Summary & Future Scope

Highlight

This chapter delivers a crisp and concise summary of the results of the current investigation. The results of the current investigation are presented in a chapter-wise briefing and concluding remarks are drawn based on the results. In addition, the chapter also addresses the future directions offered by the current investigation towards exploration and innovation of renewable resources and nanomaterials in development of renewable resources derived HPU and its nanocomposites.

7.1. Summary

The thesis elucidates the development of renewable resources derived hyperbranched polyurethane (HPU) and its nanocomposites for multi-faceted applications. The thesis comprises of seven chapters. **Chapter 1** presents a concise account of PU, with special emphasis on its hyperbranched architecture and their nanocomposites with different kinds of nano-dimensional materials. The chapter acknowledges the adaptability of renewable resources as eco-friendly and economically viable PU precursors in development of HPU nanocomposites (HPUNCs). A brief outline on the significance, preparation, characterization, properties and potential applications of HPU and their nanocomposites is put forward in this chapter. Ultimately, the objectives and plan of the proposed study are framed in relevance to the scope and opportunities of the current scenario.

Chapter 2 of the thesis describes the synthesis and characterization of castor oil modified polyol, and its subsequent employment as a branch generating moiety in the synthesis of HPU. The synthesis of HPU was achieved by pre-polymerization technique using $A_x + B_y$ ($x, y \geq 2$) approach, without employing any catalyst. The synthesized HPU was characterized by various spectroscopic and analytical techniques, and screened for notable properties and applications. The hyperbranched polymer displayed appreciable mechanical, thermal and chemical properties compared to its linear counterpart. In addition, the polymer exhibited excellent shape memory, profound biodegradability and exceptional UV-light stability. The overall results promotes optimism towards development of renewable resource based HPU as a biodegradable and UV-resistant smart material.

In a bid to improve the material aspects of HPU, and meet the modern-day demands of high performance applications, fabrication of HPUNCs with carbon based nanomaterials was proposed and accomplished. The following chapters, *viz.* **Chapter 3**, **Chapter 4**, **Chapter 5** and **Chapter 6**, present the development of different HPUNCs for multi-faceted applications. **Chapter 3** describes the fabrication, characterization and property evaluation of HPUNC with aluminium hydroxide-reduced graphene oxide nanohybrid (AH@rGO). The chapter details the preparation and characterization of AH@rGO nanohybrid, and its consequent incorporation in the *in situ* fabrication of HPUNC. The fabricated nanocomposite was characterized by various spectroscopic and microscopic techniques. Different compositions of the nanocomposite were fabricated by varying the loading of the nanohybrid. The nanocomposites demonstrated remarkable enhancement of mechanical and thermal properties, in comparison to the pristine HPU. Notably, the nanocomposites were found to exhibit excellent multi-stimuli responsive shape memory attribute under thermal energy, microwave and sunlight. The study revealed that the inclusion and loading of AH@rGO was instrumental in achieving such multi-faceted performance of the HPUNC. The overall results put forth the potential of the developed nanocomposite for advanced shape memory applications.

Chapter 4 describes the fabrication, characterization and property evaluation of HPUNC with silane-modified GO (Si-GO) nanomaterial. The chapter explains the preparation and characterization of Si-GO and its utilization towards *in situ* fabrication of HPUNC in different loadings. The nanocomposites were characterized by different spectroscopic and microscopic techniques. The fabricated nanocomposites displayed significant improvements in mechanical, thermal and chemical properties, in comparison to pristine HPU. Remarkably, the nanocomposites exhibited excellent self healing ability under microwave and sunlight as stimuli, as well as surface hydrophobicity without any external surface modifications. The overall results holds good promise for the development of such high performance polymeric materials for self healing and self cleaning applications.

