNT nanocomposites were

observed to be 2.363×10^{-5} and 0.095 S/cm at 1.0 wt% MWCNT loading, respectively. The increase in EC of the PC/PLA/LA-g-MWCNT nanocomposite as compared with the PC/PLA/MWCNT nanocomposite propose that the increased dispersion of the LA-g-MWCNT in the PC/PLA blend is due to the increased connectivity of the MWCNT-MWCNT network structure.

5.4 | EMI shielding of PC/CNT nanocomposites

The enhanced mechanical and high conductivity properties of PC/CNT nanocomposites propose opportunities to be exploited as EMI shielding nanocomposites. In today's world, EMI shielding is very important in the field of electronic devices and components.¹¹⁷⁻¹²¹ The EMI shielding in the X-band (8.2 to 12.4 GHz) is important for military and commercial applications. A few studies on the EMI shielding properties of PC/CNT nanocomposites was reported in literature, which are shown in Table 3. Han et al¹¹⁰ studied the effects of MWCNTs dispersion and poly(styrene-co-acrylonitrile)-g-maleic anhydride (SAN-g-MAH) as a compatibilizer on the EC and EMI SE of PC/ABS/MWCNT nanocomposites. The EMI SE of the PC/ABS/MWCNT nanocomposite in presence of compatibilizer was found to be in 5.4 to 8.4 dB range and that of the nanocomposite without compatibilizer ranged from 2.5 to 4.2 dB at 0.1 to 1.5 GHz frequency. Thus, these results showed that the presence of SAN-g-MAH compatibilizer affected the dispersion of the MWCNT in the nanocomposite (Table 3). Therefore, the MWCNT-MWCNT network structure had resulted in an increase in the EMI SE when compared with the PC/ABS/MWCNT nanocomposite without SAN-g-MAH. Maiti et al¹¹¹ presented a strategy to achieve high EMI shielding and ultralow percolation in PC/MWCNT nanocomposites through selective localization of CNTs. The nanocomposites showed EMI SE of -23.1 dB at 2 wt% with 70 wt% PC bead. Monnereau et al¹¹³ studied the foaming effect on PC/MWCNT nanocomposites using scCO₂. The nanocomposites

TABLE 3 Electromagnetic interference shielding of PC/CNT nanocomposites

Series	Matrix	Type of CNT	Method of Processing	CNT Content	Result	Ref.
1	PC	15 wt% MWCNTs masterbatch	Melt mixing	2 & 5 wt%	EMI SE -50 dB at 5 wt%	Han et al ¹¹⁰
2	PC	MWCNTs	Solvent casting with addition of PC beads	0.1, 1.0, 1.5, & 2.0 wt%	EMI SE -23.1 dB at 2 wt% with 70 wt% PC bead	Maiti et al ¹¹¹
3	PC	MWCNTs	Melt blending and gradient foam processing	0.5, 0.75, 1, & 2 wt%	EMI SE -15 dB at 2 wt% (20 min CO ₂ impregnation time)	Monnereau et al ¹¹³
4	PC/SAN [poly(styrene-co-acrylonitrile)] blend	MWNT-grafted Fe ₃ O ₄ nanoparticles	Two step- 1 st solution blending & then melt blending	1-3 wt%	EMI SE -32.5 dB at 3 wt% of MWCNTs-g-Fe ₃ O ₄	Pawar et al ¹¹⁴
5	PC	MWCNTs	Melt mixing and then foaming	1, 3, & 5 wt%	EMI SE -16 dB at 5 wt%	Zhi et al ¹¹⁵
6	PC/ABS blend	MWCNTs	Melt mixing	0.5, 1, & 1.5 wt%	EMI SE -2.3 dB at 1.5 wt%	Rostami et al ¹¹⁶
7	PC/PLA blend	Lactic acid-grafted MWCNTs	Melt mixing	0.1 to 4.76 wt%	EMI SE -13 dB at 4.76 wt%	Jang ⁸⁶
8	PC	15 wt% MWCNTs masterbatch	Compression molding & injection molding	2 & 5 wt%	EMI SE ~ 40 dB at 5 wt% (compression-molded samples)	Abad et al ¹²¹

Abbreviations: ABS, poly(acrylonitrile-butadiene-styrene); CNT, carbon nanotube; EMI SE, electromagnetic interference shielding effectiveness; MWCNT, multiwalled carbon nanotube; PC, polycarbonate; PLA, poly(lactic acid).

showed -15 dB EMI SE at 2 wt% loading of MWCNTs (20-min CO₂ impregnation time). Pawar et al¹¹⁴ demonstrated the production of conductive material from PC/poly(styrene-co-acrylonitrile) (SAN) and MWNT-grafted Fe₃O₄ nanoparticles. The nanocomposite with 3 wt% loading of MWCNTs-g-Fe₃O₄ showed -32.5 dB EMI SE.

