



Article

Structural and Morphology Properties of Polyaniline / Tio₂ – Cu₂O Nanocomposite for Supercapacitor Applications

Khawla Salem Mohammed¹, Hayder Mahdi Ahmed²

1,2. College of Education - Tuz Khurmatu, Tikrit, University, Salah Al-Din, Iraq

*Correspondence: Khawla.salem.tuz@tu.edu.iq¹, haider.m.ahmed@tu.edu.iq²

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Abstract: This study focused on the preparation and characterisation of polyaniline, as well as the nanostructures of titanium dioxide and copper oxide at a ratio of 30 per cent, and the nano- and hybrid structures of polyaniline with titanium dioxide and copper oxide at a ratio of 50 per cent. The X-ray diffraction results revealed a semi-crystalline nature of the polyaniline polymer, in contrast to the highly crystalline structures of both titanium dioxide and copper oxide, with clear hybrid interference between all the components. Furthermore, the scanning electron microscope revealed a clustered, cauliflower-like morphology with pores of polyaniline, characterised by particle sizes ranging from 50 to 71 nanometres, as well as the coating of polymer chains onto the oxide surfaces within the hybrid nanocomposite. Furthermore, infrared spectroscopy results confirmed the presence of functional groups in polyaniline, as well as metal-organic, with slight displacements confirming that strong physicochemical bonding is present. Finally, cyclic voltammetry and elemental analysis measurements showed that excellent supercapacitive behaviour was recorded for the titanium dioxide and copper oxide nanocomposites, and it was also found a very high oxidation current of 2,544 microamperes. Furthermore, the hybrid nanocomposite demonstrated electrochemical response and stability with high equilibrium performance, which may make it suitable for energy applications.

Keywords: Polyaniline; Titanium Dioxide; Copper Oxide; Hybrid Nanocomposite; Supercapacitive Behaviour.

1. Introduction

Energy storage devices are among the latest technologies attracting attention in the fields of physics, chemistry and materials science, due to the growing demand for clean and potentially sustainable energy sources for modern technological applications [1-2]. Supercapacitors have emerged as an ideal and highly effective choice to meet these needs, thanks to their high energy density and capacity and exceptional speed in charging and discharging the devices. [3-4] This is due to their long cycle life, measured in hundreds of thousands of cycles; when compared to conventional batteries, energy storage in these supercapacitors relies primarily on the nature of the materials used in the manufacture of the electrodes [5-7]. Therefore, polymers are, foremost among which are polyaniline and polypyrrole. These materials have attracted significant and extensive research interest for their numerous applications in supercapacitors, owing to the high electrical conductivity and high high and excellent theoretical specific resistance, as well as exceptional flexibility

in preparation and ease of chemical synthesis, in addition to low cost and environmental stability when compared to many other materials. This is a feature of great importance; however, there is one problem that these polymers suffer from, namely their limited structural stability when used in , due to the expansion and contraction of the polymer chain; this leads to a reduction in their storage capacity over the long term. This problem can also be addressed by improving the electrochemical performance of the electrodes, with recent and advanced research focusing on the manufacture of hybrid nanocomposites from by combining conductive polymers with nano-sized transition metal oxides, whereby copper oxide is combined with titanium oxide and used as a secondary nanocomposite in a single, highly significant strategic application; It is important to note the contribution of titanium oxide in supporting mechanical stability and its role in facilitating electron movement; as for copper oxide, it is considered a highly active electrochemical catalyst with very high capacitance, similar to an excellent capacitor, due to the rapid, symmetrical reactions it can induce [8 - 17]. The idea, or essence, of combining these nanocomposites with a polyaniline matrix is to create a synergistic effect, whereby this effect combines the excellent stability of the oxides with the high conductivity of the polymers; this is what gives the hybrid composite of polyaniline, titanium oxide and copper oxide its properties excellent structural properties and a highly developed morphology, which enhance charge storage efficiency. The main focus of this research is to study the structural and morphological properties of polyacrylonitrile composites with titanium oxide and copper oxide nanoparticles, and to examine and analyse the effect of incorporating nanoparticles of these oxides in varying proportions on the surface morphology and microstructure of the material, as well as to assess their suitability for applications such as high-efficiency supercapacitors in charging and discharging, amongst others [18 -20] .

2. Materials and Methods Used in Sample Preparation

Materials used in the preparation

- 1- Aniline: the primary monomer, which should preferably be freshly distilled
- 2- Hydrochloric acid: which must be of 1 M concentration and acts as an acidic solvent
- 3- Ammonium perborate: which acts as the oxidising agent and catalyst for the polymerisation reaction
- 4- Distilled water: which is used for washing and dissolution
- 5- Solvents used in washing: These are ethanol and acetone, which are used to wash the resulting polymer, thereby removing impurities and unreacted monomers

Methods used in preparation and mixing

Preparation of poly(aniline)

A solution of hydrochloric acid with a concentration of one molar is prepared by adding 8 of concentrated acid to 95 ml of distilled water; after mixing, the resulting solution is divided into two beakers, each with a capacity of 50 mg, and then a specific weight of aniline monomer is added to 50 of 1 molar hydrochloric acid in one of the beakers. The mixture is then left to stir for at least half an hour in the first solution Next, a specific weight of ammonium pyrosulphate is added to 50 ml of hydrochloric acid with a concentration of one molar in the other beaker, and this is stirred for at least half an hour. Solution No. 1 is then added to Solution No. 2, drop by drop, with continuous stirring for a period of approximately two hours. Finally, the mixture is left overnight to ensure the reaction is complete; the precipitate is then filtered and washed with distilled water

3. Result and Discussion

3.1 XRD Analysis

PANI

Figure 1 shows the X-ray diffraction pattern of the prepared sample containing polyaniline. The figure reveals the semi-crystalline and amorphous nature of the conductive polyaniline polymer, which is reflected in the diffraction pattern as broad bands centred at a convergence angle of between 20 and 25 degrees. The reason for the appearance of these broad peaks is primarily due to a periodic repetition in the structure of the interlinked and intertwined polymer chains between the benzene rings within this polyaniline matrix. This confirms that the aniline has been successfully synthesised with the desired structure, without the presence of any amorphous or foreign impurities. The figure illustrates the X-ray diffraction pattern of the prepared poly(aniline),

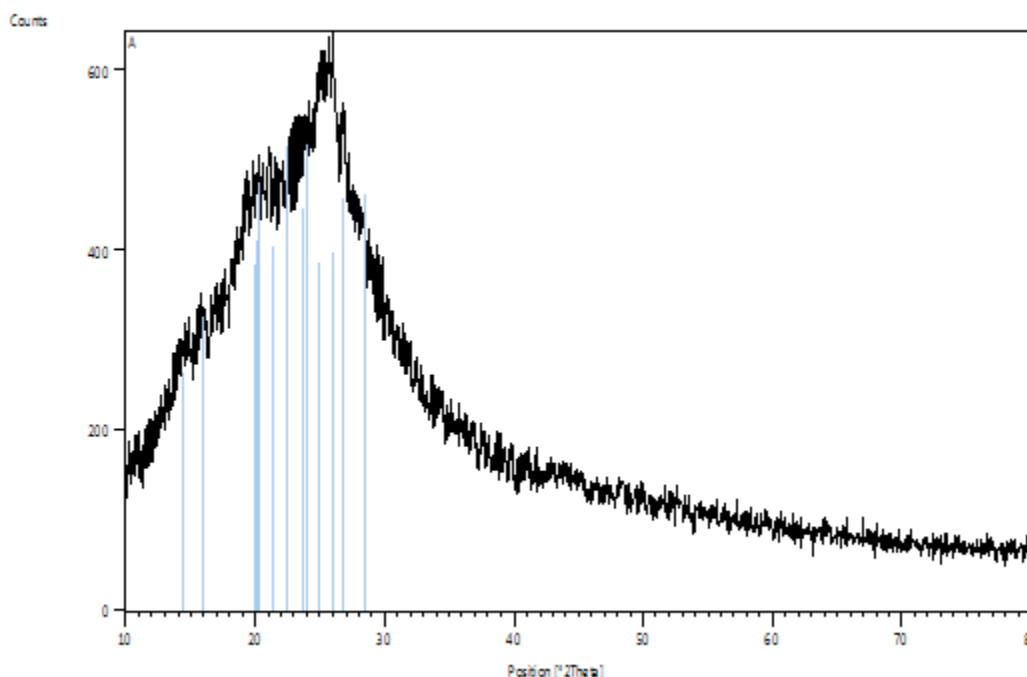


Figure 1. x-ray of PANI

showing a characteristic lenticular diffraction pattern. As can be seen in the figure, there is a broad diffraction peak extending at an angle of 20 degrees. The reason for the presence of this broad peak is the existence of parallel periodic distances that are perpendicular to the polymer chains and the planar arrangement of the benzene or conene rings present in the crystal structure. This result is fully consistent with a previous study published by the researchers [21], who confirmed that the presence of these peaks at these angles confers a crystalline nature on the amorphous polyaniline, which has been doped with a strong acid, and this is what gives it flexibility and a high capacity for electrochemical reaction

TiO₂–CuO bimetallic nanocomposites, 30%

Figure 2 shows the nanocomposite sample of titanium dioxide and copper oxide in a 30 per cent ratio where high-intensity, sharp diffraction peaks are observed, reflecting the distinctive crystalline structure of the constituent nano-metal oxides. These peaks are distributed in such a way as to reveal the crystalline characteristics of the anatase phase specific to titanium oxides, which appear at angles approaching 25. 3°, 37.8° and 48° for the (1 0 1), (004) and (2 0 0) crystal planes, respectively. Concurrently, these characteristic

peaks of the monoclinic phase of copper oxide also appear at various angles, including 35.5° , 38.7° degrees for the (1 1 1) and (1 1 0) planes, respectively. The co-occurrence of these oxygen peaks on a single diagram is a positive and excellent result, confirming the successful formation of a nanocomposite of these binary oxides with very high crystalline purity, X-ray diffraction of the nanocomposite consisting of titanium and copper nanooxides reveals diffraction peaks resulting from the anatase phase, which were recorded at various angles, including 25° , 37° , 48° and 55° , corresponding to the crystal planes (1 0 1) (0 0 4) (2 0 0) (1 0 5). The diagrams also show the presence of single-phase crystalline peaks; this result is consistent with the study conducted by the researchers cited in the source [22], which demonstrated the successful crystallisation of a binary oxide mixture, in which each oxide retains its own phase when prepared in nanoscale form.

