Sustainable Waterborne Poly(ester amide) Nanocomposites and Their Potential Applications

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Chapter 6

Summary and future scopes

Highlights

This chapter succinctly encapsulates all the findings of the contemporary investigation. In turn, each section presented a comprehensive overview, culminating in decisive conclusions drawn from the obtained results. Furthermore, the chapter delves into the future avenues for advancing bio-based poly(ester amide) nanocomposites, thereby promising continued exploration and innovation in this field.

6.1. Summary and conclusion

The thesis elaborates on the synthesis of a bio-based poly(ester amide) material and its carbon-based nanocomposites tailored for various prospective uses in different genres. In this context, the thesis is structured into six distinct chapters. **Chapter One** provides a comprehensive overview of the gradual development of bio-derived poly(ester amide)s, thereby drawing instances from the existing state-of-the-art literature reports. It identifies the gaps persisting in the field of environmentally friendly poly(ester amide)s and proposes potential as well as rational solutions, such as carrying out the incorporation of suitable sustainable strengthening materials or reinforcing agents. The chapter also briefly covers the established protocols for carrying out synthesis of the polymeric material followed up by extraction, production, characterization, and enumeration of properties of poly(ester amide)s along with the bio-based reinforcing units and nanocomposite systems. In turn, the chapter outlines the scopes, goals, and planned approaches for the present investigation, taking into consideration the significance of the work in the current scenario.

Chapter Two highlights the synthesis of a bio-based waterborne poly(ester amide) by invoking an environmentally benign route of preparation devoid of usage of any amount of organic solvent. Citric acid, glycerol, and hexamethylenediamine were considered as the key reactants to carry forth the synthesis via a melt polycondensation technique. The inherent structural intricacies of the prepared polymeric resin were assessed using the available spectroscopic and analytical methodologies. In turn, poly(vinyl alcohol) was eventually added to carry out further modifications in the matrix. Different compositions of polymeric resin/ poly(vinyl alcohol) were subsequently prepared and their properties, viz., thermal, mechanical, chemical resistance, transparency, and biodegradability attributes were explicitly recorded.

As stated earlier, poly(ester amide)s belong to a unique group of polymers, and their inherent properties can be adjusted by modifying their chemical structures. **Chapter Three** presents the entire plot of the synthesis of poly(ester amide urethane) resin, prepared to address the limitations and introduce new characteristics to the poly(ester amide) framework. In this study, different compositions of poly(ester amide urethane) were created by altering the proportions of isophorone diisocyanate. The structural analysis of the resulting polymer was conducted using various methods, including FTIR, XPS, and

PXRD. It was observed that the polymer samples displayed impressive elongation at break values, indicating the resilient elastomeric nature of the material. Diverse aging tests were carried out to evaluate the material's durability under challenging environmental conditions. The materials showed significant improvements in tensile strength parameters after exposure to various aging conditions such as heat and UV radiation. This suggests their potential as robust materials suitable for outdoor applications. Furthermore, the materials exhibited notable biodegradability and demonstrated significant compatibility with biological systems, enhancing their potency for diverse utilities.

In contemporary times, biochar, a carbon-rich material derived from organic sources, has gained attention as an eco-friendly solution for environmental challenges. **Chapter Four** deals with the fabrication of biochar from commercial Kraft lignin via pyrolysis. Lignin is considered as an attractive feedstock for carbonization purposes owing to its facile availability, low cost, and renewability. In addition, the synthesized biochar was used as a reinforcing agent in poly(ester amide urethane) material. The latter was prepared by invoking a melt polycondensation technique via an environmentally benign route. The biochar/poly(ester amide urethane) nanocomposites were further fabricated by varying the weight percentages of biochar material inside the polymer matrix. Furthermore, these systems proved to be quite efficient in carrying out dye removal. The synergy between biochar and poly(ester amide urethane) enhances the dye adsorption capacity and overall performance of the nanocomposites. The porous nature of biochar provides ample binding sites for dye molecules, while the poly(ester amide urethane) matrix offers mechanical support and stability. This approach not only addresses water pollution challenges but also utilizes bio-based materials, contributing to a greener and more sustainable future.