Zhi et al¹¹⁵ prepared PC/MWCNT nanocomposites by melt blending of PC matrix with CNTs and the foams of composites were fabricated by foaming with scCO₂. The PC/MWCNT composites showed EMI SE about -16 dB at 5 wt% MWCNT loading. Rostami et al¹¹⁶ performed a study on the effect of MWCNTs on the electrical and EMI shielding properties of PC/ABS 75/25 blend prepared by simultaneous melt blending. The PC/ABS/MWCNT nanocomposites showed the EMI SE of 2.3 dB at 1.5 wt% MWCNT loading. Jang et al⁸⁶ studied the influence of LA-g-MWCNT on the EC of PC/PLA/LA-g-MWCNT nanocomposites. The EMI SE of the PC/PLA/MWCNT nanocomposites varied from 3.0×10^{-10} to 2.8 dB, and the PC/PLA/LA-g-MWCNT nanocomposites varied from 3.8×10^{-3} to 13 dB at MWCNT content between 0.1 to 5.0 phr, respectively. Abad et al¹²¹ also investigated PC nanocomposites containing different amounts of MWNTs prepared using a twin-screw extruder. They compared the effect of different molding techniques, ie, compression and injection molding, and subsequent thermal treatment on the performance of the polymer composites. They demonstrated how different processing methods can influence the electrical and mechanical properties, SE, and morphology of PC/MWNT nanocomposites. For nanocomposites containing 5 wt% MWNTs that are compression molded, EMI SE of approximately 40 dB was observed, which would be adequate for use in electronics housings.

6 | PC/GRAPHENE NANOCOMPOSITES

The development of PC/graphene composites has been an exciting research field in the recent years. Tremendous amount of work has been performed on the preparation of monolayer graphene sheets, FLG sheets, or corresponding oxides,¹²²⁻¹²⁴ to explore the potential of these 2D graphitic nanofillers in advanced polymer composites field. However, the synthesis of monolayer graphenes or very FLG, without compromising with their properties, is a big challenge. Thus, the practical applications of graphene-filled polymer composites still need more effort. The current status of PC/graphene nanocomposites has also been reviewed in present paper. The recent research on complete understanding of on PC/graphene nanocomposites production including fabrication of PC/graphene nanocomposites and their various properties is also discussed presently.

6.1 | Functionalization of graphene

Recently, it has been reported that thermal exfoliation of graphite oxide (GO) produces carbon material consisting of functionalized graphene sheets (FGSs).^{125,126} Functionalized graphene sheet is easily produced using a process similar to that for expanded graphite (EGr), but has a higher specific surface area ($600-800 \text{ m}^2 \text{ g}^{-1}$).^{125,126} Functionalized graphene sheet shows rapid dispersion in polar solvents such as *N*-methylpyrrolidone, dimethylformamide, tetrahydrofuran, or nitromethane, which indicate the loose structure of these graphite stacks. Oxygen

functionalities on FGS increased the interaction with polar polymer matrix. Mainly, there are 2 differences between EGr and FGS. First, the resultant defects during thermal exfoliation of the precursor GO and distortions caused by the oxygen functionalization, as well as the extremely low thickness of the resulting FGS sheets, show wrinkled topology at the nanoscale.¹²⁵⁻¹²⁷ This roughness of GS surface helps in the better mechanical interconnection with the polymer chains and, thus, shows better adhesion. Such an effect has been suggested by recent molecular dynamics studies that show altered polymer mobility because of geometric constraints at nanoparticle surfaces.^{128,129} Second, the surface of EGr is relatively inert, and FGS contains pendant hydroxyl groups on the surfaces,¹²⁵ which helps in the formation of hydrogen bonds with the polymer. Thus, because of the high surface roughness and surface area of FGS, this surface chemistry leads to stronger interfacial interactions with polymer matrix and thus significant improvement in the properties of the polymer. Many research projects focused at the functionalization of graphene including chemical modification of the graphene surface, reactions of graphene (and its derivatives) with organic and inorganic functional groups, and the general description of various covalent and noncovalent interactions with graphene.¹²⁹⁻¹³⁵ Pawar et al used nickel nanoparticles decorated graphene nanosheets (G-Ni) for preparation of EMI shielding material using PC/SAN [poly(styrene-co-acrylonitrile)] blends.¹³⁶

