Chapter 6

Conclusions and Future Scopes

Conclusions

This thesis investigated the performance of various surface modified NFRECs. The current study shows that applying different chemical treatments and polymer coatings to the natural fibers has a significant influence on the fiber and its epoxy composites' morphological, chemical composition, thermal, mechanical and tribological properties. The investigation came to the following conclusions based on the experimental findings of the physical, thermal, water absorption, mechanical and tribological characterization of natural fibers and NFRECs.

6.1 Physical and thermal characterization of natural fibers

6.1.1 Physical characterization of chemically treated hemp fibers

- The SEM images of the hemp fiber surface confirmed that both the sodium carbonate treatment (ST) and peroxide treatment (PT) had removed the surface impurities sticking to the fiber surface.
- Fourier transform infrared analysis confirmed the removal of hemicellulose and lignin content of the hemp fiber after both the sodium carbonate and peroxide treatment.
- Both the ST and PT hemp fibers have a higher crystallinity index in comparison with UT fibers, and the highest crystallinity index was obtained for PT hemp fiber.

6.1.2 Physical characterization of polymer coated hemp fibers

- SEM photographs of the hemp fibers revealed that the prior treatment of sodium hydrogen carbonate and both the polymer (PHB and PLA) coating had removed the surface impurities and made the surface rough, respectively.
- Crystallinity index of polymer coated fibers was found to be higher than the uncoated fibers and the highest crystallinity index was obtained for PLA coated hemp fibers.

6.1.3 Physical characterization of glutamic acid treated sisal fibers

- SEM images showed that the waxy substances and other impurities got removed from the fiber surface through alkali treatment. The existence of a covering on the glutamic acid treated fiber surface can be seen in the SEM image. This concluded that the glutamic acid got deposited on the fiber surface.
- Chemical treatment also resulted in the improvement of the crystallinity index of sisal fibers. AGT (alkali+glutamic acid) sisal fiber showed the highest crystallinity index followed by AT (alkali), GT (glutamic acid), and UT (untreated) sisal fiber.

6.1.4 Physical and thermal characterization of eco-friendly chemically treated sisal fibers

- The application of both stearic acid and sodium citrate treatments on the sisal fiber surface can result in considerable reductions in surface impurities such as wax, dirt, and other contaminants, according to SEM results of the fiber surface.

- The elimination of amorphous components from the fiber after chemical treatments is confirmed by FTIR analysis.
- The thermal stability of fibers got marginally reduced after chemical treatment. However, stearic acid treated fibers showed better thermal stability than sodium citrate treated fibers.

6.1.5 Physical characterization of chemically treated jute fibers

- SEM photographs revealed that the waxy substances and other impurities were eliminated from the jute fiber surface by chemical modification.
- Fourier transform infrared analysis of the chemically treated jute fiber affirmed the partial elimination of non-crystalline agents like hemicellulose and lignin content from the fiber surface.
- Chemical treatment has raised the crystallinity index of jute fibers. Sodium carbonate treated jute fiber exhibited the maximum increase in crystallinity index, followed by alkali, sodium hydrogen carbonate and untreated jute fibers.

6.2 Water absorption, mechanical and tribological performance of NFRECs

6.2.1 Moisture accumulation and mechanical behaviour of chemically modified HFREC

- The water resistance of HFREC increased significantly for treated HFREC, and the best resistance to water absorption was shown by Peroxide treated HFREC.
- Both the sodium carbonate treated (ST) and peroxide treated (PT) HFREC showed considerable enhancement in tensile properties (tensile strength and

modulus). PT HFREC exhibited the maximum increase in tensile strength and modulus, followed by ST HFREC and UT HFREC.

- The microhardness values of treated HFREC were higher than of UT HFREC. There is an improvement of 7.93% and 15.03% in microhardness values of ST and PT HFREC when compared to UT HFREC. All the mechanical properties of the chemically modified HFRECs are displayed in Table 6.1.

