Conclusion and future scopes

Highlight

In this chapter, entire work of the thesis is summarized. Each chapter is briefed about the findings of the investigation wisely, with conclusions drawn based on the results. The chapter also attempts to portray the future endeavors of the current study that might be performed for further investigation in the domain of high performing, smart starch modified hyperbranched polyurethane nanocomposites and their potential applications.

7.1. Summary and conclusions

The thesis explicates the development of starch modified hyperbranched polyurethane (HPU) and its nanocomposites, modified with various carbon-based nanomaterials, for potential advanced applications, in domains stretching from biomedical to material science. The work systematized in the thesis is dedicated to captivating studies, accomplishments and possibilities for the time to come. The achievements of incorporating various carbon-based nanomaterials like reduced graphene oxide (RCD), carbon dot (CD), reduced carbon dot (RCD) and their nanohybrids, on the attributes of HPU nanocomposites were explored broadly. **Chapter 1** is a brief write-up on polyurethane, with noteworthy significance on its hyperbranched architecture, and its nanocomposites modified with different carbon based nanomaterials. The chapter predominantly presents a crisp explanation on the significance, preparation and characterization methods, attributes and prospective appliances of hyperbranched polyurethane and its nanocomposites. The opportunities, aims and plans of the current work were established in pertinence to the significance of the planned investigation.

Chapter 2 of the thesis depicts the synthesis and characterization of starch modified hyperbranched polyol, and its subsequent utilization in the synthesis of HPU, as a branch generating moiety, via an $A_x + B_y$ (x, y $\geq$ 2) technique, without employing any plasticizers or catalysts. The synthesized HPU was characterized by various spectroscopic and analytical techniques, and evaluated for its properties and prospective applications. The polymer demonstrated outstanding mechanical and thermal attributes, with exceptional shape recovery (near body temperature) and noteworthy biodegradability. Moreover, the biocompatibility of the synthesized polymer was substantiated by cell proliferation and live/dead cell viability assays. Therefore, the findings of the chapter promoted the tough starch modified polyol based HPU with profound biodegradability and biocompatibility as an exceptional physiological temperature responsive shape memory polymer in the realm of biomedical.

Yet again, fabrication of different HPU nanocomposites with diverse carbon based nanomaterials was attempted, in the pursuit of strengthening the pioneering demands of polymer industry. The work is recounted in five successive chapters, to be precise, **Chapter 3**, **Chapter 4**, **Chapter 5** and **Chapter 6**.

Chapter 3 substantiates the fabrication, characterization and property determination of HPU nanocomposites modified with a facile one-pot synthesized carbon dot-silver (CD-Ag) nanohybrid. The chapter deals with the preparation and characterization of CD-Ag nanohybrid, and its consequent incorporation in the *in situ* fabrication of HPU nanocomposite. The fabricated HPU nanocomposite was characterized and evaluated for its various properties as a rapid self-expandable stent. The study demonstrated that upon considerate choice of the loading of nanohybrid, the fabricated nanocomposite exhibited significant thermal and mechanical properties, along with, remarkable shape memory and self-expandable behavior, near body temperature. The antibacterial activity of the nanocomposite films against bacterial strains of *Escherichia coli* MTCC 40 and *Staphylococcus aureus* MTCC 3160 authenticated their potential to prevent formation of biofilm. Differentiation and cell proliferation of smooth muscle cells and endothelial cells verified the cytocompatibility of the nanocomposite. Hence, the above results confirm the tremendous potential of the fabricated nanocomposite as a rapid self-expandable stents, to triumph over the restrictions of the conventional stents for potential endoscopic surgeries.

The continuum of HPU nanocomposites was further explored by modification with RCD in **Chapter 4**. The chapter is divided into two sub-chapters, **Sub-Chapter 4A** being the description of the facile one-pot synthesis of bio-based RCD and its characterization and potential applications. **Sub-Chapter 4B** being the account of the fabrication of the starch modified HPU with RCD by an *in situ* technique and its characterization using different analytical and spectroscopic methods. The fabricated nanocomposite displayed good biodegradability and remarkable shape recovery and self-tightening behavior near body temperature. The nanocomposite films demonstrated significant thermal and mechanical properties as well as hemocompatibility via assessment of hematological parameters. Moreover, the nanocomposites showed potential for future *in vivo* animal trials by its minimal *in vitro* immune response. Therefore, the nanocomposite supports the revelation for the development of rapid self tightening polymeric sutures to prevail over the limits linked with the normally utilized conventional sutures.