6.2 | Mechanical properties of PC/graphene nanocomposites

In-plane alignment of graphite ellipsoids are favored for improving mechanical and barrier properties in selected directions. Composite stiffness will be highest in a direction along which layers are oriented, whereas gas permeation will be lowest perpendicular to the orientation.^{137,138} Shen et al¹³⁹ studied the interfacial interaction between PC and thermally reduced graphene (TRG) induced by melt blending. PC/graphene composites containing 3 wt% TRG were firstly prepared by solution mixing and subsequent melt mixing. The tensile strength of PC/graphene composite with 10-minute melt mixing time (PCG10) increased by 6.5% from 50.7 to 54 MPa and Young modulus increased by 6.8% from 1.92 to 2.05 GPa as compared with the composites with 0 mixing time (PCG0). The average elongation at break of PCG10 was also a little higher than that of PCG0. Therefore, the enhanced interfacial interaction between polymer and graphene would improve the mechanical properties of the polymer composites because of the efficient load transfer, and an enhanced interfacial interaction between PC and TRG was induced by melt blending. The efficiency of load transfer from TRG sheets to the PC matrix should be improved, thus leading to the enhanced mechanical properties. The same group¹⁴⁰ also reported a 72.1% increment of Young modulus and 20.3% increases in tensile strength using 1 wt% epoxy-functionalized GO, in which GO flakes were dispersed in dimethylformamide and PC dissolved in tetrahydrofuran. Yoon et al¹⁴¹ developed high-performance PC/graphene nanocomposites with outstanding mechanical and electrical properties by grafting PC onto graphene nanosheets (PC-g-MGNS). The PC-g-MGNS nanocomposites were synthesized by grafting hydroxyl-terminated PC onto methylene diphenyl diisocyanate-functionalized graphene nanosheets (MGNS). The PC-g-MGNS nanocomposite having

3 wt% graphene exhibits an approximately 20% increase in tensile strength and an approximately 23% increase in Young modulus. Kim et al¹⁴² prepared PC composites reinforced with FGSs produced using melt compounding and reported an approximately 6.7% and approximately 20.7% increments of Young modulus at 1 wt% and 2.5 wt% of FGS (thermally exfoliated graphite oxide) loading, respectively. Mittal et al¹⁴³ reported enhancement of approximately 23% in Young modulus with 7 wt% of RGO flakes loading in PC matrix. Lago et al¹⁴⁴ prepared PC-based graphene (PC/G) composites, by using a simple and scalable solution blending method to disperse SLG and FLG flakes. The PC/G composite showed approximately 26% increment in Young modulus at 1 wt% content of SLG/FLG flakes, and composite at 2.5 wt% loading of SLG/FLG flakes showed approximately 10% increase in ultimate tensile strength with respect to pristine PC. King et al¹⁴⁵ obtained an increase in elastic modulus by 9% and 50% for PC/GNP nanocomposites prepared by melt blending with contents of 3 and 7 wt%, respectively. Oyarzabal et al¹⁴⁶ prepared nanocomposites on the basis of PC and different amounts of untreated graphene nanoplatelets (GnP) (from 1 to 7 wt%) by melt blending. The PC/GnP composites with 7 wt% GnP loading showed 52% increase in elastic modulus as compared with neat PC. Steurer et al¹⁴⁷ reported increment of approximately 80% in Young modulus for PC/thermally reduced GO (TrGO) composites with loading of 10 wt% TrGO.

6.3 | Electrical conductivity and EMI shielding of PC/graphene nanocomposites

Graphene has recently gained importance as a revolutionary nanomaterial because of its extraordinary mechanical, electronic, and

thermal properties. These exclusive properties of graphene helps in the preparation of multifunctional nanocomposites.^{36,148-152} Nowadays, with the extensive use of sensitive electronic devices and densely packed systems, EMI becomes a more and more critical problem. Thus, considerable attention has been required to the development of novel EMI-shielded materials. As compared with the conventional metal-based EMI shield materials, electrically conductive polymer nanocomposites have their own benefits, such as lightweight, good processability, resistance to corrosion, and tunable conductivity. The electrical and EMI shielding properties of these polymer nanocomposites mainly depend on content, aspect ratio, and intrinsic conductivity of the nanofillers (Table 4).¹⁵³⁻¹⁵⁶ The high aspect ratio and EC of graphene sheets facilitate the enhancement of electrical and EMI shielding properties without sacrificing other properties of the polymer matrix. However, graphenes have been found to be much better than the CNTs.