Table 6.1 Mechanical properties of chemically modified HFREC

	Composites		
Mechanical properties	UT HFREC	ST HFREC	PT HFREC
Tensile strength (MPa)	30.24 ± 3.13	35.38 ± 2.56	39.09 ± 3.33
Tensile modulus (GPa)	2.69 ± 0.22	2.86 ± 0.31	3.19 ± 0.28
Micro-hardness (HV)	15.76 ± 0.89	17.01 ± 0.96	18.13 ± 1.15

6.2.2 Moisture retention and mechanical behaviour of polymer coated HFREC

- The water absorption resistance of the hemp fiber composites improved considerably for the composites reinforced with polymer coated fibers. PLA coated HFREC showed maximum resistance to water absorption.
- Both the PHB coated HFREC and PLA coated HFREC exhibited appreciable improvement in tensile strength, tensile modulus, impact strength, and microhardness values in comparison to uncoated HFREC. PLA coated HFREC showed the maximum improvement in mechanical properties among all the mechanically tested composites. All the mechanical properties of the polymer coated HFRECs are displayed in Table 6.2.

Table 6.2 Mechanical properties of polymer coated HFREC

	Composites		
Mechanical properties	UT HFREC	PHB HFREC	PLA HFREC
Tensile strength (MPa)	31.84 ± 2.02	37.55 ± 2.98	40.93 ± 3.08
Tensile modulus (GPa)	2.75 ± 0.17	2.99 ± 0.29	3.21 ± 0.23
Impact strength (KJ/m^2)	9.24 ± 0.78	12.93 ± 0.96	13.61 ± 1.02
Micro-hardness (HV)	16.36 ± 0.91	19.85 ± 0.86	20.98 ± 0.52

6.2.3 Water accumulation and mechanical performance of glutamic acid modified SFREC

- The water absorption resistance of the sisal fiber composites improved appreciably for the composites reinforced with chemically treated fibers. AGT SFREC showed maximum resistance to water absorption.
- AT SFREC, GT SFREC and AGT SFREC exhibited considerable improvement in tensile properties (strength and modulus), flexural properties (strength and modulus) impact strength, and microhardness values in comparison to untreated SFREC. AGT SFREC showed the maximum improvement in mechanical properties among all the mechanically tested composites. All the mechanical properties of the glutamic acid modified SFRECs are displayed in Table 6.3.

Table 6.3 Mechanical properties of glutamic acid modified SFREC

	Composites			
Mechanical properties	UT SFREC	AT SFREC	GT SFREC	AGT SFREC
Flexural strength (MPa)	155.23 ± 9.21	167.42 ± 8.51	160.25 ± 7.65	178.84 ± 8.78
Flexural modulus (GPa)	5.89 ± 0.28	8.25 ± 0.19	7.14 ± 0.22	9.57 ± 0.25
Impact strength (KJ/m^2)	7.60 ± 0.29	9.20 ± 0.20	8.50 ± 0.21	9.90 ± 0.19
Micro-hardness (HV)	17.76 ± 1.10	21.23 ± 0.95	18.05 ± 1.01	19.05 ± 0.89

6.2.4 Mechanical properties of eco-friendly chemically treated SFREC

- Both stearic acid and sodium citrate treatment improved the mechanical properties (tensile properties, flexural properties and ILSS strength) of the treated SFREC. However, SCT SFREC exhibited the best mechanical properties followed by SAT SFREC and UT SFREC.
- SEM analysis of the tensile and flexural fracture surface of the specimens signifies that both the chemical treatment was indeed helpful in the improvement of fiber-matrix bonding. All the mechanical properties of the chemically modified SFRECs are displayed in Table 6.4.

