Chapter V
Applications
CHAPTER V

Applications

Introduction

Nanostructured PANI and its nanocomposites can improve its electrical, thermal and mechanical stabilities. These materials can have an important impact for applications in various fields, owing their extremely high surface area, synthetic versatility and low-cost. Due to their special properties they became attractive candidates for various technological and industrial fields such as electronics, batteries and supercapacitors, chemical and biological sensors electromagnetic shielding etc.

Herein, after the successful synthesis and characterization we have tested our material for various applications in different fields such as sensor for volatile organic compounds (VOC), optical pH sensor, as an antibacterial and ant biofilm agent and for electrochemical applications.

This chapter describes the applications of the synthesized nanostructured polymers (PANI and POT) and their nanocomposites in sensor for VOC and pH, for biological and in electrochemical fields.

5.1 Sensor Applications

With rapid industrial development and population explosion two major problems i.e. Depilation of natural energy sources and environmental pollution due to increased level of environmental dangerous gases SO$_2$, CO$_2$, (NO)$_x$ etc. Variety of toxic organic compounds like chloroform, carbon tetrachloride, Benzene, Toluene etc. Sensing and monitoring of, different process parameters such as temperature, toxic chemicals, humidity, pH, pressure etc. has been the subject of great interest. There is now increased need for low cost, low power, highly sensitive and selective sensors in various fields. Future progress in the field of microelectronics, energy storage, sensors and biosensors is concerned with new multifunctional nanostructured materials. Conducting electro active organic polymers are relatively new materials studied from last two decades in sensing applications [1-5]. Due to their interesting electrical, optical and mechanical properties they can be used in a position where, inorganic materials are not suitable. The reversible doped and dedoped chemistry of conducting polymers and their wide range of conductivity make them very useful in sensors. This utilizes the ability of such materials to change their electrical properties during
reaction with various redox agents (dopants). Therefore, they are sensitive to wide range of volatile organic vapors [6], humidity [7], pH [8] etc. Selective sensing of various organic vapors such as NH₃, alcohol, chloroform, etc. shows good potential in remediation of environmental pollution.

In the present work we have tested the Polyaniline, poly(o-toluidine) and their nanocomposites with MWCNTs for sensing Volatile organic compounds like Benzene, Toluene and chloroform also used for optical pH sensing.

5.1.1 Volatile Organic Compounds (VOC) Sensor

Prolonged exposure to various Volatile organic compounds often used in industrial area causes severe health effects such as headache, eyesight disturbance, kidney failure, lungs congestion, cancer etc [9]. Therefore it is necessary to develop low cost sensor with high sensitivity at low concentration and selectivity for detection of VOCs. Among the conducting organic polymers Polyaniline and its substituted derivatives are used as sensing material due to low cost, easy preparation, room temperature selectivity [10-12]. It is well known that the sensing mechanism of polyaniline to volatile organic compound vapours is due to physical interactions of analyte with polymer chains which would results in change in conductivity with good reversibility and reproducibility [13].

In the present work we have tested polyaniline and poly (o-toluidine) for sensing chloroform, Benzene and toluene vapours at room temperature.

5.1.1.1 Sensor –Testing

The synthesized polyaniline/Poly O-Toluidine in the form of free flowing powder were converted in to the pellet form having of diameter 15mm by applying the pressure of 7 tons by hydraulic press using pelletizer and these pellets were used as a sensor element. The electrical contacts were made using the room temperature curable silver paste and very thin copper wires. The sensing performance was tested by exposing the pellet sensor to saturated vapours of the volatile organic compounds in a close container. The dc electrical resistance was measured by using digital multimeter (simple two probe technique). The container was filled with 50 ml of volatile organic compounds and then tightly closed for 24 hrs. to ensure that the empty space of the container was saturated with volatile organic compound vapours.
Then the pellet was exposed to saturated vapours by suspending it about 2cm above the analyte surface. The change in the resistance was measured as a function of time on a digital millimeter. Experimental set-up used for the sensing measurements is shown in Fig. 5.1. Resistance data was collected by exposing the sensor repeatedly to VOCs for 5 min and re-exposing to atmosphere for 5 min. The resistance was recorded at 30 sec. interval of time.