Gedler et al^{157,158} investigated the EMI shielding properties of foamed PC/graphene nanocomposites processed in 2 steps and even in a single step with scCO₂ (Table 4). In 2-step foaming method, maximum EMI SE (−14 dB) was achieved for foamed composite samples, which was 70 times higher than that of the unfoamed composite samples (−0.2 dB).¹⁵⁷ In 1-step foaming method, composites presented a maximum specific EMI SE (−7 dB), which is approximately 35 times greater than that of unfoamed composite (−0.2 dB).¹⁵⁸ In a recent study, electrically conductive PC composites were prepared by blending thermally exfoliated graphene and *p*-phenylenediamine (PPD)-functionalized and reduced GO (GO-PPD) with PC.¹⁵⁹ The PC/GO-PPD nanocomposites showed EC approximately 0.7×10^{-1} S/m at 3 wt% GO-PPD. Pawar et al¹³⁶ designed conductive PC nanocomposites using

TABLE 4 Electrical conductivity and electromagnetic interference shielding of PC/graphene nanocomposites

Series	Matrix	Filler	Method of Processing	Graphene Content	Result	Ref.
1	PC	Conductive graphene nanoplatelets	Solution and emulsion mixing	0.027-2.27 vol.%	EC = 0.512 & 0.226 S/cm at 5 wt% for emulsion & solution mixing resp.	Zhang et al ¹⁵⁵
2	PC	Graphene nanoplatelets	Melt mixing & 2-step foaming by supercritical CO ₂	0.5 wt%	EMI shielding ~14 dB	Gedler et al ¹⁵⁷
3	PC	Graphene nanoplatelets	Melt mixing & 1-step foaming by supercritical CO ₂	0.5 wt%	EMI shielding ~7 dB	Gedler et al ¹⁵⁸
4	PC	Thermally exfoliated graphene and GO-PPD	Solution compounding and batch foaming process	0.5-3 wt%	EC ~0.05 S/m at 3 wt% of PC/graphene, EC ~ 0.5×10^{-1} S/m at 2 wt% of PC/graphene foam, EC ~ 10^{-1} S/m at 4 wt% of PC/GO-PPD EC ~ 0.7×10^{-1} S/m at 3 wt% of PC/GO-PPD foam	Ma et al ¹⁵⁹
5	PC/SAN (poly(styrene-co-acrylonitrile))	Nickel decorated graphene sheet	Melt blending	3 wt%	3 wt% G-Ni showed EMI Shielding – 29.4 dB over 3 wt% graphene (−13.7 dB) EC ~ 10^{-4} S/cm at 3 wt% G-Ni	Pawar et al ¹³⁶
6	PC	Graphene nanoplatelets	Melt compounding and batch foaming	0.5 wt%	EC = 1.34×10^{-8} S/cm at 0.18 wt% (0.09 vol%) of GNP	Gedler et al ¹⁶⁰
7	PC	FLG	Solution mixing	1-7 wt%	EC ~0.01 S/cm at 7 wt% of FLG	Sain et al ¹⁶¹

Abbreviations: EC, electrical conductivity; EMI, electromagnetic interference; FLG, Few layer graphene; GO-PPD, PPD-functionalized and reduced graphene oxide; PC, polycarbonate; PPD, *p*-phenylenediamine.

PC/SAN blends containing nickel nanoparticles decorated FLG nanosheets (G-Ni). The PC/SAN blend with 3 wt% G-Ni loading showed a drastic improvement in EMI SE (-29.4 dB) over blend with 3 wt% graphene loading (-13.7 dB) at 18 GHz frequency. The G-Ni loaded composites also showed an impressive enhancement in thermal transport properties and storage modulus as compared with composites having only graphene sheets.