Chapter 5 is conveniently divided into two sub-chapters, Chapter 5A and Chapter 5B, to showcase functional nature of metal/CQD nanohybrid and its suitability in formation of HPUNC. **Chapter 5A** details the preparation of Pd-Ag@CQD nanohybrid by a facile photo-assisted process using CQD as a key component, and its characterization by various sophisticated analytical tools. The chapter vividly covers the performance of the bimetallic-cum-carbonaceous nanohybrid as an efficient heterogeneous nanocatalyst for catalytic enhancement of C-C cross coupling reaction under ligand-free and ambient conditions. **Chapter 5B** illustrates the fabrication of HPUNCs with Pd-Ag@CQD nanohybrid in various loadings by an *in situ* technique and their characterization using different spectroscopic and analytical methods. The fabricated nanocomposites displayed loading-dependent enhancement of mechanical and thermal properties, in comparison to pristine HPU. Strikingly, the nanocomposite demonstrated exceptional efficiency as a high performing heterogeneous catalyst for rapid oxidative *ipso*-hydroxylation of aryl boronic acids to phenols. The overall results augur well for crafting high performance HPUNCs for catalytic applications in direct organic transformations.

Chapter 6 elucidates the fabrication, characterization and property evaluation of HPUNC with oxygeneous g-CN nanodot (oxy-g-CND). The chapter details the preparation and characterization of oxy-g-CND and its *in situ* nanocomposite fabrication with HPU. The nanocomposites were characterized by various spectroscopic, microscopic and analytical techniques. The fabricated nanocomposites showed enhancement of mechanical and thermal properties, consistent with the loading of the nanomaterial. Remarkably, the nanocomposite exhibited excellent optical photoluminescence property, which can be an attractive innovation among photoluminescent polymeric materials. Additionally, the nanocomposite displayed the trait of solar light harvesting material and mesoporous architecture to perform well as a heterogeneous metal-free photocatalyst for oxidation-reduction reactions with high efficiency. The striking attributes of the fabricated HPUNCs advance the development for such high performance material towards anti-counterfeiting and photocatalytic applications.

The final chapter, **Chapter 7**, presents a summary of the significant findings of the current work and conclusion. Finally, the chapter delivers a future prospect of the current work.

The significant findings of the current investigation can be briefly summarized in the following points:

(i) The study shows that a castor oil modified polyol can be utilized as a renewable resource for the synthesis of HPU, along with other conventional reactants. Employment of such renewable resource provides a suitable approach for addressing socio-economic and environmental concerns like material safety, bio-disposability, etc.

(ii) The study shows that incorporation of the castor oil modified polyol as a branch generating moiety can help to develop HPU with shape memory attribute, UV-light stability and biodegradability.

(iii) The study confirms the suitability of carbon based nanomaterials as effective nano-reinforcing agents for the improvement of mechanical and thermal stabilities of the pristine HPU.

(iv) The study substantiates the tunability of carbon based nanomaterials like GO and rGO in developing HPUNC for multi-faceted applications. Appreciable material property and remarkable smart attributes like shape memory, self-healing and self-cleaning can be achieved by employing tunable carbon based nanomaterials as nano-reinforcing agents.

(v) The study shows a facile way of synthesizing nanohybrid of CQD with heavy metals like Pd and Ag, and the utility of the nanohybrid in developing HPUNC with catalytic applications in organic synthesis.

(vi) The study shows the aptness of g-CN as a nanomaterial to develop HPUNC with optical and photocatalytic attributes. Incorporation of oxy-g-CND in HPU evokes photoluminescence property and solar light driven-photoactivity that can be exploited for anti-counterfeiting applications and photocatalytic applications, respectively.

Thus, the current investigation illustrates the innovation of renewable resource in synthesis of HPU and the role of nanotechnology-based modifications in development of renewable resource derived HPUNCs. The overall results showcase their potential as high performance materials for multi-faceted advanced applications.

7.2. Future scopes

The thesis compiles a comprehensive study on eco-friendly high performance HPUNCs for potential applications. However, the current work may open up several possibilities and options for future research, which could be relevant for the development of such polymeric materials. The current work may provide a platform for future discourse under the following perspectives:

(i) Development of renewable resource based diisocyanate for synthesis of polyurethane,

(ii) Upgradation of the developed renewable resources based polymeric material with more than 50 wt% renewable resource content,

(iii) Life cycle assessment study of the developed nanomaterials and nanocomposites,

(iv) Enhancement of optical properties of CQD and g-CN by doping or functionalization or nanohybrid systems,

(v) Utilization of CQD and g-CN based polyurethane nanocomposites for opto-electronic, photo-sensing and photo-catalytic applications, etc.