**Fig. 5.1. Experimental set-up of VOC sensor Testing**

### 5.1.1.2 Result and Discussion:-

The sensor responded to the VOCs by undergoing the change in its resistance. Response given by polyaniline/poly (o-toluidine) to volatile organic compounds have been represented in figure 5.2 From the figure it was observed that PANI/POT sensor shows change in resistance when exposed to saturated vapours of volatile organic compounds and air. The resistance was found to be increased when the polymer was exposed to the VOCs. While, there is decrease in the resistance of the sensor up on exposure to air. This change in resistance of the polymer upon exposure to VOCs is due to the physical interactions (adsorption or absorption) of volatile organic vapours with polymer chains, when comes in contact with it. There are different types of response mechanisms for detection of organic vapours by polymeric material.
Fig 5.2 Sensing response of PANI/POT given to Volatile organic compounds (VOC).
These include weak physical interactions, polymer chain conformational change, swelling of polymers, change in the doping level and electrostatic and dipole interactions [14-17].

It has been reported that all these vapours diffused into the polymer chains causes increased in interchain distance which makes difficulty in hopping of electrons over the polymer matrix results in increasing the resistance that is clearly observed in the response presented in Fig 5.2. Additionally, Structural features of VOCs are also play an important role in deciding the extent of diffusion of VOC into polymer matrix. Larger size aromatic hydrocarbon part of Benzene, Toluene makes their adsorption restricted into polymer chain. While small size, moderate polar nature of chloroform increases its Van der-waal interactions with polymer matrix. Because of that it diffuses deeply into polymer chains which make its desorption from polymer matrix difficult. Therefore, the resistance of the polymers, upon exposure to chloroform vapours does not reach to its original / initial value as clearly seen from on-off cycles. Further work is needed to study the interactions of VOCs with the polymers as well as other sensor characteristics such as sensitivity, selectivity and stability of the sensor and will be the future scope of this work.

5.1.2 Optical pH Sensor

One of the routinely measured parameter of chemical and biological processes is pH and hence measurement and control of pH are of great interest in various fields, industrial, environmental [18,19]. Health and medicine [20] and food. Measurement of pH is usually achieved by the electrochemical approach using glass electrode. However a lot of drawbacks like electromagnetic interference, limitations in measuring the PH of low ionic solutions, difficult in miniaturization, now a days electrochemical sensors are mostly substituted by optical pH sensors. This allows more sensitivity and accuracy for measurements and moreover, they are easy to carry and operate [21,22].

The combination of metal like conductivity, doping and dedoping reversibility, possibility of fine tuning the conductivity by adjusting the doping level, flexibility proven for conducting organic polymers to work in variety of electronic applications as gas sensors, biosensors, electrode materials for Li-ion batteries and in Solar cells [23,24]. Conducting organic polymer PANI is an ideally suited candidate for optical sensor on account of its interesting characteristics such as high electrical conductivity, stability, exists in different oxidation states and undergoes colour change when
exposed to different pH. Though these properties make PANI as a promising material, its poor processibility because of insolubility / very low solubility in common solvents make its use restricted. Many researchers have succeeded in overcoming these problems by generating PANI Nano composites which can show better properties through synergic effect.[25,26]. Maser et al (2003), Bhadra.et al (2009), S.B Kondwar et.al (2012) have shown that Introduction of functionalized multiwalled carbon nanotubes (MWCNTs) in polyaniline matrix enhance the electrical properties of resulting composite material due to improving charge transfer processes . As a result of their good electrical, electrochemical properties, ultra high mechanical strength, high specific area, water solubility, reversible control of conductivity both by charge-transfer doping and protonation PANI and functionalized MWCNTs composites offer improved performance in sensor applications [27,28,29].

5.1.2.1 Optical pH Sensing Study

After successful synthesis and characterization PANI-functionalized MWCNTs and POT- functionalized MWCNTs composites were dispersed in water by ultrasonication and resulting dispersion was tested for different pH solutions.