Gedler et al¹⁶⁰ successfully prepared lightweight PC/graphene nanocomposites having improved graphene dispersion using a scCO₂ dissolution foaming process (high-pressure batch foaming process). After foaming, the highest EC was obtained with graphene volume fractions which is similar to the values reported in the literature for unfoamed PC/graphene nanocomposites. In this study, almost 70% reduction in weight of material is also observed, which makes it very attractive material for applications in sector, ie, transport, electronics, and aerospace. Sain et al¹⁶¹ developed a flexible and lightweight FLG-based PC composite. The EC of the composites was increased from 10⁻⁹ (without FLG) to 10⁻² S/cm (with 7 wt% of FLG). Thus, from the above studies, it can be concluded that foamed samples of PC/graphene showed better electrical and EMI shielding properties at lower loading of graphene than other PC/graphene nanocomposites. Authors feel that there is still lot of scope to further improve the electrical and EMI shielding properties of PC/graphene nanocomposites by using functionalized graphene, eg, different metal-decorated graphenes. Use of different metals for functionalization (decoration) of graphene may be studied for the improvement of these properties.

7 | PC AND CNT/GRAPHENE HYBRID NANOCOMPOSITES

Polymer nanocomposites based on SWCNT/MWCNT, carbon nanofiber, and graphene nanoplate (GNP) have been an exciting research area because of their unique, outstanding, and extraordinary electrical and physical properties and different applications in various fields. The mechanical, electrical, and thermal properties of the polymer nanocomposites can be significantly increased with the incorporation of CNT and GNP hybrid nanofiller in the polymer. However, the different properties of the polymer nanocomposites are strongly affected by the uniform and homogeneous dispersion of these hybrid fillers throughout the host polymer matrix. Both CNTs and graphene are remarkably stable materials with great mechanical strength and electronic properties. Hence, a wide range of smart materials have been developed for practical applications, addressing challenges in advanced aerospace, mechanical parts, medical technologies, and bionics with these carbon nanomaterial.^{162,163}

Maiti et al¹⁶⁴ studied PC/GNP/MWCNT hybrid nanocomposites, which were prepared by melt mixing method. High value of EMI SE about 21.6 dB at 4 wt% (GNP/MWCNTs) loading and the EC about approximately 6.84 × 10⁻⁵ S/cm were obtained at extremely low 0.3 wt% (GNP/MWCNTs) loading. Wegrzyn et al¹⁶⁵ also studied the thermoplastic nanocomposites of PC with hybrid nanofiller system (MWCNTs and GNP), which were prepared by melt mixing method. The nanocomposites were compressed molded and then characterized by different techniques. Highest EC of PC hybrid nanocomposites was observed about approximately 0.9 S/cm at 5MWCNTs/15GNP concentration of hybrid

nanofiller. Smith et al¹⁶⁶ also studied the interactions of MWCNT and graphite nanoplatelet in PC. They noticed from this study that the GNP geometry was found to shield the CNT from fracture and damage during processing while still allowing full dispersion of both fillers during high power sonication. This leads to the formation of a hybrid network and a lower electrical percolation compared with single filler systems at the same loading. Hybrid systems were found to have up to an 8 magnitude decrease in resistivity at only 0.25 total wt%. In addition to the increased electrical properties, the composites are able to maintain most of the transparency of the pure PC film samples. Yu et al¹⁶⁷ reported that thermal conductivity of polymer composites synergistically improved by the simultaneous incorporation of MWCNT and GNP nanofillers into the PC matrix. Zhang et al¹⁶⁸ studied the thermal conductivities of carbon fillers, including carbon black (CB), MWCNTs, and exfoliated graphite-based PC nanocomposites. In this study, with the addition of 10 mass% EGr filler loading to PC matrix, the thermal conductivity of the nanocomposite reached to 1.06 W m⁻¹ K⁻¹, 5 times that of PC, which was much higher than that of PC nanocomposites filled with MWCNTs or carbon black alone. The maximum thermal conductivity about 1.19 W m⁻¹ K⁻¹ reported at the loading of the EGr/MWCNTs hybrid with ratio 9:1, indicating that the combination of EGr and MWCNTs shows synergistic effect. The thermal conductivity of PC/EGr/MWCNTs nanocomposite increased by 26-fold over the PC at 40 mass% loading, which may provide a broader view for their further use in electronics, aerospace, and LED lamps. In other interesting study, Pawar et al¹⁶⁹ designed a high-performance electromagnetic wave absorber with high surface resistivity and an enhanced EMI shielding using uneven distribution of nanofiller like MWNTs and magnetic ferrite (Fe₃O₄) nanoparticles decorated reduced GO sheets (rGO-Fe₃O₄) in PC/SAN blends. Poosala et al¹⁷⁰ prepared PC/oxygen-plasma-treated graphene nanoplatelet (OGnP)/MWCNT hybrid composites via a melting blending. Tensile Young modulus of nanocomposites was approximately in the range of 2.5 to 3.0 GPa, higher than that of the neat PC (2 GPa). The PC/OGnP/MWCNT composites having 1.5 to 5.0 phr loading of OGnP-exhibited electrostatic discharge properties. Kumar et al¹⁷¹ studied thermal and mechanical properties of graphene nanoplatelet (GNP) and MWCNT-filled PC nanocomposites fabricated through injection molding. The addition of GNPs and MWCNTs to the PC matrix decreased the yield strength and the elongation at the break of the nanocomposites, while an improvement of 10% to 16% in the elastic modulus was observed with the addition of 2 wt% GNPs and MWCNTs.