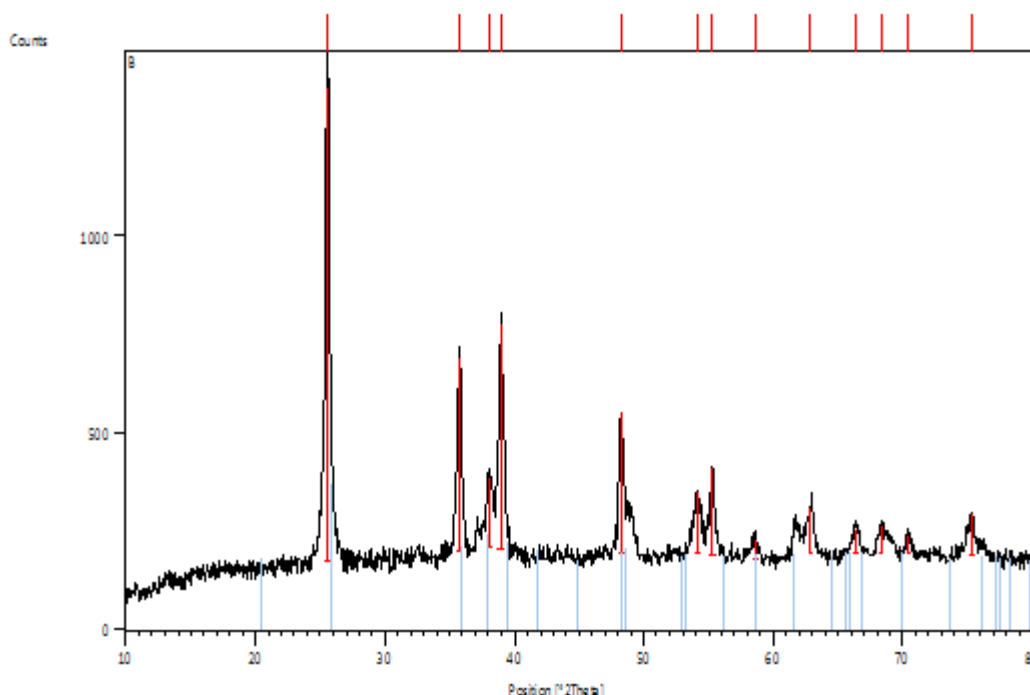


Figure 2. x-ray of $\text{TiO}_2\text{-CuO}$ bimetallic nanocomposites, 30%

PANI/ $\text{TiO}_2\text{-CuO}$ hybrid nanocomposites, 50%

Figure 3 shows the X-ray diffraction pattern of a hybrid nanocomposite consisting of aniline and a titanium and copper oxide composite in a 50:50 ratio. This pattern illustrates the X-ray diffraction reflection resulting from the synergy and hybrid interaction between the semi-crystalline nature of the aniline polymer and the highly crystalline structure of the nano-oxides, as evidenced by the spectral pattern showing diffraction peaks specific to titanium oxide and copper oxide, albeit with lower intensity compared to the oxides when they are present on their own. This is due to the surface coating formed by the poly-aniline matrix on the oxide particles, where the broad bands of the poly-aniline interfere at angles of approximately 20 to 25 degrees, whilst the crystalline oxide peaks appear without leading to changes in the crystalline structure of the oxides. This confirms the occurrence of a successful, physically coherent synergistic interaction between these polymer chains and the oxide nanocomposites. We can use the half-width at half-maximum to calculate the average crystal size of these hybrid oxide composites using the De Bay-Scherer equation. These results are exactly in line with those reached by the two researchers cited in the source [23] who studied hybrid composites, demonstrating that this structural interaction between the polymer and the oxide composites used in this study indicates a

strong synergistic bond between the polymer and these oxides, which leads to surface stability and the material's chemically-induced performance.

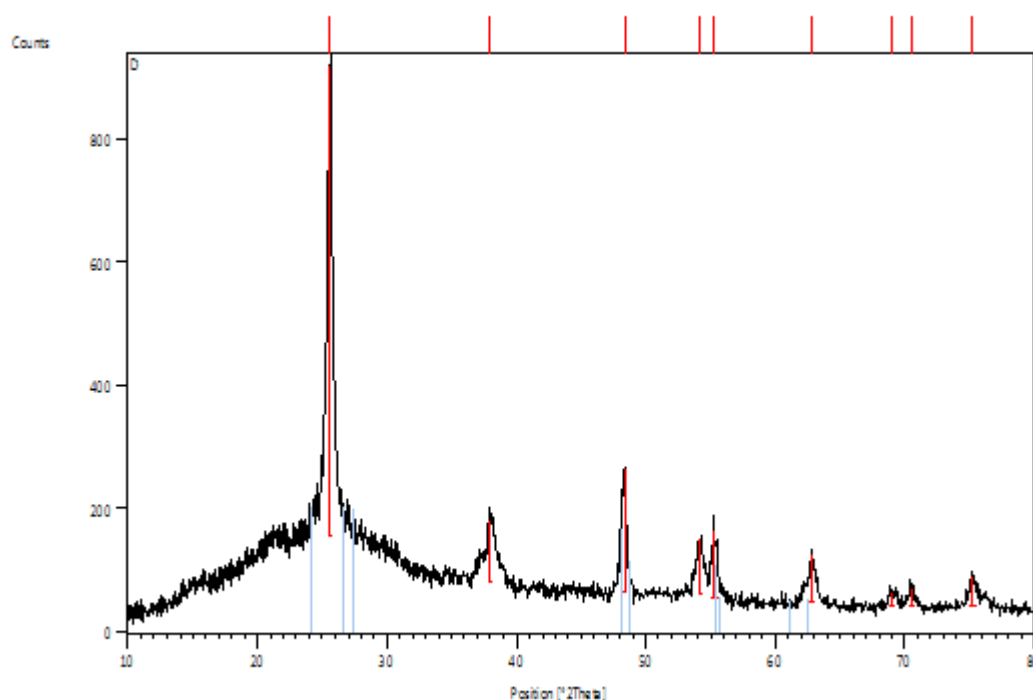


Figure 3. x-ray of PANI/TiO₂-CuO hybrid nanocomposites, 50%

3.2 SEM Analysis

PANI

Figure 4 illustrates the morphological characteristics examined using a scanning electron microscope of a sample composed of pure polyacrylonitrile. The electron microscope images of the sample reveal a granular morphological structure with uniform pores, resembling the shape of cauliflower, where the matrix consists of conductive polyaniline matrix consists of regularly packed spherical nanoclusters. High magnification of up to 100 kX may reveal the presence of individual nanoparticles with diameters ranging from 50.99 nanometres and 71.70 nanometres, which should result in an average nanoparticle size of approximately 61.75 nanometres. This structure is characterised by an interlaced network of voids and pores, which gives the material a highly effective surface area; this facilitates the movement of electrochemical ions in a wide range of applications, including supercapacitors. These findings are consistent with the study carried out by the researchers[12].

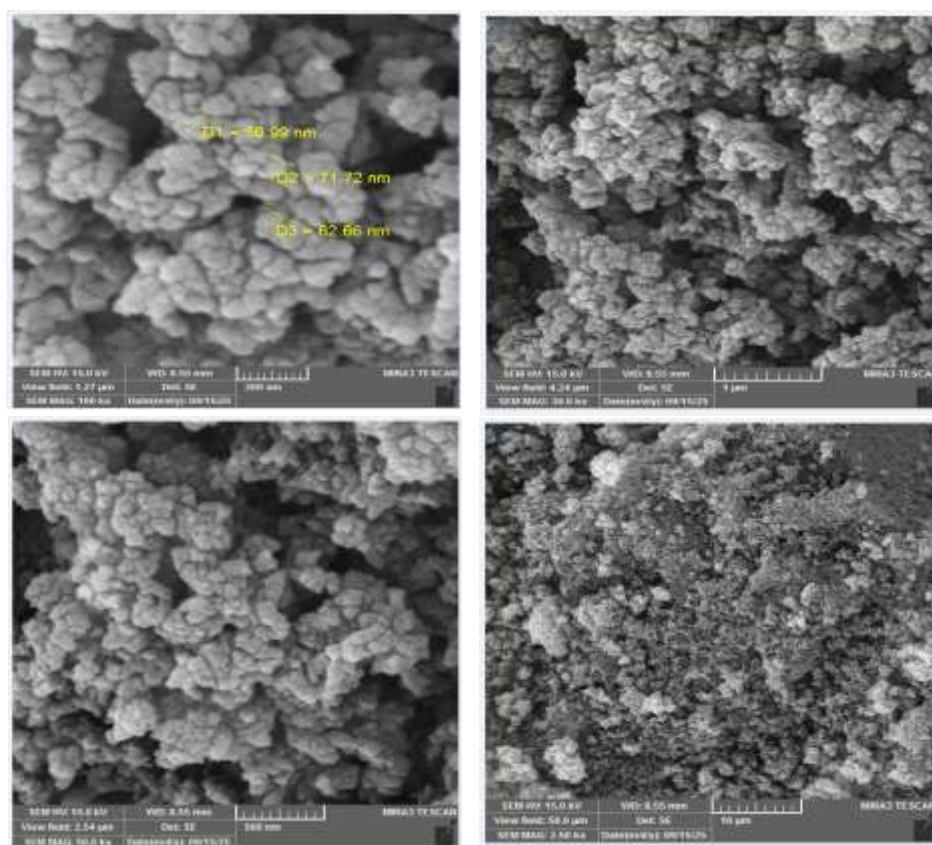


Figure 4. SEM of PANI

TiO₂-CuO bimetallic nanocomposites, 30%

Figure 5 illustrates the morphological characteristics, as observed by scanning electron microscopy, of a binary nanocomposite consisting of titanium oxide and copper oxide, with the latter constituting 30 per cent. This sample reveals a morphological structure of a heterogeneous crystalline nature, reflecting the successful physical integration between the nano-sized titanium oxide particles and the copper oxide particles; the nanoparticles of these oxides appear as spherical grains and may be agglomerated together, taking on a polygonal, whilst the homogeneous distribution of the material prevents excessive agglomeration; this contributes to and enhances the stability of the surface structure and provides numerous highly active sites for rapid electrochemical reactions, researchers studied the same compound using a different method, and their findings showed that they were consistent with these results[10].