5.1.2.2 Result and Discussion

Polyanilines and its nanocomposites acts as a smart material for pH sensor in solid as well as solution form. It shows good sensitivity and stability in the pH range between 1-13 [30-32]. In the present work we studied the pH sensing measurement of PANI –MWCNTS and POT-MWCNTs nanocomposite in solution form. It shows colour change in the pH range from acidic to Basic. In strong Acidic pH at 1 Polyaniline nanocomposites can be found in its doped conductive emeraldine salt (ES) form which is dark green colour. When the pH changes from acidic to basic, there is decrease in intensity of green colour. In strong basic pH-13 ES is converted to non-conducting blue coloured emeraldine base (EB) form, which turns solution intense dark blue colour. At neutral pH - 7 polyaniline present in both the forms showing combination of green and blue colour. This pH dependent change in colour reflects the change in the oxidation states of polyaniline, thus polyaniline has a large potential for pH sensing applications and has been extensively used to develop optical pH sensor measurements at solution state. Fig 5.3. shows a change in colour of
PANI- MWCNTs nanocomposite dispersion in water. These optical changes are also attributed from the electronic spectra of polyaniline at different pH. Fig.5.4 represents the UV-Vis spectra of nanocomposites at different pH. The emeraldine salt form at pH-1 shows characteristic absorption bands at 315nm contributed for $\pi-\pi^*$ transition of benzenoid ring. The peak at 465 nm is corresponds to the excitation of Quinone diimmine structure (N=Q=N, Q: quinoid) While, the increasing absorption at higher wavelength (~ 800) nm associated with the transition from valence band to polaron band characteristics of the emeraldine salt form of PANI confirms the conducting state of the polymer. This consistent with the green colour. The emeraldine base form (EB) form of polyaniline gives two peaks with maxima at 345 nm for $\pi-\pi^*$ transition of benzenoid ring and at 650nm for quinoid excitation bands [33,34]. Disappearance of a high absorption peak at 800 nm in EB proves the transformation of doped form of polyaniline to dedoped form Functionalized MWCNTs not only play an important role in the formation of PANI-CNT nanocomposite but also improved its properties such as electrical conductivity, solubility/dispensability in aqueous medium. These improved properties shows more intense colour change than the pure polyaniline.
Fig 5.3(a) Colour change at different pH shown by PANI-MWCNTs nanocomposite

Fig 5.3(b) Colour change at different pH shown by POT-MWCNTs nanocomposite
Fig. 5.4 Electronic spectra of (a) PANI-MWCNTs and (b) POT-MWCNTs at different pH
5.2 Biological Applications

Antibiotics act by inhibiting the growth (microbiostatic) or killing the microorganisms (microbicidal). They act by inhibiting bacterial functions that are essential for growth. However, the action of antibiotics imposes a selective pressure that fosters the growth of antibiotic-resistant strains, and thus, the treatment of antibiotic-resistant strains of a post-antibiotic era is looming as a challenge of 21st century [35]. Therefore, antimicrobial therapies that are neither bacteriostatic nor bacteriocidal (i.e. that reduce selective pressure) have to be explored to treat the menace of antibiotic resistant pathogenic microorganisms. As the most pathogenic organisms acquire the pathogenicity by virtue of the phenomenon of biofilm formation [36, 37] inhibiting biofilm formation can be one of the effective strategies to curb such microbial pathogens. Biofilm formation has been shown to occur in 80% of human bacterial infections [38] and pathogens contained in biofilm have a 1000-times higher tolerance to antibiotics than the same organisms in a planktonic state [39]. The biofilm formation in the opportunistic pathogen Pseudomonas aeruginosa has been the focus of considerable attention, partly because of this bacterium’s rapidly growing resistance to traditional antibiotics and prevalence in lung infections associated with cystic fibrosis [40,41]. The P. aeruginosa grows into biofilms as drug resistant organisms at high cell densities, which make P. aeruginosa infections particularly difficult to treat [42]. Therefore, inhibiting the formation of biofilm will be an suitable alternatives/supporting strategy to antibiotic therapy to curb the menace of antibiotic resistant microorganisms. In this regard, conducting polymers (CPs) are emerging as an exciting class of materials with an ability to enable new approaches to material design and synthesis. [43,45]. Their freely conducting electrons along with any intrinsic charges associated with the polymer backbone allow CPs to complex with metal ions in solution and subsequently reduce them to zero-valent metals in the absence of any externally applied electric field [46].