8 | PATENTS

Several patents are available on PC/MWCNTs or PC/graphene nanocomposites in literature. The patents taken out over the last 12 years are summarized in Table 5. This table also gives indication of the range of possible uses.

9 | APPLICATIONS OF PC NANOCOMPOSITES

Though PC is being a stronger polymer and this has large number of applications as reported in literature.¹⁹¹⁻¹⁹³ However,

TABLE 5 Patents on polycarbonate nanocomposites

Sr. no.	Patent	Filling Date	Publication date	Applicant	Title
Patents on polycarbonate MWCNTs nanocomposites					
1.	US20040266063 A1	Jun 25, 2003	Dec 30, 2004	Montgomery Stephen W., Faneuf Barrett M., Montgomery Richard W.	Apparatus and method for manufacturing thermal interface device having aligned carbon nanotubes ¹⁷²
2.	US20080187725 A1	Oct 10, 2007	Aug 7, 2008	Exatec, LLC	Functional layers for polycarbonate glazing ¹⁷³
3.	US20080207824 A1	May 24, 2006	Aug 28, 2008	Nanocyl SA	Method for dispersing carbon nanotubes in a polymer matrix ¹⁷⁴
4.	US20090162637 A1	Oct 22, 2008	Jun 25, 2009	Xerox Corporation	Carbon nanotube filled polycarbonate anticurl back coating with improved electrical and mechanical properties ¹⁷⁵
5.	US20090318043 A1	Mar 5, 2007	Dec 24, 2009	Nanoleedge Inc	Method for making polymeric extruded composite products and carbon nanotubes ¹⁷⁶
6.	US20100255185 A1	Nov 25, 2008	Oct 7, 2010	Bayer MaterialScience ag	Method for the production of a conductive polycarbonate composites ¹⁷⁷
7.	US20107811542 B1	Nov 26, 2002	Oct 12, 2010	Unidym, Inc	Carbon nanotube particulates, compositions, and use thereof ¹⁷⁸
8.	US20110054107 A1	Jul 3, 2008	Mar 3, 2011	Idemitsu Kosa Co, Ltd	Flame-retardant polycarbonate resin composition and molded article thereof ¹⁷⁹
9.	US20118044127 B2	Jun 28, 2007	Oct 25, 2011	Idemitsu Kosan Co, Ltd	Thermoplastic resin composition, polycarbonate resin composition, and molded article thereof ¹⁸⁰
10.	U2013S8398949 B2	Sep 11, 2008	Mar 19, 2013	Bayer MaterialScience ag	Carbon nanotube powder, carbon nanotubes, and processes for their production ¹⁸¹
11.	US20148846801 B1	Feb 17, 2011	Sept 30 2014	University of South Florida	Self-healing polycarbonate containing polyurethane nanotube composite ¹⁸²
12.	US20159029458 B2	Feb 28, 2008	May 12, 2015	Arkema Inc	Process and performance aid for carbon nanotubes ¹⁸³
13.	US20160032062 A1	Mar 14, 2014	Feb 4, 2016	XOLVE, INC	Polymer nanocomposites ¹⁸⁴
Patents on polycarbonate graphene nanocomposites					
14.	US20130270188 A1	Mar 15, 2013	Oct 17 2013	Massachusetts Institute of Technology, King Fahd University of Petroleum & Minerals	Graphene-based filter ¹⁸⁵
15.	US20140220290 A1	Oct 16, 2013	Aug 7, 2014	Toshiba Samsung Storage Technology Korea Corporation and Seoul National University R&DB Foundation	Disk for fabricating graphene and method of manufacturing the same ¹⁸⁶
16.	US20140216919 A1	Oct 17, 2013	Aug 7, 2014	Seoul National University R&DB Foundation and Toshiba Samsung Storage Technology Korea Corporation	Method and apparatus for fabricating graphene using a plurality of light sources ¹⁸⁷
17.	US20140272286 A1	Mar 7, 2014	Sep 18, 2014	Lockheed Martin Corporation	Nanoporous membranes and methods for making the same ¹⁸⁸
18.	US20150368439A1	Oct 29 2014	Dec 24, 2015	ENERAGE INC	Graphene polymer composite material ¹⁸⁹
19.	US20150110972 A1	Dec 30, 2013	Apr 23, 2015	Korea Institute of Ceramic Engineering and Technology, Hyundai Motor Company	Graphene-ceramic hybrid coating layer, and method for preparing the same ¹⁹⁰