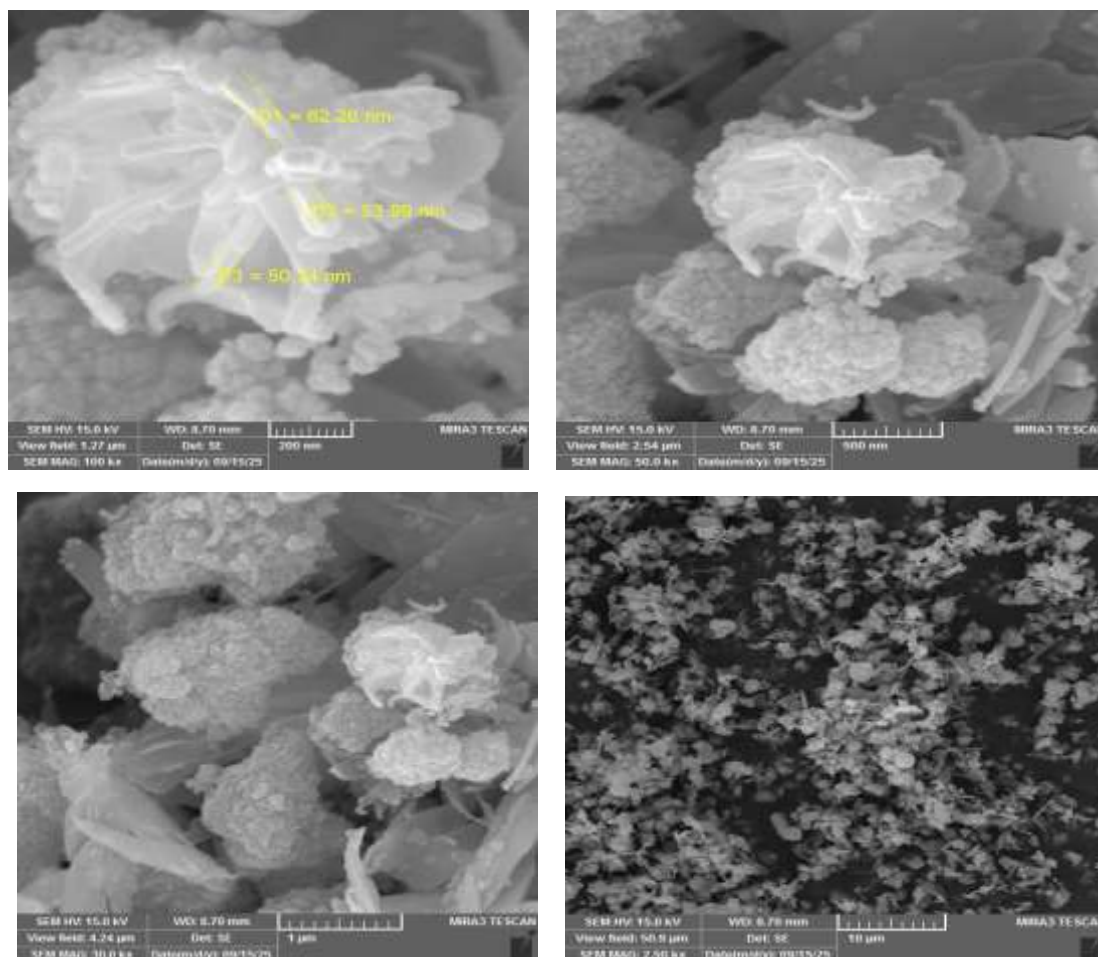


Figure 5. SEM of $\text{TiO}_2\text{-CuO}$ bimetallic nanocomposites, 30%

PANI/ $\text{TiO}_2\text{-CuO}$ hybrid nanocomposites, 50%

Figure 6 shows the electron microscope morphological characteristics of the sample consisting of a hybrid nanocomposite made up of titanium oxide and copper oxide mixed with the polymer aniline in a 50 per cent ratio. The electron microscope images illustrate the hybrid morphology resulting from the intercalation of the polyaniline matrix with the oxide nanocomposites; this process, through which these components were combined, leads to the surface particles of the titanium oxide being coated by the polyaniline polymer chains, and nano-copper oxide particles, which are completely encapsulated. This results in a reduction in the polymer's free pores, whilst increasing the contact efficiency between these metallic components and the polymer, thereby imparting high structural stability to the sample and preventing the contraction and expansion of the polyaniline polymer during repeated charging and discharging cycles. This result can be compared with that of a researcher who carried out the same tests, and it may correspond to some extent in terms of the source[10].

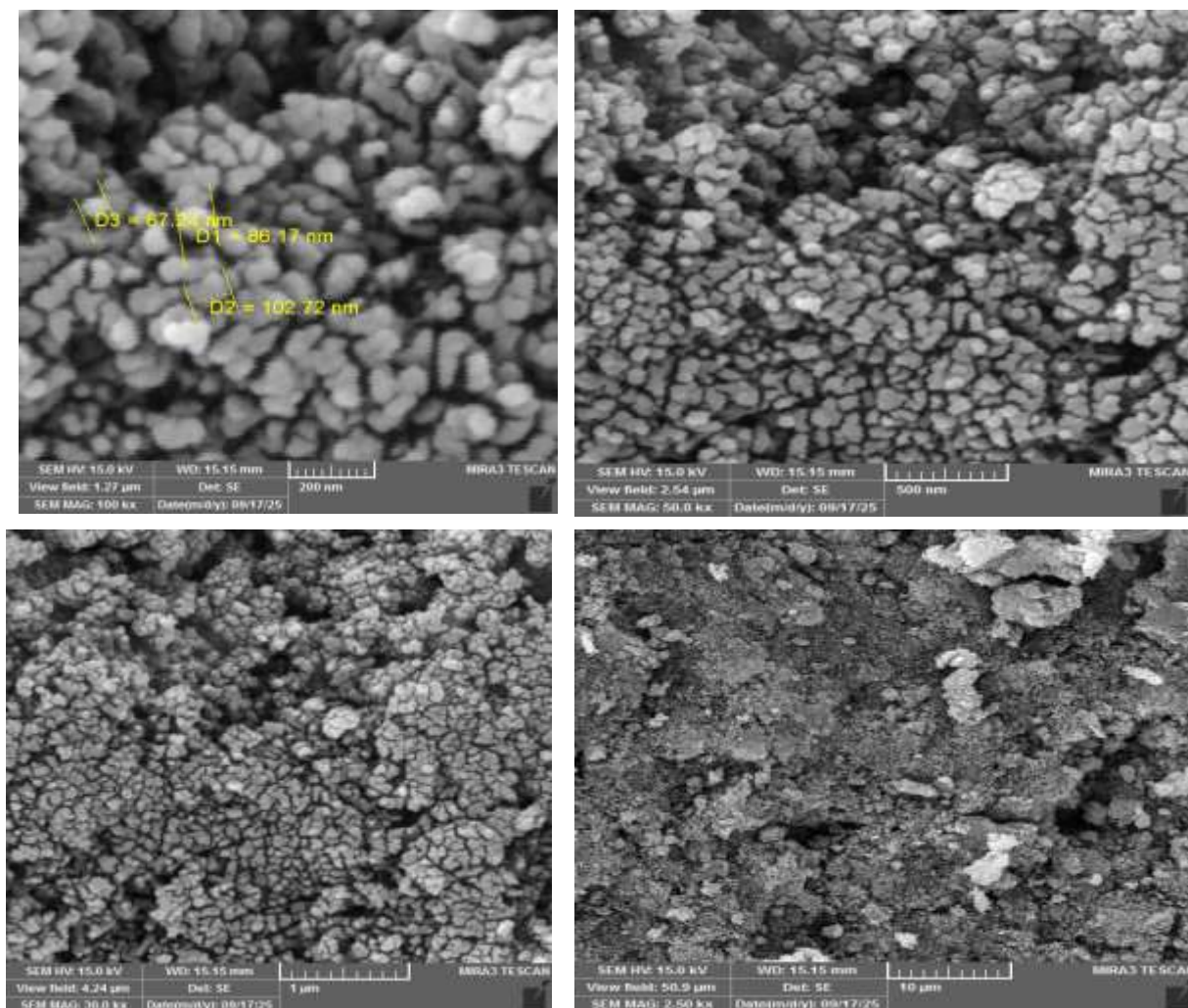


Figure 6. SEM of PANI/TiO₂-CuO hybrid nanocomposites, 50%

3. FTIR Analysis

PANI

Figure 7 shows the infrared spectrum of the lens composed of pure polyaniline, revealing a distinct absorption band characteristic of the chemical structure of the material present in the lens—namely, conductive polyaniline—which exhibits a broad absorption band at a wavelength of 3155.54 cm⁻¹, attributable to the stretching of the C-H bond in those secondary amine groups, where these bands are accompanied by the stretching of carbon-hydrogen bonds in the aliphatic and aromatic structures at various frequencies estimated at 2954.95, 366 and 3500 cm⁻¹, where strong and distinctive peaks are observed at frequencies including 1610 cm⁻¹ and 1570 cm⁻¹; these confirm the presence of bonds in the quinone rings, whilst the peak at 1483 cm⁻¹ corresponds to the benzene rings. This demonstrates the successful incorporation of the tain and the polymerisation, as evidenced by the stretching of the urea carbon-nitrogen bond at frequencies including 1303.88 and 1244.9, as well as the presence of another strong peak at 1112.93 when subjected to intense electrochemical vibration, which is caused by electrical conduction; this completes the structure of the out-of-plane bending peaks of the carbon-hydrogen bonds of the dihydric ring, with compensation at a frequency of 821.68 cm⁻¹ in the fingerprint region. These confirmed results in the infrared spectrum, showing the characteristic bonds of titanium dioxide and copper oxide as well as the pyrrole ring vibration in this study, are fully consistent with the source[11].