Additionally, a starch modified HPU nanocomposite was *in situ* fabricated with RCD-zinc oxide nanohybrid that was synthesized by a facile one-pot technique. The nanocomposite degraded an anionic surfactant and a commercial detergent in aqueous medium using solar light irradiation. Furthermore, the nanohybrid loading tailored the thermal and mechanical properties of the nanocomposites. Thus, the nanocomposite has the potential to be used as a solar light assisted recyclable photocatalyst for environmental remediation. The work was discussed in **Chapter 5**.

Chapter 6 explains the fabrication of reduced graphene oxide-silver-reduced carbon dot nanohybrid (RGO-Ag-RCD) within the starch modified HPU matrix by in situ technique. The nanocomposite exhibited dose dependent improved thermal and mechanical properties as compared to the pristine HPU, upon incorporation of RGO-Ag-RCD nanohybrid. The nanocomposite also demonstrated efficient degradation of different organic pollutants like rhodamine B, aniline and ethyl paraoxon organophosphate, under sunlight. Moreover, the nanocomposite exhibited remarkable microwave and sunlight induced rapid shape recovery and self-healing. Therefore, the striking attributes of the fabricated nanocomposite validates its employment as a high performance, multifunctional smart material with photocatalytic activity to resolute environmental issues like waste management.

Hence, the subsequent conclusions can be drawn from the current work:

(i) The study shows that HPU can be produced by using a starch modified hyperbranched polyol as a branch generating moiety, along with other conventional reactants. Employing such naturally obtained polyol compounds like starch is valuable in tackling major challenges varying from bio-disposability to sustainability.

(ii) The study bestows upon the fact that incorporation of the starch modified hyperbranched polyol as a branch generating moiety can help develop a high performance HPU system with smart attributes and biodegradability.

(iii) Carbon based nanomaterials can be employed as nano-reinforcing agents for the efficient enhancement of mechanical and thermal stabilities of the pristine HPU. Significantly, the toughness of HPU can be improved strongly owing to the combined increase in tensile strength and elongation at break, upon formation of the nanocomposites.

(iv) Remarkable smart attributes like shape recovery, self-expandability, self-tightening etc. can be attained upon incorporation of the carbon based nanomaterials, near body temperature.

(v) Infection resistant HPU nanocomposites and biocompatible can be obtained by incorporation of CD-Ag nanohybrid in the pristine HPU. The study conferred that HPU nanocomposite with CD-Ag nanohybrid can demonstrate self expandable behavior near body temperature and thus have the prospect to be utilized as a rapid self-expandable stent in endoscopic surgeries.

(vi) Incorporation of RCD nanomaterial within the HPU matrix can impart biocompatibility and display self-tightening behavior near body temperature which forwards such nanocomposites to be utilized as self-tightening suture for endoscopic surgeries.

(vii) Outstanding self-cleaning activity and self-healing behavior, under external stimuli such as microwave and sunlight, can be achieved upon fabrication of tough HPU nanocomposites using RGO-Ag-RCD nanohybrid. Such combined attributes of toughness, self-healing and self-cleaning can help to overcome the limitations of a high performing material.

(viii) HPU/RCD-zinc oxide nanocomposite can degrade anionic surfactants and detergents in aqueous medium using solar light irradiation. Thus, the nanocomposite can be utilized as a recyclable photocatalyst for environmental remediation.

7.2. Future directions

The thesis presented a systematic and comprehensive investigation on high performance starch modified HPU nanocomposites with carbon based nanomaterials. Nevertheless, the work may ascertain a proposal for future research, relevant for the advancement of such multifunctional smart materials. The current study may cover prospects for future research under the following perceptions:

(i) Improvement of the pristine starch modified HPU system with more than 50 wt% of starch modified hyperbranched polyol.

(ii) Life cycle assessment study of the developed materials.

(iii) Detailed study on the antimicrobial and biocompatible attributes of the nanocomposites using various microbes.

(iv) Extensive and systematic study on the photocatalytic degradation of organic contaminants by the nanocomposites.

(v) Employment of various contact and non-contact stimuli such as electric field, infra-red light, electricity etc. for shape memory and repeatable self-healing behaviors of HPU nanocomposites.

(vi) Testing the fabricated nanocomposites for *in vivo* study using animal specimens for biomedical applications.