the combination of PC with conductive nanofillers such as CNTs and graphene has led to several very interesting properties in nanocomposites, which made these nanocomposites as one of the most important material in industrial research. Such nanocomposites would find many practical applications in the manufacture of electronic devices and sensors, as EMI shielding materials to replace metal housings (which are heavier, expensive, and corrosion prone). On industrial scale, melt blending is the most widely used method to produce PC/CNT and PC/graphene nanocomposites.

Figure 6 depicts some of the interesting applications of the PC nanocomposites.

Curran et al¹⁹⁴ studied the ultrahigh electrical conductive properties in PC nanocomposites by mixing the suitable CNTs with PC matrix. As a result, the inexpensive plastic was used to make optical discs with features in military aircrafts to shield them against buildup of electrical charges and pulses, which can lead to significant failures. Additionally, by modifying the amount of CNTs added to the PC-nanotube mix, the EC of the nanocomposite could be increased from that of silicon

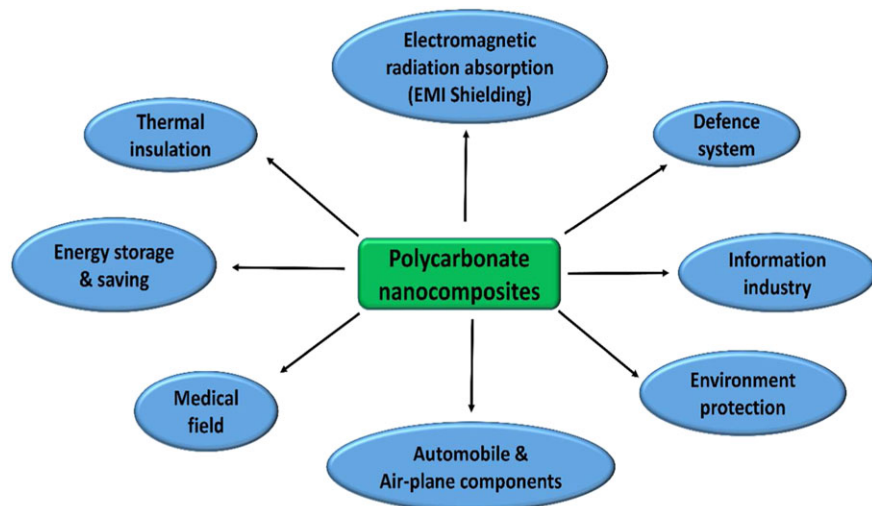


FIGURE 6 Applications of polycarbonate nanocomposites in different fields

to a few orders. These composites with ultrahigh conductivity are used for improving the integrity of electronics in aircraft, iPhones, and computers. The development of this ultrahigh conductive composite material has led to its use in diverse applications ranging from military jets to personal computers and to portable electronic devices. The next level of this research is to develop ink formulations to paint these PC composites onto various electrical components. Generally, metal plates are used to dissipate electrical charge in aircrafts. The development of PC/CNT nanocomposite paintable ink could replace metal plates owing to its lightweight properties. This will finally lead to a much lighter aircraft requiring comparatively lesser fuel. The PC/CNT nanocomposite is used in grounding plug earth pin by replacing brass alloy because PC/CNT nanocomposite grounding pin is recyclable, 80% lighter, and 40% cheaper than brass.¹⁹⁵ PC/CNT membrane has also medical applications. Polycarbonate membrane coated with CNT (CNT scaffold) is used in cell culture.^{196,197} A research group from University of California, Berkeley, prepared light reactive material by using CNTs and PC. They used that material in smart curtains and light-driven motors.¹⁹⁸ PC/CNT nanocomposites are also used as material for connect mobile cases by different companies. Lin et al¹⁹⁹ demonstrated the clean transfer of graphene and suspension by using PC. These high quality surface graphene have high-performance applications in surface chemistry, biotechnology, and high-mobility electronics.