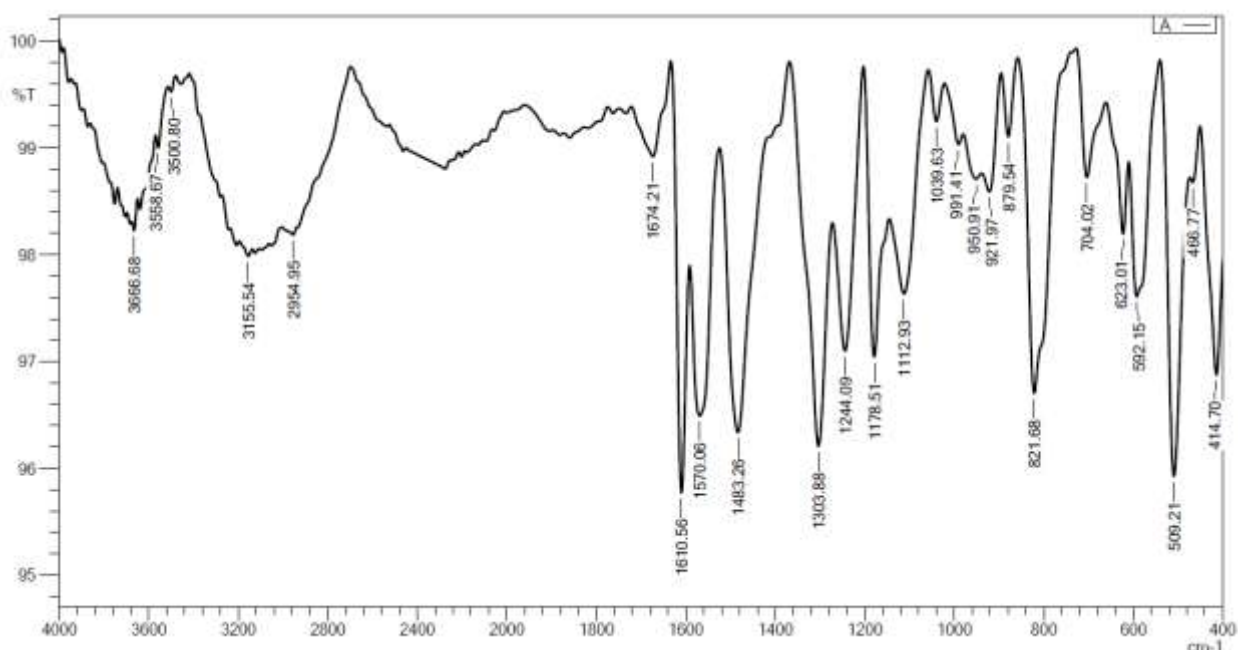


Figure 7. FTIR of PANI

TiO₂-CuO bimetallic nanocomposites, 30%

The infrared spectrum of a sample of a titanium dioxide/copper oxide in figure 8 nanocomposite with a 30 per cent copper oxide content. The infrared spectrum of this sample is characterised by the presence of absorption bands characteristic of the vibrational modes of nano-sized metal oxides, with two strong, sharp bands prominent in the high-frequency region at 3643 and 3304; these peaks may be attributed to the absorption of hydroxyl groups on the oxide surface and the moisture content of the sample. The spectrum also reveals bending vibration peaks of the oxides with hydrogen at frequencies of 1699 cm⁻¹ and 1593.2 cm⁻¹. In the region below these areas, which is less than 1 cm and is known as the metal-oxygen bond region, a broad and intense absorption band is observed, with its sharp, high peak centred at 445 cm, supported by peaks at frequencies including 667.37 cm, 621.8 cm and 569 cm. These peaks clearly indicate the overlap between the stretching vibration of the copper(I) oxide bond and the vibration of the titanium oxide bond, which confirms the successful chemical formation of the oxide nanocomposite. Similarly, researchers carried out a study of this kind, and the results were very similar, as they used the same method or one similar to it, which is consistent with the study[7].

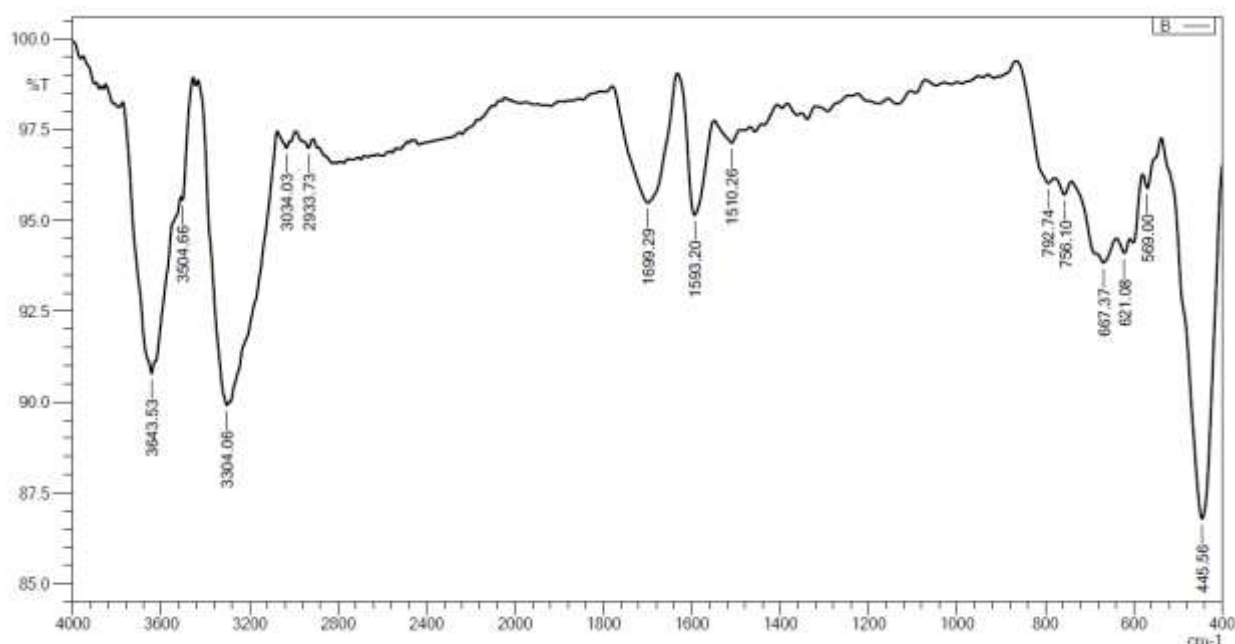


Figure 8. FTIR of $\text{TiO}_2\text{-CuO}$ bimetallic nanocomposites, 30%

PANI/ $\text{TiO}_2\text{-CuO}$ hybrid nanocomposites, 50%

Figure 9 shows the infrared spectrum of the sample consisting of copper and titanium oxides mixed with 50 per cent polyaniline. The infrared spectrum reflects the chemical interaction and overlap between the polyaniline and the nano-composite of titanium and copper oxides. The figure shows a strong absorption band for the hydroxyl-amine groups, which overlap at frequencies of 3653 and 3. 296 cm. The peaks characteristic of the poly(aniline) polymer chains, such as the quinone and benzopyran rings, are clearly visible at frequencies including 1581, 1568 and 1460, with a very slight shift in their spectral positions compared to the polymer in its pure state; this is due to the physical effects and the formation of hydrogen bonds between the surface of the nano-oxides and the amine groups in polyaniline. In addition, we observe carbon-nitrogen chain stretching and conductive vibrations at frequencies including 1292 and 1163 cm^{-1} , followed by the appearance of vibrational peaks characteristic of metal oxides in a region spanning from 422 to 692 cm^{-1} , which confirms the successful formation of the composite and the polymer encapsulation of the oxide nanoparticles. These results are similar to those obtained using the same preparation method and tests carried out in the study[18].