Polyaniline (PANI) is a highly functional synthetic polymer, unique among the family of π-conjugated polymers because of its ease of synthesis, good environmental stability and simple acid/base doping/dedoping chemistry [47,48]. As polyaniline has been shown to be non-toxic and biocompatible [49-51], conducting polymers of polyaniline have been used in the development of cardiac muscles[52], controlled drug release [53] and as an antimicrobial agents [54].
Silver nanoparticles and its composites have been shown to possess an excellent antimicrobial activity. Therefore, incorporation of silver nanoparticles into the matrix of conducting polymers can provide a composite material with excellent properties combining antimicrobial resistance. Cotton is one of the natural biodegradable, versatile fibre can be easily blended or coated. It’s unique properties like biocompatible, good mechanical strength, high surface porosity, absorbency make them an ideal fabric for medical products such as bandage [55,56]. Multifunctional fibres are obtained by deposition of an organic polymers onto fibrous substances. The use of organic conducting polymers together with cotton cellulose fibres has advantages such as processibility, flexibility with elimination of low mechanical properties and Increasing biocompatibility of resultant nanocomposite [57]. Therefore, in the continuation of our previous endeavour to synthesize and evaluation the bioactive potential of PANI- Ag nanomaterials, in present study we have performed an in-situ synthesis of PANI- Ag/POT-Ag nanocomposites in cellulose fibres and showed its bioactive potential as an antibacterial and ant biofilm agent.

5.2.1 Bioactivity Study

In the present study, two biological applications of PANI/POT- Ag—Cellulose and were studied, (i) an antibacterial activity and (ii) antibiofilm activity. Whereas the antibacterial studies were performed by colony forming units in Bacillus subtilis NCIM 2063 and E. coli NCIM 2931, the antibiofilm studies were performed by crystal violet retention assay and FEMES analysis of biofilm in Pseudomonas aeruginosa O1.

5.2.1.1 Antibiocellular Study

Briefly, a 6-well microtitre plate containing a basal media layer of about 10 [Muller Hinton (MH) agar] (Hi-Media Mumbai, India) was prepared. A 2.5 x 2.5 cm of Ag-PANI-Cellulose containing Ag-PANI nanocomposites in the concentration range of 0-100 µg/mL was dipped in 10 mL sterile and molten agar (1.2% agar) inoculate with test strains (final cell density of appr. 1 x 10^4 CFU/mL) and incubated at 37 °C for 15 h for the formation of visible colonies.
5.2.1.2 Antibiofilm Study

Since biofilm formation requires a hydrophobic surface, the biofilm inhibition studies by Ag-PANI nanocomposites were performed with composite powder. In short, *P. aeruginosa* O1 was grown overnight in Luria Bertaini (LB) medium at 37 °C with agitation. After growth, the culture was diluted with LB medium (OD$_{600}$ 0.02), and 50 µL of the diluted culture was added to 950 µL of LB medium and allowed to form biofilm. After formation of biofilm on polystyrene plastic surfaces, the planktonic cells (suspended cells in the medium) were replaced with fresh medium supplemented with 0-100 µg/mL of PANI-Ag nanocomposites and incubated statically for 18 h at 37 °C. After incubation, planktonic bacteria were discarded, and the biofilms were washed three times with phosphate buffered saline buffer. Washed biofilms were fixed with 1 mL of methanol (99%). After 15 min, the methanol was discarded, and the plates were dried at room temperature. Crystal violet (0.1% in water) was then added to each well (1 mL/well), and the plates were incubated for 15 min at room temperature. Crystal violet was then discarded, and stained biofilms were washed three times with 1 mL of water. Acetic acid (33% in water) was added to the stained biofilms (2 mL) in order to solubilize the crystal violet, and the absorbance of the solution was read at 590 nm with a spectroscopy (Schimadzu, Japan). For FE-SEM analysis, the samples were dehydrated in a series of ethanol solutions (10–100 %, each for 15 mins). The samples were dried, mounted on aluminium stubs with conductive carbon cement, and finally coated with a gold film. The samples were observed under FE-SEM (Hitachi S-4800 II).

5.2.2 Results and Discussions

5.2.2.1 Antibacterial Activity

The advances in the field of nanotechnology over last decade have introduced several nanomaterials that may potentially prevent bacterial functions that lead to infections [42,43]. As silver nanoparticles/composite has been shown to act as an antimicrobial agent against various multidrug resistant organisms [44-46] with the recent reports of PANI as a biocompatible material for *invivo* use in humans, [47] we have attempted to synthesize *in-situ* Ag-PANI nanocomposites in cellulose fibres and showed its bioactive potential as an antibacterial and antibiofilm agent.

When a Ag-PANI Cellulose was inoculated with test stains, and observed for the presence of colonies, it was found that whereas control (only cellulosic cotton)
showed a lawn of bacterial colonies, Ag-PANI Cellulose showed a reduced number of colonies. A Ag-PANI Cellulose containing a 10 mg/mL of Ag-PANI showed a 83 number of colonies and no colonies were observed for Ag-PANI Cellulose containing a 100mg/mL of Ag-PANI.