Table 6.4 Mechanical properties of eco-friendly chemically treated SFREC

	Composites		
Mechanical properties	UT SFREC	SAT SFREC	SCT SFREC
Tensile strength (MPa)	45.67 ± 2.15	49.35 ±2.87	56.30 ± 2.51
Tensile modulus (GPa)	2.24 ± 0.19	2.38 ± 0.22	2.62 ± 0.26
Elongation at break (%)	1.38 ± 0.08	1.87 ± 0.10	2.01 ± 0.09
Flexural strength (MPa)	160.54 ± 8.21	174.20 ± 7.12	181.63 ± 7.62
Flexural modulus (GPa)	7.68 ± 0.18	9.15 ± 0.23	9.36 ± 0.25
ILSS (MPa)	10.23 ± 0.97	13.24 ± 0.94	15.45 ± 1.01

Table 6.5 Mechanical properties of chemically modified JFREC

	Composites			
Mechanical properties	UT JFREC	AT JFREC	ST JFREC	SHT JFREC
Tensile strength (MPa)	29.84 ± 3.02	41.15 ± 2.15	50.67 ± 2.98	37.16 ± 2.75
Tensile modulus (GPa)	2.62 ± 0.19	3.39 ± 0.27	3.46 ± 0.31	2.83 ± 0.25
Impact strength (KJ/m^2)	8.44 ± 0.98	11.06 ± 1.12	11.87 ± 1.02	10.30 ± 9.90

6.2.5 Water absorption and mechanical behaviour of chemically modified JFREC

- The aversion of the composites to moisture accumulation is also improved by chemical modification. The sodium carbonate-treated JFREC showed the best resistance to water absorption.
- All the chemically modified jute fiber composites showed an appreciable increase in tensile properties (both tensile strength and modulus). ST JFREC showed the highest increase in both tensile strength and modulus. The impact strength of the JFREC also increases after the chemical treatments. ST JFREC showed the highest increase in both tensile strength and impact strength. All the mechanical properties of the chemically modified JFRECs are displayed in Table 6.5.

6.2.6 Tribological properties of chemically treated HFREC

- Chemically modified HFREC showed an improvement in both wear resistance and frictional properties. PT HFREC exhibited the best wear and frictional properties, followed by ST HFREC and UT HFREC.
- Improved mechanical interlocking between the chemically modified hemp fibers and matrix was also confirmed by the SEM images of fractured and worn surfaces of treated HFREC.

6.2.7 Tribological properties of polymer coated HFREC

- Polymer coated fiber composites also exhibited appreciable enhancement in wear resistance and friction properties. PLA coated hemp fiber composites showed the best tribological properties, followed by PHB coated HFREC and uncoated HFREC.

- Improved interfacial adhesion between the polymer coated fibers and the epoxy matrix was also validated from SEM images of tensile fracture and wear surfaces of coated HFREC.

6.2.8 Tribological properties of eco-friendly chemically treated SFREC

- SFREC reinforced with treated fibers also showed improvement in tribological properties. Amongst all the wear-tested samples, SCT SFREC exhibited the best friction and wear properties followed by SAT SFREC and UT SFREC.
- These findings demonstrate that both treatments improve fiber–matrix interfacial adhesion, lowering polymer chain mobility and increasing stress transmission. Furthermore, the sodium citrate treatment is superior to the stearic acid treatment in improving the composites' mechanical and tribological properties.

6.2.9 Tribological properties of chemically treated JFREC

- Wear resistance and frictional properties of chemically modified JFREC were better than untreated JFREC. The best wear and frictional properties were shown by ST JFREC, followed by AT JFREC, SHT JFREC, and UT JFREC.
- SEM images of tensile fractured and worn surfaces of the chemically treated JFREC also showed enhanced fiber-matrix bonding caused by chemical treatments.

8.2 Recommendation for further research

The current study opens the door for future researchers to investigate many other facets of NFRPCs. Some future research suggestions include:

- The present investigation only involves modification of fiber surface. However, matrix modification can also be carry out by addition of nano-particles, etc to improve the performance of the NFRPCs.
- Dynamic mechanical analysis (DMA) is a technique used to study the viscoelastic behaviour of polymer composites can be done for the developed NFRPCs.
- The mechanical properties of the NFRPC after the water absorption tests can also be investigated to check their usage for external applications.
- Tribological properties of the NFRPC can also be studied for different environment (dry, wet & freezing).
- The present research work includes only the experimental investigation of the NFRPC. So, there is a scope for generating numerical modells and simullations for the developed NFRPCs.