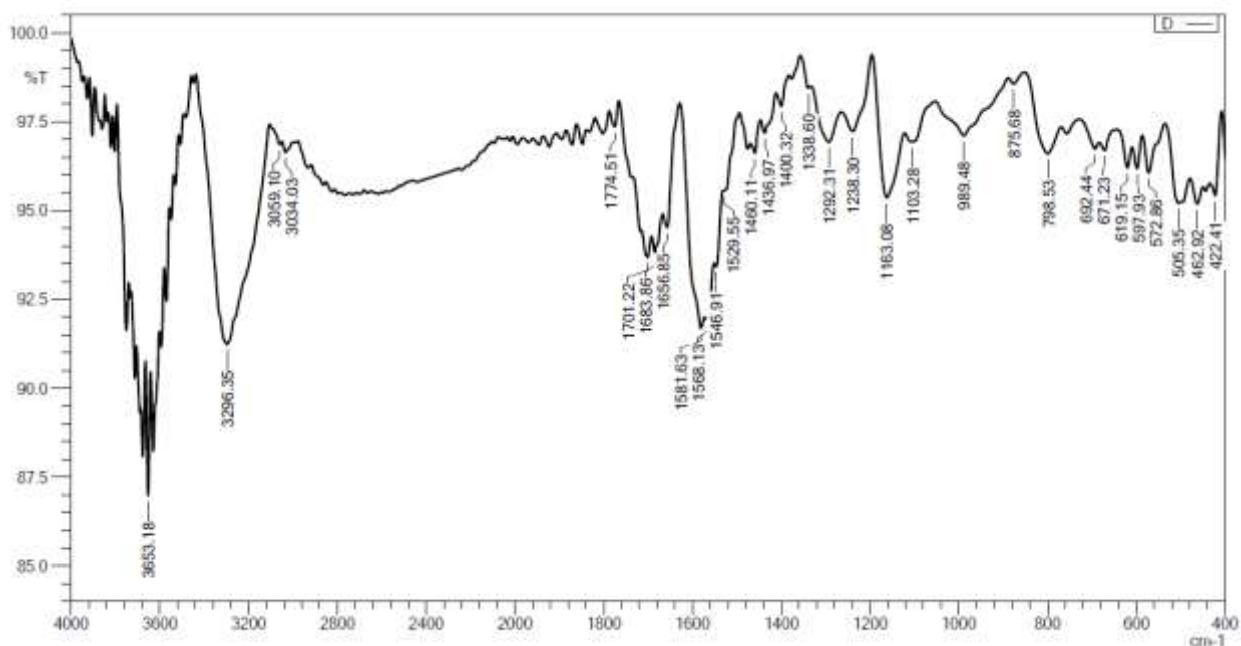


Figure 9. FTIR of PANI/TiO₂-CuO hybrid nanocomposites, 50%

4. EDS Analysis

PANI

Figure 10 shows the EDS elemental analysis of pure polyaniline. The figure illustrates the X-ray energy-dispersive spectroscopy (EDS) spectrum, which reveals the basic structural composition of the doped conductive polyaniline, with carbon emerging as the primary element, present at a proportion of 56.41 per cent and an atomic percentage of 67.75 per cent; this is a result of the uromatic structure of the benzene and quinone rings. This is followed by nitrogen, present in a weight percentage of 12.92 per cent and an atomic percentage of 13.32 per cent, represented by the polymeric amine groups. The figure also shows that oxygen is present in a weight percentage of 11.58 per cent and an atomic percentage of 10.45 per cent which may be due to moisture absorbed onto the surface; furthermore, sulphur is present with a weight percentage of 11.11 per cent, as is chlorine with a weight percentage of 6.94 per cent Both of these confirm the successful sulphurisation process, carried out by hydrochloric acid and the sulphonic acids present in the polyacrylonitrile matrix, with the possibility of a very small proportion of silicon, estimated at 1.04 per cent, attributable to the substrate present at the testing centre Findings of this nature were reported in the research, which confirmed a similarity or correspondence with the study in this research[19].

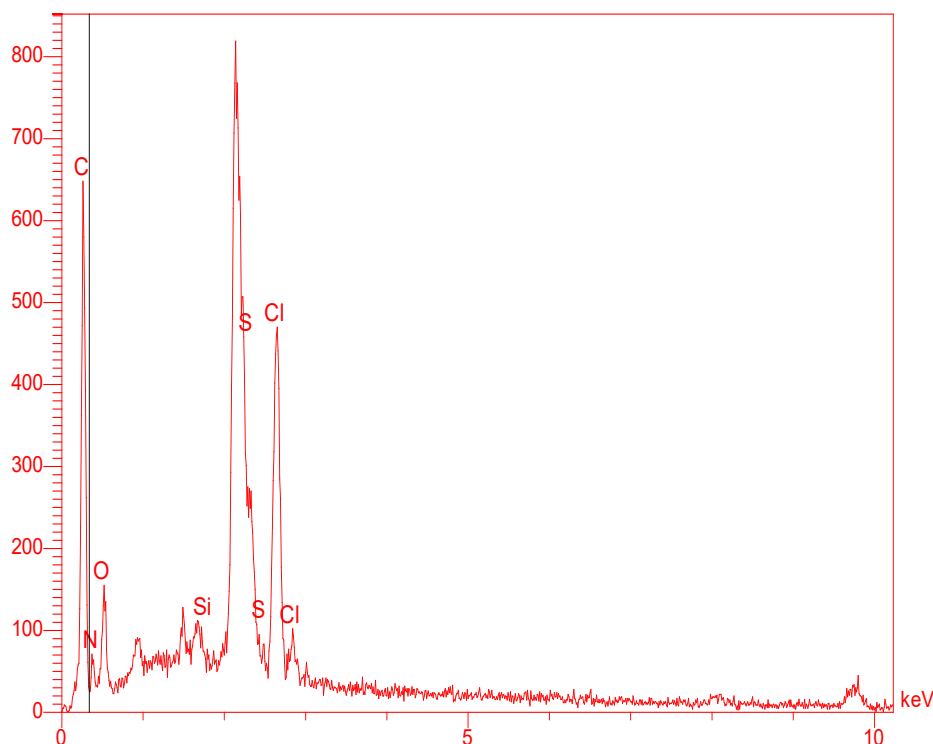


Figure 10. EDS of PANI

TiO₂–CuO bimetallic nanocomposites, 30%

Figure 11 shows the elemental analysis of the sample consisting of a binary titanium dioxide and copper oxide nanocomposite, present at a concentration of 30 per cent. The EDS results demonstrate the high purity and chemical composition of the binary nanocomposite, which consists exclusively of metal oxides, with titanium having the highest metallic content at a weight percentage of 44.26 per cent and an atomic percentage of 32.40 per cent, followed by copper with a weight percentage of 34.94 per cent and an atomic percentage of 19.28 per cent, completing the oxide composition and resulting in a peak for oxygen with a weight percentage of 17.06 per cent and a high atomic percentage of 37.40 per cent. This reflects the bonding of diatomic oxygen with both titanium and copper to form these oxides, whilst recording a very low carbon content of 3.74 per cent, resulting from the conductive mounting strip used during the microscopic examination. This result was found to be similar to the method of preparing the polymer with nano-oxides of the same properties used in the study[17].

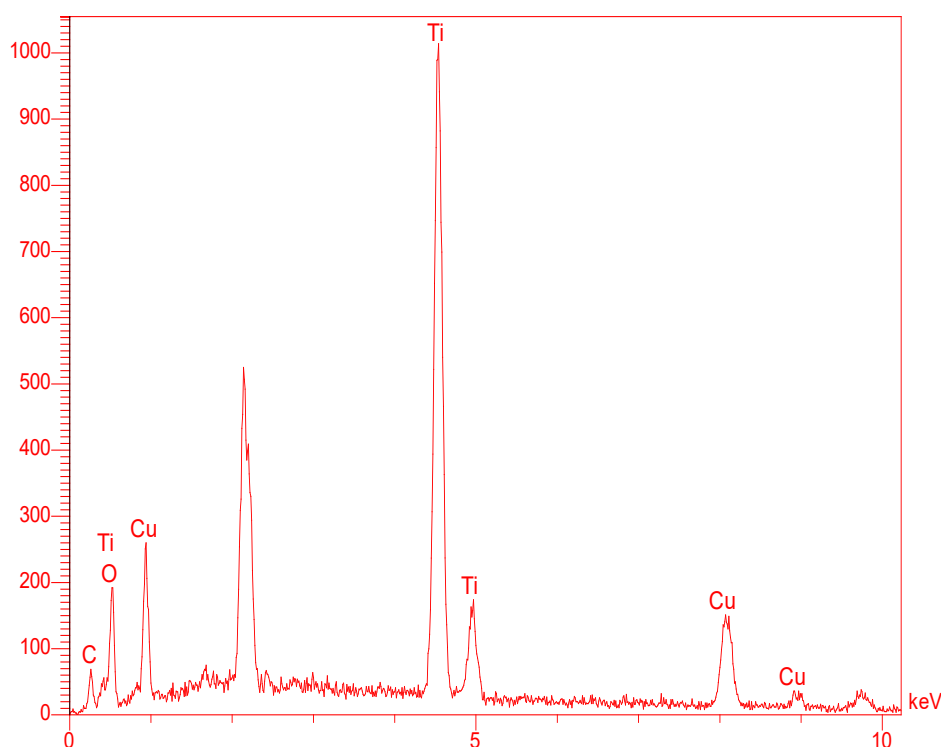


Figure 11. EDS of $\text{TiO}_2\text{-CuO}$ bimetallic nanocomposites, 30%

PANI/ $\text{TiO}_2\text{-CuO}$ hybrid nanocomposites, 50%

Figure 12 shows the elemental analysis of the hybrid nanocomposite consisting of titanium oxide and copper oxide combined with polyaniline in a 50 per cent ratio. The ADS adsorption spectrum and the successful composites between the polyaniline polymer matrix and the nano-metal oxide composite show that carbon is a major element, constituting a weight percentage of 44.20 per cent by weight and 56.15 per cent by atomic weight, resulting from the polymeric structure of polyaniline, which is accompanied by nitrogen at a weight percentage of 14.95 per cent. The oxide elements are also clearly present in the form of oxygen, at a weight percentage of 20.92 per cent. Titanium is estimated at 93 per cent by weight, whilst copper is estimated at 0.74 per cent by weight. In addition, there are traces of impurities such as chlorine, the proportion of which can be estimated at 6.86 per cent. Very small amounts of aluminium and silicon are also present, at 1.92 per cent and 1.10 per cent respectively. This demonstrates that the incorporation of nano-oxides into the polymer network results in a hybrid composite structure with very high efficiency [18].

