Conclusions and future scopes

Highlights

The entire work of the thesis is tried to summarize in this chapter. The conclusion and most significantly the future scopes of the present works are highlighted here.

7.1. Summary and conclusions

The thesis is devoted to the development of waterborne hyperbranched polyester (WHPE) and its carbon-based nanocomposites for different potential applications. The works assemble in the thesis disclose a number of attractive observations, achievements and scopes for future works. The effect of inclusion of different nanomaterials like graphene oxide (GO), carbon dot (CD) and CD-based nanohybrids on the properties of WHPE nanocomposites was widely investigated. The thesis is divided into seven chapters. The first chapter illustrates a general introduction and concise review on polyesters (both waterborne and solvent borne), carbon-based nanomaterials especially GO, CD and its nanohybrids as well as their nanocomposites. The chapter mostly highlights the importance, preparation and characterization techniques of different polyesters and their nanocomposites. The scopes, objectives and plan of the present work are also mentioned in this chapter.

The second chapter of the thesis describes the synthesis of aliphatic WHPE and aliphatic and aromatic moiety containing WHPE. This chapter was divided into two sub-chapters, where the first chapter deals with the synthesis of WHBP through polycondensation reaction using aliphatic and aromatic moieties containing glycerol based hyperbranched polyol as a branch generating moiety along with other easily available reactants in the absence of solvent, catalyst and neutralizing agent. On the other hand, second chapter demonstrates the synthesis of WHPE using three different branch generating moieties such as citric acid, 2, 2-bis(hydroxymethyl)propionic acid and glycerol by using the same synthetic protocol. The characterization and evaluation of mechanical, thermal and chemical properties along with biodegradability behavior of both the polyesters were described in this chapter. Glycerol based epoxy and poly(amido amine) cured WHPE polyesters exhibited good mechanical, thermal and chemical properties along with excellent biodegradability.

Again, to address the shortcomings of WHPE, different nanocomposites were fabricated using various types of carbon-based nanomaterials. These works were presented in four consecutive chapters namely, Chapter 3, 4, 5 and 6. The third chapter of thesis deals with the fabrication, characterization and property evaluation of functionalized GO-based WHPE nanocomposites. GO was first functionalized with toluene diisocyanate and 1, 4-butanediol and incorporate in WHPE matrix through in situ polymerization technique in absence of solvent and compatibilizing agent. They showed significant improvement in mechanical and thermal properties along with good biodegradability behavior. Further, it was used as a heterogeneous catalyst for Aza-Michael addition reaction.

The fourth chapter describes fabrication, characterization and property evaluation of highly fluorescent CD-based WHPE nanocomposites. The nanocomposite showed improvement in mechanical, rheological and thermal properties along with excellent biodegradibility behavior against both gram-positive and gram-negative bacterial strains. Further, the nanocomposites exhibited wavelength dependent both down- and up-conversion photoluminescence properties as well as emitted different colors on exposure of different wave lengths of UV light. The thermosets of the nanocomposites were highly transparent under visible light and also demonstrated self-cleaning activity towards the removal of organic pollutants like formaldehyde and methylene blue on exposure of normal sunlight.

The fifth chapter demonstrates the fabrication of WHPE nanocomposites by the inclusion of clay@CD nanohybrid as well as their characterization and evaluation of different properties. The development of these nanocomposites not only showed improvement in mechanical and thermal properties but also exhibited good adsorption capacity for Pb(II) ion. They also retained the transparency of the thermosetting nanocomposite and showed good photoluminescence behavior. Further, they were found to be highly biodegradable against gram negative bacterial strain.

The field of WHPE nanocomposites was further extended by the incorporation of CD@TiO_2 nanohybrid into the polyester matrix. The works on these nanocomposites are described in sixth chapter. This chapter contains two sub-chapters, where the first sub-chapter describes the synthesis, characterization and property evaluation of CD@TiO_2-based nanohybrid. Subsequently, second sub-chapter demonstrates the fabrication of CD@TiO_2-based WHPE nanocomposites. It also deals with characterization and evaluation of different properties of the nanocomposite. The nanocomposite not only exhibited excellent mechanical, optical and thermal properties but also introduce some special properties like anti-reflecting, anti-icing, anti-fogging, self-cleaning, antibacterial, anti-counterfeiting, etc. Further, the nanocomposite also showed good photocatalytic activity towards the reduction of 4-nitrophenol under visible light. Further, it was also used for separation of crude oil and water from their mixture with excellent removal efficiency. Thus, from the present works following conclusions can be briefed.

