TABLE OF CONTENTS

Chapter 1: Introduction and Literature survey
1.1 Introduction
1.2 Energy Scavenging or Harvesting
1.3 Sources and Mechanisms for Energy Harvesting
1.4 Piezoelectric Energy Harvesting
1.4.2 Piezoelectric effect
1.4.2 Mechanism7
1.4.3 Piezoelectric Parameters
1.4.3.1 Piezoelectric charge coefficient (dij):
1.4.3.2 Piezoelectric voltage constant (gij):
1.4.3.3 Electromechanical coupling coefficients (kij): 10
1.5 Piezoelectric Materials11
1.6 Poly (vinylidene fluoride)13
1.7 Processing methods to impart piezoelectricity in PVDF
1.7.1 Stretching:
1.7.2 Poling:
1.7.3 Electrospinning:

1.7.4 Copolymerization:	
1.7.5 Incorporation of electroactive filler:	
1.8 Literature Review:	
1.8.1 Effect of processing techniques:	
1.8.2 Polymer based composites / nanohybrids:	
1.8.3 Applications:	
1.9 Objective of the Thesis work:	
Chapter 2: Experimental	
2.1 Materials:	
2.1.1 Polymer:	
2.1.2 Fillers:	
2.1.2.1 Nanoclay:	
2.1.2.2 Ionic Liquid:	
2.1.2.3 Carbon nanofibers:	
2.2 Preparation of Polymer-filler solution:	
2.2.1 Procedure for Electrospinning:	
2.3 Device Designing:	

2.4 Characterization Techniques:	
2.4.1 Morphological Study:	35
2.4.1.1 Polarized Optical Microscopy (POM):	
2.4.1.2 Scanning electron microscopy (SEM):	
2.4.2 Structural Analysis:	
2.4.2.1 X-ray diffraction (XRD):	
2.4.2.2 Fourier-transform infrared spectroscopy (FTIR):	
2.4.2.3 Ultra-violet visible (UV-vis) spectroscopy:	
2.4.3 Thermal behavior study:	
2.4.3.1 Differential scanning calorimetry (DSC):	
2.4.3.2 Thermogravimetric analyser (TGA):	
2.4.4 Mechanical properties study:	
2.4.4.1 Tensile testing:	
2.4.5 Electromechanical response measurement:	
2.4.5.1 Piezoelectric coefficient (d33):	
2.4.5.2 Output voltage and Power measurement:	
2.4.5.3 Output current measurement:	

2.4.5.4 Dielectric Study:	39
Chapter 3: Effect of induced piezoelectric phase in the PVDF-based	hybrids for
energy harvesting applications	
3.1 Introduction	41
3.2 Experimental	44
3.3 Results and Analysis	45
3.4 Conclusion	55
Chapter 4: Enhanced piezoelectric response in nanoclay induced electro	spun PVDF
nanofibers for energy harvesting	
4.1 Introduction	57
4.2 Methodology	60
4.3 Results and discussion	60
4.3.1 Influence of nanoparticle on morphology of nanofiber	60
4.3.2 Structural, thermal and mechanical alteration of nanofiber	62
4.3.3 Induced piezoelectricity for energy harvesting:	67
4.4 Conclusion	
Chapter 5: Ionic liquid based electrospun polymer nanohybrid for energy	harvesting
5.1 Introduction	75

5.2 Experimental
5.2.1 Electrospun nanohybrid preparation77
5.3 Characterization
5.4 Results and Discussion
5.5 Conclusion
Chapter 6: Effect of Functionalization on Electrospun PVDF Nanohybrid for
Piezoelectric Energy Harvesting Applications
6.1 Introduction
6.2 Experimental
6.2.1 Functionalized carbon nanofibers synthesis:
6.2.2 Nanofiber preparation
6.2.3 Theoretical / computational evaluation
6.3 Results and Discussion:
6.3.1 Evidence of functionalization
6.3.2 Effect of functionalization on the electrospun fibre
6.3.3 Theoretical and computational perspective of phase transition
6.3.4 Functionalized filler induced piezoelectricity and its applications 113
6.4 Conclusion