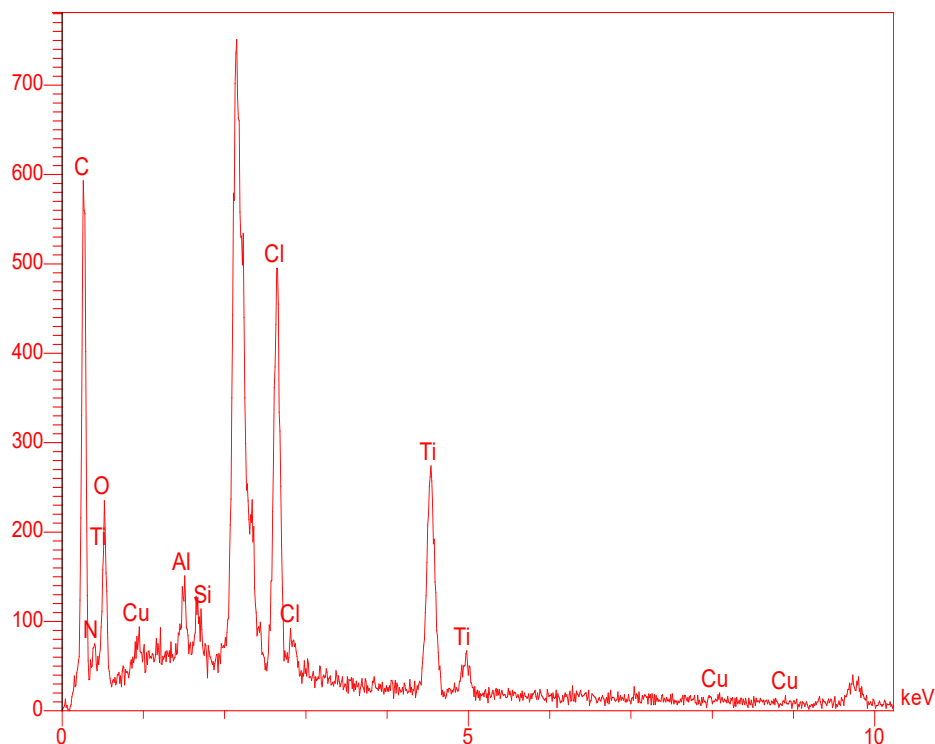


Figure 12. EDS of PANI/TiO₂-CuO hybrid nanocomposites, 50%

5. CV Analysis

PANI

Figure 13 illustrates the cyclic voltage and electrochemical measurements for a sample of pure polyacrylonitrile; the results of this analysis show that the sample exhibits distinctive electrochemical behaviour, consisting of pure polyacrylonitrile, within a voltage range extending from 0.75 V positive to 1.25 V negative. This reflects a semi-circular open-circuit curve with a high capacitance contribution, which may result from rapid, reversible oxidation and reduction reactions within the conductive poly-aniline polymer chains. These results, as well as the data in the attached table, reveal the presence of oxidation and reduction peaks recorded at , which may be significant, as the first oxidation peak appears at a potential of -0.25 V, with a current rise of approximately 23.14 microamperes, followed by the second main oxidation peak, which is somewhat pronounced and was recorded at a potential of +0.44 volts, with a high current of 40.94 microamperes; this reflects a structural transition of the polyacrylonitrile from one phase to another. Similarly, in the reverse direction of the very slight reduction, a reduction peak appears at a voltage of +0.091 volts, with a current of 15.70 microamperes, followed by a second reduction peak recorded at a voltage of -0.839 volts, with a current of -6.20 microamperes. This clearly demonstrates the sample's successful response to charge transfer and its role in enhancing the polymer material's high efficiency and excellent electrochemical performance As regards polymers, the results are almost identical or similar; numerous studies have been carried out, including one that yielded results very close to those obtained by the researcher[20].

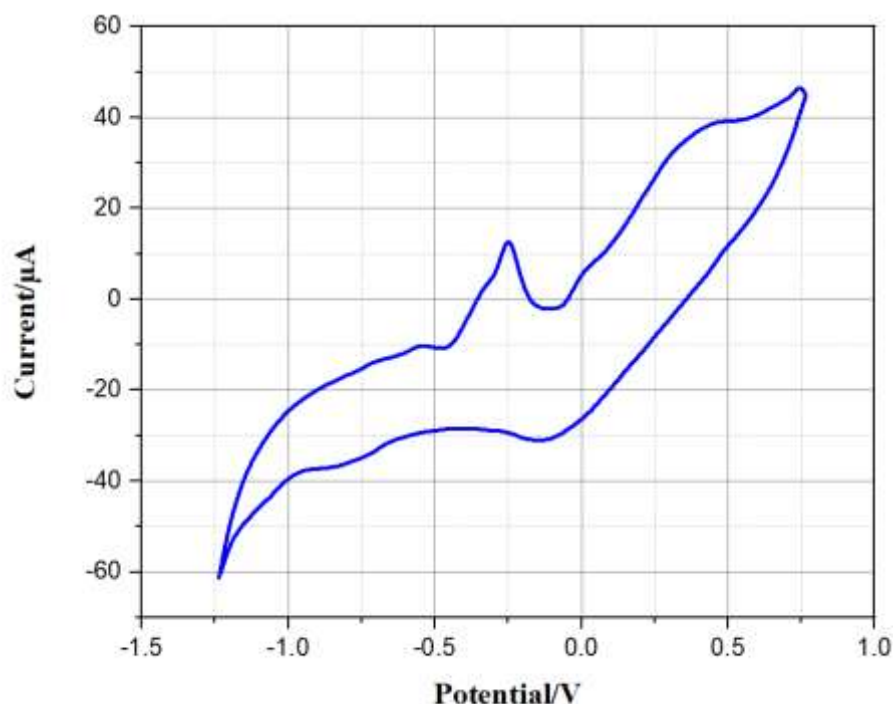


Figure 13. CV of PANI

Table 1. The voltage and current values for the peaks

Peak	Potential/V	Height/ μ A	Y Offset/ μ A	Max slope/ μ A/V	Min slope/ μ A/V	Sum/ μ A/V
1	-0.71579	7.05492	-21.1266	18.4798	-13.5991	32.0789
2	-0.55727	4.81596	-15.2321	124.144	101.069	225.214
3	-0.25013	23.4094	-10.8166	106.278	-201.860	308.138
4	0.44836	40.9426	-2.28246	-71.8687	-136.013	207.881
5	0.09169	15.7011	-35.9318	-72.3141	-200.119	272.433
6	-0.83964	-6.19799	-30.6232	25.2376	-18.2396	43.4772

TiO₂-CuO bimetallic nanocomposites, 30%

Figure 14 shows the results of the cyclic voltammetry analysis of the sample, which consists of a chemical composition of titanium and copper oxides. It reveals a good and strong electrochemical response, indicating the oxidation and reduction behaviour of the nanoscale layer of metal oxides within a potential range recorded at approximately -1.25 volts to a positive potential of 0.75 volts. According to the attached table, which shows the first oxidation peak—which is very sharp and clearly defined at a potential of -0.354 volts—at an exceptional current of 2,544 microamperes, this represents the oxidation states of titanium and copper, indicating the exchange of charges with electrons. In the reverse reduction process, the sample exhibits a first reduction peak recorded at a potential of minus 0.042 volts and a reduction current of -317 microamperes, followed by a sharp reduction peak at a potential of -0.631 and a high reduction current of -754 microamperes. This process demonstrated that the electrochemical reaction is efficient and exhibits a high current response resulting from the nano-oxide surface compared to the pure polymer[20].

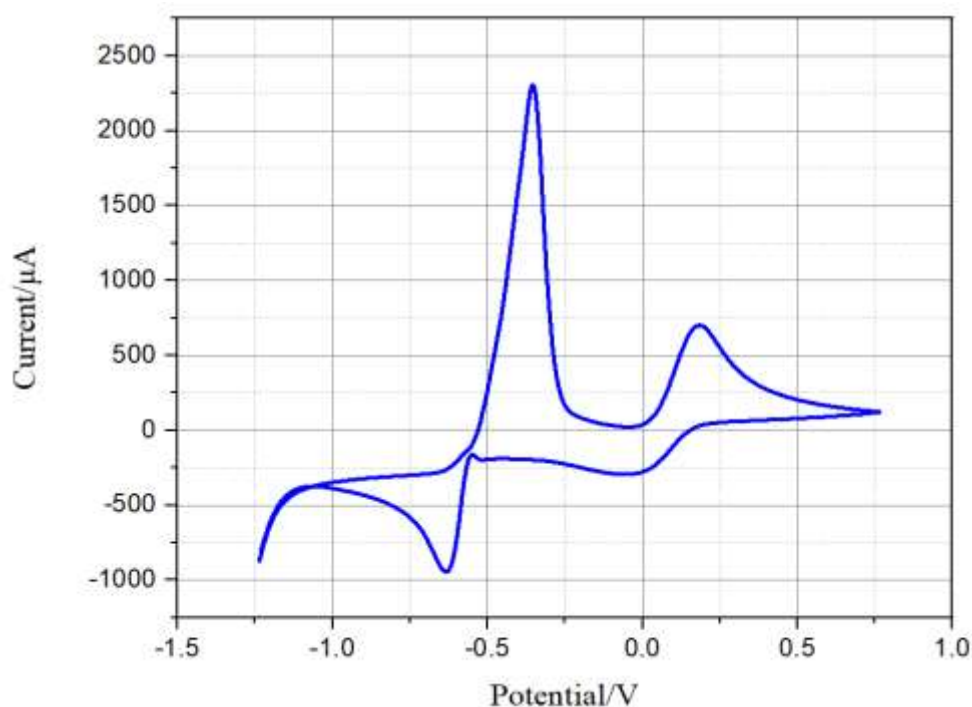


Figure 14. CV of $\text{TiO}_2\text{-CuO}$ bimetallic nanocomposites, 30%

Table 2. the voltage and current values for the peaks

Peak	Potential/V	Height/ μA	Y Offset/ μA	Max slope/ $\mu\text{A/V}$	Min slope/ $\mu\text{A/V}$	Sum/ $\mu\text{A/V}$
1	-0.35416	2544.98	-239.903	17571.6	-37082.4	54654.0
2	0.18581	680.597	21.2061	5840.79	-3113.77	8954.56
3	-0.04207	-317.707	25.5037	5840.79	-3113.77	8954.56
4	-0.49782	-4.42076	-190.026	-67.3570	-117.514	184.871
5	-0.63157	-754.531	-190.522	17571.6	-37082.4	54654.0

PANI/ $\text{TiO}_2\text{-CuO}$ hybrid nanocomposites, 50%

Figure 15 shows the results of the cyclic voltammetry analysis of the sample, which consists of aniline polymer with titanium and copper oxides, and in which a peak appears within a potential range extending from -1.25 V to $+0.75\text{ V}$. The numerical analysis provided in the table indicates that the curve exhibits three main oxidation peaks: the first was recorded at a potential of -0.498 V and a current of $13.46\text{ microamperes}$; this is followed by a second peak recorded at a potential of -0.225 volts and a current of 7.59 microamperes ; and finally, a broad third peak at a potential of $+0.344\text{ volts}$, with a current of 16.1 microampere . These processes reflect a dual oxidation process for both the polymer chains and the nano-oxides. Furthermore, in the reverse direction, the first reduction peaks were recorded at a potential of -0.55 volts and a current of $-0.73\text{ microamperes}$, in addition to a second peak recorded at a potential of -0.805 volts , with a reduction current recorded at $-4.49\text{ microamperes}$, with a noticeable drop in current towards the ultra-negative region as a result of the voltage drop associated with the reduction reactions; this demonstrates the successful formation of the hybrid composite and its electrochemical stability. Furthermore, this result is consistent with that obtained by the researcher in a study involving the synthesis of polymers[6].