Silver nanoparticles and its composites/materials have been shown to possess an antibacterial activity. Different forms of silver nanomaterials have been reported to possess an antimicrobial including metallic silver nanoparticles, silver-impregnated zeolite powders and activated carbon materials, dendrimer–silver complexes and composites, polymer silver nanoparticles composites, silver-titanium dioxide composite nanopowders, and silver nanoparticles coated onto polymers like polyurethane [49]. However, there are only few reports of the Ag-PANI as an antimicrobial agent. Except the report Jia et al [50] and Boomi et al. [51] and a recent report by our group [55], there have been no other reports of the antibacterial activity Ag-PANI. In comparison to others, Ag-PANI nanocomposites synthesized by our group were better as the amount required to bring the reduction in the number of viable cells were less than others. Not only this, but the material also have shown a biofilm inhibition activity (in following section), which is yet unreported. Although, synthetic polymeric materials owing to excellent structural uniformity, multivalency, high degree of branching, and architectures have been proposed for the bio-fabrication of antimicrobial materials, however, many of them possesses drawbacks, and rendered noncompatible in human body usage [52]. As polyaniline shown as a biocompatible polymer with human tissues [53] and cells, [54,55] the antimicrobial activity shown by Ag-PANI-Cellulose can be rendered as significant.

5.2.2.2 Antibiofilm activity

Most pathogenic organisms acquire the pathogenicity by biofilm. The biofilm formation in the opportunistic pathogen P. aeruginosa has been the focus of considerable attention, partly because of this bacterium’s rapidly growing resistance to traditional antibiotics and prevalence in lung infections associated with cystic fibrosis [40,41]. Biofilms protect their constituent cells in various ways, which makes both clinical and industrial contamination difficult to treat. In order to control biofilm formation on medical devices and industrial instruments, a large number of new strategies and approaches have been developed in the last few years, including: antimicrobial locks; surface modification of biomaterials with antimicrobial coatings;
antimicrobial peptides as a new class of antibiotics; enzymes that dissolve biofilms, nitric oxide; electrical or ultrasound enhancement of antimicrobial activity; the application of light activated antimicrobial agents [56] the use of quorum sensing (QS) inhibitors [57] and nanotopography of the material [58]. Nevertheless, nanoscale materials have recently appeared as one of the most promising strategies to control biofilm infections related to indwelling medical devices and industrial instruments, especially due to their high surface area to volume ratio and unique chemical and physical properties.

When the cells of *P. aeruginosa* were subjected sub-inhibitory concentration of PANI-Ag/ POT-Ag nanocomposites, there was a decrease in the biofilm formation (Figure 5.5). The decrease in the biofilm was concentration dependent. At 6.25 µg/mL, there a very less decrease in the biofilm (3%), however, at 12.5 and 25 µg/mL, respectively, a 37 and 83 % inhibition in biofilm were observed. At 50 µg/mL, a complete inhibition of biofilm were observed. A clearer demonstration of the inhibition of biofilm was revealed under FESEM. When the cells of *P. aeruginosa* were subjected Ag-PANI/ POT-Ag. nanocomposites, and observed under FESEM, distinguished individual cells were observed with distinct cellular morphology, indicating that there was a reduction of the biofilm, however, under control conditions, the biofilm formation was not disturbed, and hence agglomeration of the cells were observed (Fig.5.5). Thus, Ag-PANI/ POT-Ag. nanocomposites inhibited biofilm formation in *P.aeruginosa* as well. The advances in the field of nanotechnology over last decade have introduced several nanomaterials that may potentially prevent bacterial functions that lead to infections. [43,44] As silver nanoparticles/composite has been shown to act as an antimicrobial agent against various multidrug resistant organisms [45-47] with the recent reports of PANI as a biocompatible material for *invivo* use in humans [48]. We have attempted to synthesize *in-situ* Ag-PANI nanocomposites in cellulose fibres and showed its bioactive potential as an antibacterial and antibiofilm agent.