Chapter 7: Conclusion and Future work

7.1 Conclusions	
7.2 Future Scope:	
References	

LIST OF FIGURES

Figure 1.1: Common energy harvesting sources and applications
Figure 1.2: Schematic representation of the (a) direct piezoelectric effect and (b) indirect
piezoelectric effect
Figure 1.3: Direction of forces for piezoelectric material
Figure 1.4: Structure of primary phases of PVDF
Figure 1.5: Effect of poling on piezoelectric ceramic
Figure 1.6: Electrospinning set up
Figure 1.7: Chemical structure of a) PVDF; b) P(VDF-TrFE); c) P(VDF-HFP) and d)
P(VDF-CTFE)
Figure 1.8: FESEM micrographs of electrospun PVDF and PVDF/RTIL nanofibers with
different RTIL contents: (a) 0 wt % (neat PVDF); (b) 5 wt %; (c) 10 wt %; (d) 20 wt %; (e)
30 wt %; (f) 40 wt %, respectively
Figure 1.9: Three-dimensional (3D) models representing (a) electromagnetic punch and (b)
PVDF film, PVDF@P, and PVDF/graphene@P; (c) Output voltage of prepared PVDF
film, PVDF@P, and PVDF/graphene@P; (d) The output voltage signals of hitting the front
(black signals) and back (red signals) side of PVDF/graphene@P; (e) The relationship
between voltage output and different strength input (from 0.05 to 0.45 N); (f) durability of
prepared device for more than 125 cycles of voltage output of PVDF/graphene@P27

Figure 1.10: (a) Pictorial view of the wearable fish-scale-like energy harvester and its
corresponding output signal (b) Schematic representation of the prepared energy harvester
attached to bicycle and the corresponding digital picture and output voltage generation
through (c) pressure on handgrip, (d) pressure on seat (e) movement of tire; and (f)
capacitor charging due to rolling of the tire
Figure 1.11: Some applications of piezoelectric PVDF films
Figure 2.1: Chemical structure of PVDF
Figure 2.2: Organic modifier for Nanoclay 30B
Figure 2.3: Chemical Structure of Ionic liquid
Figure 3.1: a) XRD study of the prepared PVDF hybrids from TP and CTN (inset shows
the XRD curve for the CTN and TP); b) FTIR-ATR spectra of the P, P+TP-40 and P+CTN
(the FTIR-ATR spectra for the TP and CTN); c) DSC thermograms of the PVDF and its
hybrids (inset showing the DSC curve of the CTN and TP) and d) TGA plot of the PVDF
and its hybrids (DTG plot of the PVDF and its hybrid)
Figure 3.2: FESEM images of the a) Pure PVDF film; b) P+TP-40 film; c) TP; d) pure
cotton and e) PVDF-CTN hybrid 48
Figure 3.3: a) Schematic representation of the effect of filler addition onto the PVDF
matrix; b) piezoelectric coefficient of the prepared PVDF and its hybrids and the fillers; c)
output voltage generated through finger tapping mode on to the prepared device from
PVDF, TP, P+TP-40, CTN and PVDF+CTN; d) output current obtained from the finger
tapping on to the prepared samples as indicated on the bar; e) power density vs. resistance

plot for the	prepared	device;	f) charging	g – dischar	ging plo	t of the	device	prepared	from
P+TP-40 and	d P+CTN	for 2.2 µ	F capacito	r					50

Figure 4.4: a) Stacked arrays of output voltage responses from indicated nanofibers namely P, C10 and C15 produced through finger tapping under multiple hits; b) Comparative study of power density generated using nanofibers like P, C10 and C15 as a function of resistance; c) Comparison of output voltage measured through instantaneous load on the prepared unimorph (P, C10 and C15) as a function of time for a single hit; d) Voltage and

current vs. resistance curve for devices using P, C10 and C15 nanofibers; and e) Schematic representation of charge separation in templated system to understand the mechanism behind the enhanced piezoelectricity for the developed device using hybrid nanofiber. 69

Figure 6.2: SEM micrographs of the electrospun scaffolds of a) P; b) P-C; c) P-C-S; and d) the fiber diameter distribution from SEM images of electrospun fibers as indicated...... 103

Figure 6.7: Generated output voltage from a) foot tapping mode; b) pinning with glass slide; c) bending mode on fabricated device; d) power density plot against load resistance for the different modes as indicated; e) charging – discharging phenomenon for P-C-S at

LIST OF TABLES

Table 1.1: Common sources present in surrounding for energy harvesting4
Table 1.2: Common classes of piezoelectric materials 11
Table 1.3: Piezoelectric parameters and their values for some common piezoelectric
materials13
Table 1.4 Physical properties of PVDF. 15
Table 1.5: Processing methods, properties, and electromechanical response of PVDF-
based hybrids
Table 4.1: Comparison of mechanical strength of electrospun nanofibers
(pristine vs. hybrid nanofiber)