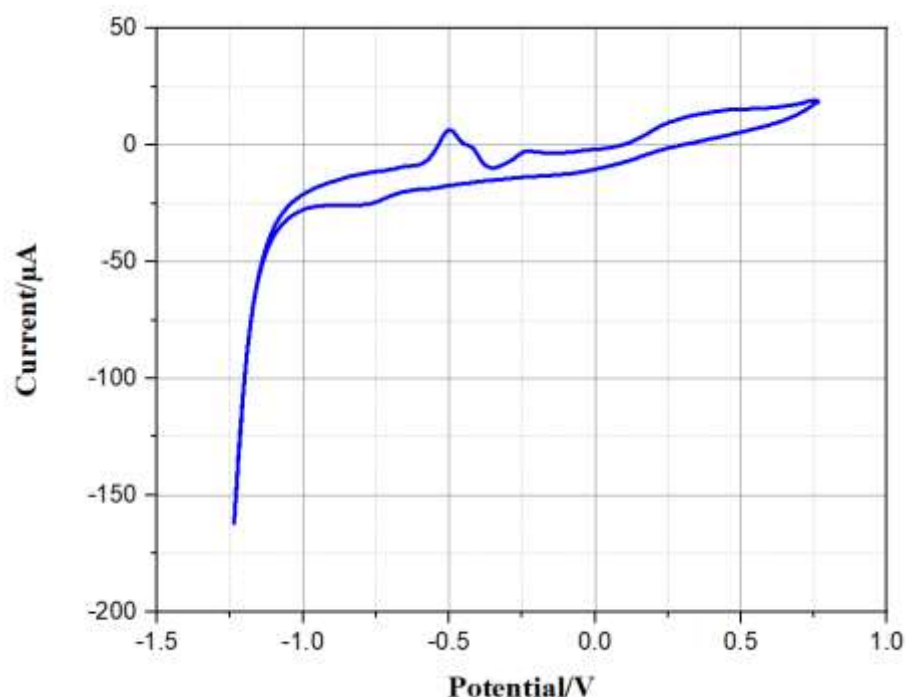


Figure 15. CV of PANI/TiO₂-CuO hybrid nanocomposites, 50%

Table 3. the voltage and current values for the peaks.

Peak	Potential/V	Height/μA	Y Offset/μA	Max slope/μA/V	Min slope/μA/V	Sum/μA/V
1	-0.49782	13.4608	-6.95217	223.890	-186.872	410.762
2	-0.22536	7.58876	-10.1595	95.5790	-82.5247	178.104
3	0.34433	16.0079	-3.02289	74.2713	-82.5247	156.796
4	-0.55727	-0.73459	-17.8241	-14.3332	-25.8547	40.1878
5	-0.80496	-4.48537	-21.1756	-9.26811	-52.4559	61.7240

6. UV-Vis Analysis

PANI

Figure (16) illustrates the absorbance of pure polyaniline polymer, showing a distinct absorption band recorded at a wavelength of 250 nm with an absorbance of 0.057 Abs; these transitions are attributed to $\pi \rightarrow \pi^*$ electronic transitions within the aromatic benzene rings that make up the polymer's structure. An absorption region extending into the visible and infrared regions, close to 800 nm, was also observed; this is due to the presence of a polaron band, which confirms the occurrence of a transition towards an electrochemical conductive state. This result is consistent with a previous study in which the researchers [18] and which the researchers confirmed: that the absorption of polyaniline occurs in the near-ultraviolet region, reflecting the aromatic transitions of the polymer chains that have been doped into the conductive phase.

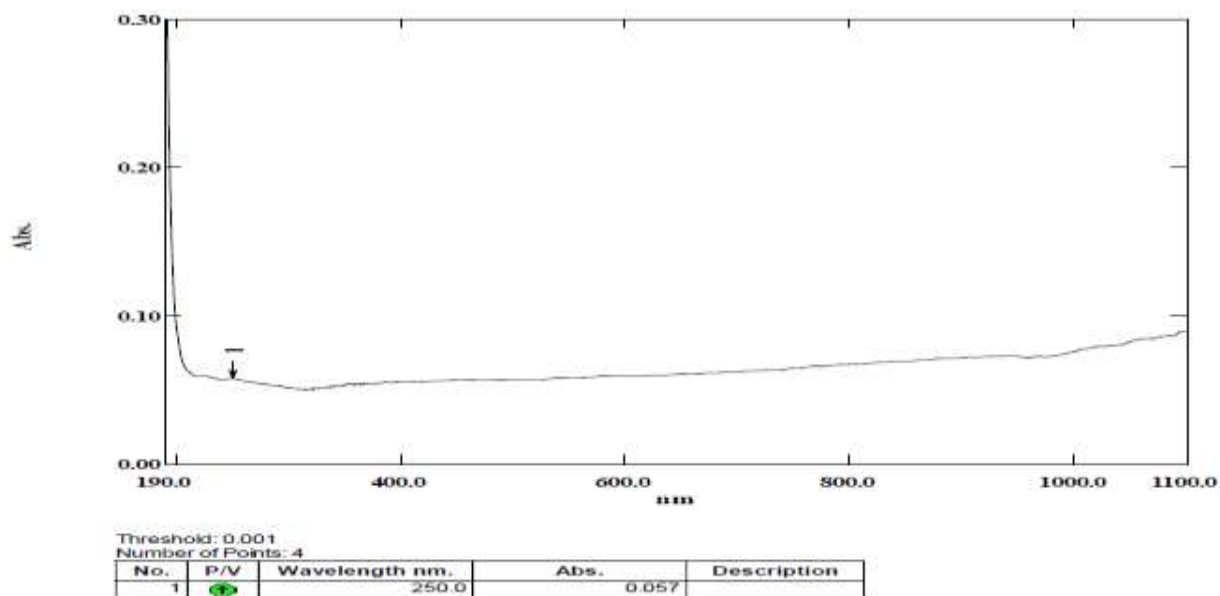


Figure 16. UV-Vis of PANI

TiO₂-CuO bimetallic nanocomposites, 30%

Figure (17) shows the light absorption spectrum of the titanium dioxide-copper dioxide nanocomposite, revealing two main absorption peaks. The first peak, recorded in the ultraviolet region at a wavelength of 340 nm, has an absorbance of 0.127 Abs. This peak is attributed to an electronic transition known as the bandgap transition, which occurs between the valence and conduction bands, in the titanium dioxide phase. as for the second peak, it appears in the infrared region, close to a wavelength of approximately 1017 nm, with an absorbance of 0.161 Abs; this is produced by orbital transitions of copper ions in the monolayer structure of copper oxide, This result is consistent with a reference study conducted by the researcher [13], which demonstrated that combining copper oxide with titanium oxide broadens the range of light absorption towards longer wavelengths, thereby reducing the energy gap of the nanocomposite.

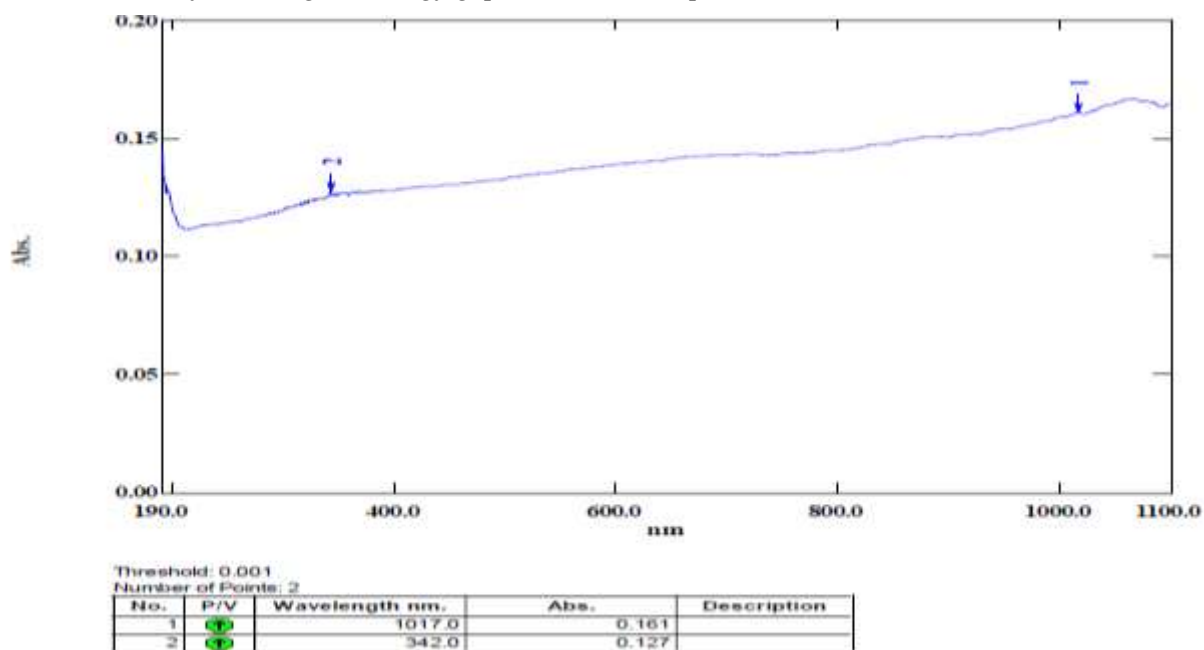


Figure 17. UV-Vis of TiO₂-CuO bimetallic nanocomposites, 30%

PANI/TiO₂-CuO hybrid nanocomposites, 50%

The absorption spectrum shown in Figure (18) for the hybrid nanocomposite reveals two distinct, closely spaced and overlapping absorption bands, recorded at wavelengths of 338 nm and 342 nm, with an absorbance of 0.038 Abs. The first absorption peak at 338 nm is attributed to a $\pi \rightarrow \pi^*$ electronic transition in the doped aromatic polyaniline network, whilst the second peak at 342 nm is attributed to the bandgap absorption of titanium oxide, where a shift in the spectral peaks and a decrease in their intensity were observed when compared to pure niobium oxides; this confirms strong physicochemical interaction and the coating of the poly-aniline chains onto the surface of the nanoparticles. This result for the hybrid is consistent with the study conducted by the researcher [20], who demonstrated that the hybrid composite of binary oxides and poly-naphthalene causes spectral shifts in the ultraviolet region due to the formation of nitrogen bonds and electron transfer between the oxides and the polymer.