Chapter Five of the thesis elucidates the synthesis of another nanocomposite unit, fabricated by integrating bentonite nanoclay and modified biochar particles. Biochar particles underwent significant chemical modification by carrying out a reaction of the hydroxyl groups present at the periphery with epichlorohydrin and triethylamine. Subsequently, the nanocomposite units synergistically amalgamated the distinctive attributes of biochar, clay, and poly(ester amide urethane), yielding a multifunctional material endowed with exceptional adsorptive capacities.

Biochar, a product of organic material pyrolysis, endows the nanocomposite material with a substantial surface area and a porous matrix conducive to entrapping heavy metal ions. The inclusion of clay minerals, recognized for their cation exchange proficiency, further augments the adsorption potential of these nanocomposite units. Simultaneously, poly(ester amide urethane) integration serves to consolidate the composite structure, while introducing customizable physicochemical properties. Thus, this proficiently engineered system adeptly captured heavy metal ions such as lead, zinc, and copper from aqueous media, ameliorating the inherent perils associated with these pernicious contaminants.

Chapter Six, that is the present chapter concisely outlines the summary and conclusions derived from the current study, while also highlighting the forthcoming directions for further research.

The principal accomplishments of this endeavor are outlined as follows:

- ☑ The study enumerated the successful preparation of a bio-derived poly(ester amide) material via a melt polycondensation reaction between citric acid, glycerol, and hexamethylenediamine by a facile mode of preparation.
- ☑ The synthesized polymeric films demonstrated splendid mechanical attributes along with satisfactory thermal stability. Additionally, they exhibited biodegradability on exposure to accelerated bacterial environments as well as possessing excellent transparency parameters.
- ☑ Poly(ester amide urethane) polymeric materials displayed excellent elongation at break values coupled with remarkable toughness values. They rendered the traits of a sturdy elastomeric material.
- ☑ They also exhibited cytocompatibility features along with biodegradability traits. In turn, they served the purpose of a weathering-resistant structural material.
- ☑ Biochar was successfully synthesized from Kraft lignin via the pyrolysis technique. The formation of biochar was substantiated using different analytical and spectroscopic methods.
- ☑ Biochar was successfully integrated into the poly(ester amide urethane) matrix via an *in-situ* mode of application. Moreover, these biochar-infused polymer matrices exhibited increment in toughness parameters with significant improvement in the thermal stability parameters.

- ☑ These biochar-integrated nanocomposites exemplified good dye adsorption capacities.
- ☑ Modified biochar was prepared by using epichlorohydrin and triethylamine. Furthermore, this modified material was used as a nanoreinforcing agent in the poly(ester amide urethane) matrix.
- ☑ Successful fabrication of bentonite nanoclay/modified biochar poly(ester amide urethane) nanocomposite was carried out which was further confirmed by conducting various instrumental analyses.
- ☑ These nanocomposite materials demonstrated good adsorptive capacities towards heavy metal ions, especially lead metal ions.

Therefore, the present study shows the pathways for the formation of environmentally benign poly(ester amide) and its nanocomposites with different potential applications.

6.2. Future scopes

The thesis presents a thorough and systematic evaluation of environmentally friendly poly(ester amide urethane) nanocomposites, thereby highlighting their diverse potential applications. Moreover, this work identifies several avenues for future research within the realm of polymeric materials. Some of these prospects include:

- ☑ Exploration of different resources apart from citric acid and glycerol such as succinic acid, sebacic acid, 11-aminoundecanoic acid, etc. can be carried out to synthesize various poly(ester amide)s.
- ☑ Synthesis of sustainable and eco-friendly poly(ester amide)s with biological properties for applications in biomedical fields, viz. drug delivery systems, tissue engineering scaffolds, bio-imaging, etc. can be carried out.
- ☑ Fabrication of other propitious meso as well as nano structures can be executed via various environmentally friendly approaches.
- ☑ Various clinical trials can be conducted in order to assess the toxicity levels of the polymeric material as well as the nanocomposites.
- ☑ Investigation into modification of biochar material using different activating agents can be conducted along with their utilization in different domains.

- ☑ Assessments of environmental repercussions of the polymeric material along with their nanocomposites using various risk assessment, life cycle assessment studies, etc. can be carried out.