(i) The unique hyperbranched architecture with the unison of aromatic-aliphatic moieties can offer high performing tough waterborne polyester to overcome the shortcomings of solvent borne polyester.

(ii) The amount and nature of branch generating moieties of WHPE strongly influence the ultimate performance of the thermosets.

(iii) The water solubility of polyester can be achieved without using any neutralizing agent by proper choice of the reactants.

(iv) Solvent and catalyst free synthesis of WHPE makes the process environmentally benign.

(v) Incorporation of functionalized GO into WHPE matrix showed significant improvement in mechanical and thermal properties. Further, the nanocomposite can be used as an efficient heterogeneous catalyst for Aza Michael addition reaction.

(vi) Further, highly fluorescent and transparent thermosets of WHPE can be achieved by the incorporation of CD into the polyester matrix. The CD-based nanocomposite also exhibited enhancement in mechanical, thermal and chemical properties as well as in biodegradability behavior. Most interestingly, they showed self-cleaning activity by photocatalytically degrading organic pollutants under visible light.

(vii) Excellent performance, photoluminescent behavior and good adsorption capacity of Pb(II) ions can be achieved by inclusion of clay@CD nanohybrid in WHPE.

(viii) Incorporation of CD@TiO_2 nanohybrid into WHPE matrix not only resulted improvement in mechanical, thermal and rheological properties but also imparted interesting attributes like anti-icing, anti-fogging, antibacterial, anti-reflecting and anti-counterfeiting abilities. They also enhanced the photocatalytic activity of the nanocomposites and showed excellent self-cleaning activity. Further, they can be used as photocatalyst for reduction of 4-nitrophenol. In addition, they can be utilized for separation of crude oil and water from their mixture.

Therefore, it can be concluded from this research that the studied nanocomposites have strong potential to be used as multi-functional materials for different advanced applications.

7.2. Future directions

The thesis presented a comprehensive and systematic study on environmentally friendly WHPE nanocomposites. Although, these study presents number of prospective applications, still there are enough future scopes for further studies in the field. Some of these scopes are underlined below.

(i) Sustainable similar polyesters with tuneable mechanical properties can be used as tissue engineering scaffolds. Hyperbranched polyesters with unique physicochemical and biological properties have a high efficiency to encapsulate bioactive agents including genes, drugs and proteins owing to their globular nanostructure. Thus, these types of highly branched polyester can be utilized for different biomedical applications.

(ii) GO-based different nanohybrids can be fabricated using different metal and metal oxide nanoparticles and subsequently be used to produce WHPE nanocomposities. These nanocomposites can be utilized for different potential applications including catalysis, supercapacitors, solar cells, etc.

(iii) CD-based WHPE nanocomposites can also be used in the field of bio-imaging, as well as tissue engineering.

(iv) CD-based nanohybrids can be fabricated using other metal and metal oxide nanoparticles like silver, platinum, gold, palladium, iron oxide, zinc oxide, copper oxide, etc. and the nanohybrid can further be used for fabrication of WHPE nanocomposites. These nanocomposites can be utilized in different advanced applications such as solar cells, supercapacitors, catalysis, sensors, electrocatalysis, electrochemical oxidation of water, etc.

(v) The study on biodegradability, antibacterial activity and self-cleaning properties of similar WHPE nanocomposites can be further conducted using different other types of bacterial strains, microbes and organic and inorganic pollutants, respectively. Also, these properties can be studied extensively and systematically.

(vi) Different models and theoretical studies can be performed to understand the anti-icing and anti-fogging behaviors of WHPE nanocomposites.

(vii) The nanocomposite can be further utilized for some other important organic transformations as a heterogeneous catalyst.