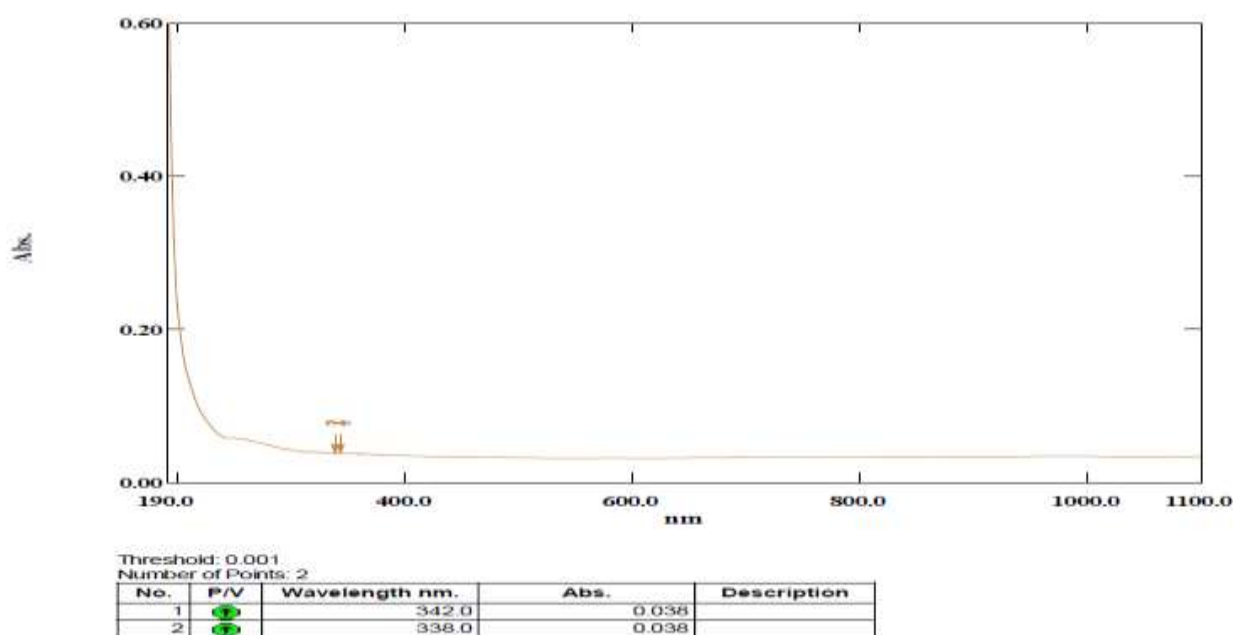


Figure 18. UV-Vis of PANI/TiO₂-CuO hybrid nanocomposites, 50%

4. Conclusion

The diagnostic results demonstrated the success of the polymer in pure polyacrylonitrile in its conductive phase, with a clustered morphology featuring pores that allowed rapid ion passage, as well as an electrochemical response that is reversible. As for the nanostructures of both titanium dioxide and copper oxide, the test results confirmed that these oxides possess crystalline purity and a soft, monoclinic anatase phase, such that the charged particles are distributed evenly; this gives the composite a higher electrochemical oxidation current due to the high conductivity of the metal as well as rapid charge exchange. Ultimately, the nano-composite and the poly(aniline) hybrid with titanium oxide and copper oxide proved successful through encapsulation within a poly(aniline) matrix for the nano-oxides; hydrogen bonds were formed, thereby combining the capacitive properties of poly(aniline) with the high stability of the oxides to achieve excellent, high, balanced and consistent electrochemical performance.

REFERENCES

- [1] An overview of recent developments in polyaniline-based supercapacitors. *Journal of Advanced Polymer Technologies* 30 (8), 1902–1921 (2019)
- [2] Z. Zhao, K. Xie, Y. Hu, K. Zhang, Z. Yi, J. Lu, Design of flexible, smart and self-sustaining supercapacitors for portable/wearable electronic devices: from conductive polymers. *Journal of the Chemical Society*, Vol. 50 (22), pp. 12702–12743 (2021).
- [3] HB Wu, G. Zhang, L. Yu, XWD Lou, One-dimensional hybrid metal oxide–carbon nanostructures for electrochemical energy storage. *Nanoscale Horizons*. 1 (1), 27–40 (2016)
- [4] B. Beta, E. Obraztsov, F. De Souza, W. Kotner, Composites of conductive polymers and various carbon nanostructures for supercapacitors. *Journal of the Electrochemical Society: Solid State Science and Technology* 2 (10), M3120 (2013)
- [5] Fu, Q. Qu, R. Holze, V.V. Kondratiev, Y. Wu, Compounds of metal oxides and self-conductive polymers as electrode materials for supercapacitors: the best of both worlds? *Journal of Materials Chemistry A* 7 (25), 14937–14970 (2019)
- [6] C. Huang, C. Hao, W. Zheng, S. Zhou, L. Yang, X. Wang, L. Zhu, Synthesis of a poly(aniline)/nickel oxide/sulphurised graphene tripolymer for an asymmetric, all-solid-state supercapacitor. *Journal of Applied Surface Science* 505, 144589 (2020)
- [7] K. P. Gautam, D. Acharya, A. Bhatta, V. Subedi, M. Das, S. Nyupan, A. P. Yadav, Poly(aniline) nanocomposites incorporating nickel oxide as an effective electrode material for supercapacitor applications. *Inorganic Materials*. 10 (6), 86 (2022)
- [8] B. R. Deshmukh, S. V. Patel, R. N. Polakhi, S. D. Sartali and C. D. Lokhande deposited a thin composite film of porous polyaniline and titanium oxide for supercapacitor applications. *Journal of Materials Communications Today*, 8, 205–213 (2016).
- [9] H. S. Roy, M. M. Islam, M. Y. A. Mullah, M. A. B. H. Susan, (2020). In situ prepared polyaniline-MnO₂ composites during the oxidative polymerisation of aniline for supercapacitor applications. *Materials Today: Proceedings*, 29, 1013–1019
- [10] FZ Dahou, MS Belardja, I. Moulefera, L. Sabantina, A. Benyoucef, Preparation of a poly(aniline)@CuO-zeolite tripartite composite, and discussion of its properties, advantages and applications in supercapacitors and the adsorption of cationic dyes. *Polym. Int.* 72 (11), 1025–1037 (2023)
- [11] M. Rahman, I. Khan, D. L. Field, K. Tishato, K. Allama, 'Powering Agriculture: Current Status, Future Potential, and Challenges for Renewable Energy Applications'. *Renewable Energy*. 188, 731–749 (2022)
- [12] Omar, Energy, Environment and Sustainable Development. *Journal of Renewable and Sustainable Energy* 12 (9), 2265–2300 (2008)
- [13] SA Arote, *Electrochemical Energy Storage Devices and Supercapacitors: An Overview* (IOP Publishing, 2021)
- [14] S. Madukuri, D. Malka, M.S. Chai, Y. Elias, S. Losky, D. Orbach, 'The challenge of large-scale energy storage using electrochemical devices'. *Journal of Electrochemistry* 354, 136771 (2020)
- [15] C. Arbizani, M. Mastragostino, F. Suavi, 'New trends in electrochemical supercapacitors'. *Journal of Energy Sources* 100 (1–2), 164–170 (2001)
- [16] C. Zhong, Y. Ding, W. Hu, J. Qiao, L. Zhang, J. Zhang, A review of electrolyte materials and formulations for supercapacitors. *Journal of the Chemical Society*, Vol. 44 (21), pp. 7484–7539 (2015).
- [17] A. Kanwal, M. Rahman, R. Star, K. H. Thibou, M. Qadi, High-efficiency tin oxide and polyaniline-tin oxide nanomaterials for the photodegradation of organic dyes. *Journal of Molecular Synthesis* 1312, 138454 (2024)
- [18] L. M. Santino, Y. Lu, Y. Diao, H. Wang, J. M. Darcy, *Conductive Polymers for Electrochemical Capacitors (Conjugated Polymers)*, 2019, pp. 561–586
- [19] A. Malinauskas, J. Malinauskienė, A. Ramanavičius, 'Conductive polymer-based nanomaterials: electrochemical aspects'. *Nanotechnology*. 16 (10), R51 (2005)

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- [20] A. Afkhari, L. Li, Y. Yang, Supercapacitors made from polyaniline. *Journal of Energy Sources*. 347, 86–107 (2017)
- [21] Mostafaei & Zolriyatn, 2012; *Progress in Natural Science: Materials International*
- [22] Reddy et al., 2020; *Journal of Alloys and Compounds*
- [23] Ghanbari & Salavati-Niasari, 2015; *Journal of Industrial and Engineering Chemistry*.