9.1 | Emerging applications of PC nanocomposites

Polymeric biomaterials are also being extensively used for the treatment of various diseases, traumata, and defects in human beings because of ease in their synthesis. As biomaterials have direct contact with the extracellular environment in the biological system, biocompatibility is a topic of great concern. The introduction or improvement of biocompatibility of certain polymers is still a challenge. Polymer biocompatibility can be controlled by surface modification using various physical and chemical methods (eg, chemical and plasma treatment, ion implantation, and ultraviolet irradiation etc.).²⁰⁰⁻²⁰² Different surface and bulk properties of biomaterials are often desirable for biomedical applications. Because extreme UV radiation penetration is quite limited even in low-density medium, it would be possible to use

it for surface modification without influencing the bulk material. The degree of biocompatibility of PC polymer can be controlled by surface modification for various biomedical engineering applications.²⁰³ Tyrosine-derived PC has also been widely used for biomedical applications.²⁰⁴ Authors feel that in future, PC nanocomposites may find applications in the development of artificial organs. However, a considerable amount of research would be required to make this useful nanocomposites biocompatible. Therefore, further research in this area may be extended. Polycarbonate nanocomposites are already finding wide applications in the field of artificial intelligence and robotics because of its strength and transparency.

10 | SCOPE OF FUTURE WORK

PC/CNT or PC/graphene nanocomposites have wide applications in different fields due to amazing properties of these nanoparticles. However, in future, one can synthesize CNTs by using some cheaper precursor such as nonedible seed oil, carbon dioxide, and coal. Graphene can also be prepared by using carbon dioxide, MWCNTs, etc. New method for the preparation of PC nanocomposites with better dispersion of nanoparticles can be developed. Different methods can be used for the functionalization of CNTs and graphene for better dispersion of nanofiller in polymer matrix, which may give excellent properties at lower loading of nanofiller. Metal nanoparticles can be used with these nanofillers for better electrical and EMI shielding properties. Nowadays, researchers are working on foaming of PC/CNT and PC/graphene nanocomposites because foamed nanocomposites are lighter in weight and have better properties than nonfoamed nanocomposites. Different foaming techniques can be used for the formation of PC nanocomposite foam. Polycarbonate is also one of the important polymers, which have been used for manufacturing of the robots, and the application of this polymer in the robotics field can become very wide by preparing different nanocomposites.²⁰⁵ Therefore, the PC nanocomposites would offer a wide scope in their applications in the robotics where several different types of robots would be required for the wide range of applications to mimic the human actions especially where human cannot go. Another emerging area of the application of PC nanocomposites could be in the

field of development of artificial organs where the surface properties of these nanocomposites may have to be modified, and there is a wide scope of research in this area also.

11 | CONCLUSIONS

CNT and graphene are the excellent nanofillers in polymer nanocomposite material system. Structures of polymer nanocomposites is found to be significantly lighter and stronger than conventional material, ie, aluminum, alloys, and CF-filled polymer nanocomposites. Multifunctional structural materials have been synthesized using CNT and graphene because of the tremendous electrical, mechanical, thermal, magnetic, and optical properties. Therefore, nowadays, CNT and graphene-based polymer composites have gained so much interest among researchers, which result in the number of publication in this area. New technologies have been explored for CNT and graphene nanocomposite processing, and existing technologies should be upgraded to control the dispersion and orientation of the CNTs and graphene in the polymer matrix. The field of materials science is currently undergoing a shift from developing traditional materials such as metals, ceramics, polymers, and composites to a more revolutionary trend of developing nanostructures, which are functionalized, self-assisting, and occasionally even self-healing materials. In this article, we reviewed various studies performed on processing and different properties of CNT and graphene-based PC nanocomposites and also the applications, opportunities, and new challenges that have emerged that also need to be addressed, along with the challenges of dispersion, load transfer, and alignment of nanofiller. The mechanical, electrical, and EMI shielding properties of these nanocomposites are studied in detail. Here, we also discussed about the sequestration of CO₂ for synthesis of PC. We hope this review will be helpful for those researchers who are working in this field.

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