When a Ag-PANI Cellulose was inoculated with test stains, and observed for the presence of colonies, it was found that whereas control (only cellulosic cotton) showed a lawn of bacterial colonies, Ag-PANI/ POT-Ag. Cellulose showed a reduced number of colonies (Figure 5.5). A Ag-PANI Cellulose containing a 10 mg/mL of Ag-PANI/ POT-Ag. showed a 83 number of colonies and no colonies were observed for Ag-PANI/ POT-Ag. Cellulose containing a 100mg/mL of Ag-PANI/ POT-Ag.
Fig. 5.5 (a) Inhibition of biofilm by PANI-Ag nanocomposite under SEM
Fig. 5.5 (b) Inhibition of biofilm by POT-Ag nanocomposite under SEM
5.3 Electrochemical Properties

The electroactive property of the synthesized nanocomposite is tested using typical cyclic voltammetry (CV), Galvanostatic charge/discharge and electrochemical impedance methods. Cyclic voltammetry is an important tool to reveal the nature of electrochemical reaction (redox reaction) and electrochemical reversibility [59]. Cyclic voltamgrams of the prepared electrode material were recorded at three electrode systems consisting of working electrode, counter electrode and reference electrode in a 3M KOH supporting electrolytes at various scan rates such as 0.5, 10, 20, 50 and 100 mV/sec. as shown in Fig. 5.6. Typical rectangular shape and appearance of redox peaks in cyclic voltamgrams, suggests the good electrochemical reversibility and stability during electrochemical reactions [60]. CV curves PANI-MnO$_2$ nanocomposite polyaniline shows anodic and cathodic peaks. It is corresponds to the transition of leucomeraldine to emeraldine salt phase of the polymer and oxidation of Mn$^{2+}$ to Mn$^{3+}$. The large value of current density of PANI-MnO$_2$ nanocomposite is because of observing this redox pair. The specific capacitance values calculated for pani-MnO$_2$ nanocomposite are 751, 539, 282, 184, 142 F g$^{-1}$ at the scan rates 0.5, 10, 20, 50 and 100 mV/sec. which are very large as compared to pure polyaniline or pure MnO$_2$ observed from literature survey.

Chronopotentiometry (CP) Technique Galvanostatic charge-discharge measurement were conducted at different current densities from 0.5-10 A/g and the resultant galvanostatic curves are display in fig. 5.7. (a) & (b). The good symmetric profiles and linear slopes with respect to charging and discharging shows good capacitive behavior for PANI-MnO$_2$ nanocomposite. The specific capacitance of the composite can be calculated by using equation. Sp.cap=I*dt/m*dv The capacitance of the composite are 483, 468, 435, 311, 223 F g$^{-1}$ at 0.5, 1, 2, 5 and 10 A/g. At lower current density, the electrolyte ions can be diffused sufficiently into the electrode, resulting more surface available from embeded MnO$_2$ and therfore specific capacitance is higher. While at larger density specific capacitance is reduced due to limited diffusion time into the electrode surface (shown in fig. 5.7 (c)) [61]. To test the material stability for long term use, the charge discharge measurements were conducted of 2500 cycles at 0.5 A/g as shown in fig. 5.7 (d). 91% of the original
Fig. 5.6 Cyclic voltagramms of PANI-MnO$_2$ nanocomposite at different scan rate.

Fig. 5.7 (a) Galvanostatic charge-discharge curves at 0.5 and 1A/g. (b) Galvanostatic charge-discharge curves at various current densities. (c) Dependance of Sp. Capacitance on the current density. (d) Display cycling capacity of electrode material for 2500 continuous cycle.
capacitance was retained by the nanocomposite at the end of 2500 cycles, showing good cycling performance. The high specific capacitance and better rate capability of nanocomposite electrode is attributed for its distinct structural morphology. The well defined mesoporous structure allows fast diffusion of electrolyte and hierarchical hollow macroporosity acts as ion buffering reservoirs for fast redox reactions [62].

In order to further confirmed the higher electrochemical performance of PANI-MnO$_2$ nanocomposite electrode, electrochemical impedance measurements (EIS) were also carried out and the resulting Nyquist plot is shown in fig.5.8. Observing the semicircle in the high frequency region is a visual indication of the charge transfer resistance (Rct)[ ]. Rc obtained from the intercept of the impedance curve at X- axis is 0.56 ohm. The smallest Rct suggest the faster faradic reaction with lower resistance.[64].

Fig.5.8 Nyquist plot of PANI-MnO$_2$ nanocomposite.
References:
41. Hoiby N., BMC Medicine, 9, 32 (2011).