Journal of Materials & Environmental Sustainability Research (2024), 4(4): 1-13
p-ISSN: 2811-1338; e-ISSN: 2811-132X
DOI: https://doi.org/10.55455/jmesr.2024.011

Original Research Paper

Synthesis and Characterization of Eco-Engineered Ternary Iron-Clay-Silver Nanocomposites: A Novel Multifunctional Material

Utibe B. Orok[1], Solomon E. Shaibu[1,2*], Eno A. Moses[1], Emmanuel I. Uwah[1]

[1] Department of Chemistry, University of Uyo, Uyo, Nigeria
[2] International Centre for Energy and Environmental Sustainability Research, University of Uyo

*Corresponding author: Solomon E. Shaibu (shaibusolomon@uniuyo.edu.ng)

Received: October 20, 2024; Received in revised form: December 3, 2024; Accepted: December 9, 2024; Published: December 19, 2024

Abstract

This aim of this study was to develop and characterize a novel ternary clay nanocomposite (TCN) comprising iron nanoparticles, clay, and silver nanoparticles, synthesized through an eco-friendly approach using *Carica papaya* leaf extract as a reducing agent. This eco-engineered nanocomposite was synthesized via a facile and environmentally friendly route using *Carica papaya* leaf extract as reducing agent by leveraging the principles of green chemistry. The nanocomposite's structural, morphological and compositional properties were thoroughly investigated using analytical techniques, including X-ray diffraction (XRD), transmission electron microscopy (TEM), scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS); Brunauer-Emmett-Teller (BET) and Fourier transform infrared spectroscopy (FTIR). The results revealed a homogeneous distribution of silver and iron nanoparticles within the clay matrix with a mean particle size of 33.5 nm, indicating a strong interfacial interaction between the components. The nanocomposite exhibited high surface area, distinctive morphology, dispersion and functional properties, making it a promising candidate for various sustainable applications, such as wastewater treatment, biomedical devices and environmental remediation. This study demonstrates a significant advancement in the design, synthesis and characterization of multifunctional nanomaterials with promising potentials.

Keywords: novel multifunctional material, clay, silver nanoparticle, iron nanoparticles, eco-engineering

DOI: 10.55455/jmesr.2024.011

1. Introduction

Nanotechnology has become a global topic of interest with significant potential for several applications and has undergone significant development in recent times. It deals with the design, synthesis and manipulation of materials on a scale between 1 – 100 nm (Laurent *et al.*, 2010). The significant development of this emerging technology has opened up researches into novel and eco-friendly synthetic routes as well as increased application due to its unique properties like particle size, great surface – to – volume ratio, biocompatibility and stability (Khan *et al.*, 2020), etc. There are different types of nanomaterials (nanoparticles, nanocomposites, carbon nanotubes, graphenes, fullerenes, etc.) as reported by Obadimu *et al.* (2024). Nanocomposite refers to multiphase materials with nanoscale addition in one of the phases (Al–Mutairi *et al.*, 2022). It consists of at least two components made up of continuous matrix and non-continuous reinforcement phases giving rise to combined features of the two materials for improved application (Hassan *et al.*, 2021). Nanoparticles can be engineered into nanocomposites with organic or inorganic materials, with resulting biological, optical, magnetic, adsorptive (Adebayo *et al.*, 2019), mechanical, thermal, or solvent-resistant (Hassan *et al.*, 2021) properties for specifically tailored applications. Nanocomposites, being heterogeneous in nature can be either binary (two material components) or ternary (three material components). Binary nanocomposites have received wide research attention (Li *et al.,* 2017; Obadimu *et al*. 2024) while the research into ternary composites is still in the early stages and more studies are needed to improve their properties and widen applications (Oluwafemi *et al.,* 2021). Two primary approaches are often available for nanocomposite synthesis; the physical or chemical techniques (which use organic/inorganic reducing agents or electrochemical and physicochemical reducing methods), or the biological synthetic method (Jacob *et al.,* 2022).

Biogenic synthesis of nanocomposites entails synthesis through biological processes utilizing organisms such as bacteria, fungi or plants (Sidhu *et al.,* 2022). Previous studies show that biological entities like yeast (Mandal *et al.,* 2006), algae (Madhavi *et al.,* 2013), fungi (Yehia and Al – Sheikh, 2014), bacteria (Kianpour *et al.,* 2017) and higher plants (Iravani *et al.,* 2016; Herlekar *et al.,* 2014) are good source of reducing, stabilizing and capping agents for biosynthesis of clean, eco – friendly, sustainable and stable nanocomposites. Synthesis of nanocomposites from biological organisms like fungi and bacteria (microbe–based synthesis) is costly and time – consuming whereas synthesis from plant materials do not require expensive and extensive procedures (Nahari *et al.,* 2022). The biogenic synthetic method has numerous advantages over the conventional synthetic methods such as simplicity of synthesis (one-pot synthetic route), elimination of the use of harsh, toxic or expensive chemical substances, high reduction potential, stability and minimum environmental impact (Ohiduzzaman *et al.,* 2024). Plant extracts have been extensively used in biogenic synthesis due to its biodiversity and the numerous secondary metabolites (alkaloids, flavonoids, saponins, tannins, etc.) (Enin *et al.*, 2023) in different plant parts (seeds, roots, stems, leaves, flowers and barks) (Enin *et al.*, 2021) which act as reducing, stabilization and capping agents during the synthesis (Sidhu *et al.*, 2022 and Shaibu *et al*., 2022). Successful preparation of ternary nanocomposites using conventional physical and chemical methods have been reported by Manikandan *et al.* (2022), they carried out a biogenic synthesis of $TiO_2/ZrO_2/SiO_2$ ternary nanocomposite using plant extract.

Carica papaya which belongs to the family Caricaceae is well known for its various nutritional and health benefits. The fruit and leaf extract exhibit antioxidant and antimicrobial properties while their extracts can be used to treat diabetes, indigestion and even for curing open wounds. Biomolecules like caffeic acid, chlorogenic acid, kaempferol, quercitin, carpaine, choline, etc. present in *Carica papaya* are responsible for their reducing, capping and stabilizing properties, making it possible for the formation of nanocomposites (Jacob *et al*., 2022). Jahangir *et al*. (2023), Alam (2022) and Konjari *et al*. (2015) conducted studies on the use of *Carica papaya* in biogenic synthesis of nanoparticles and nanocomposites leveraging on the abundance of biomolecules in this plant. Also, Mude *et al.* (2009) reported spherical and rod-like shapes and 30 nm size of silver nanoparticles using callus extract of *Carica papaya*. Similar works on the use of *Carica papaya* in the biosynthesis of nanomaterials are presented in **Table 1**. This study aims to develop novel ternary metal nanocomposite materials through biogenic synthesis, providing an environmentally friendly, sustainable and easy one–pot synthetic route, to enhance its importance for various applications.

Table 1. Application of *Carica papaya* in the biosynthesis of nanomaterials

S/N	Plant Part	Nanoparticle	Biomolecules responsible for reduction	Morphological features	References
1	Leaves	AgNPs	Proteins, Carbonyl compounds	Helical shape, no aggregation	Swapna *et al.* (2022)
2	Leaves	Fe_2O_3 NPs	Phenolic compounds, carboxylic acid, secondary alcohols	Crystalline, non-uniform, agglomerated, 21.59 nm in size	Bhuiyan *et al.* (2020)
3	Shell extract	TiO_2 NPs	Phenolics	Crystalline, superficial morphology, spherical shape	Saka *et al.* (2022)

Table 1. Continued

4	Leaves	AgNPs	Phenolic compounds	Crystalline, face-centred cubic structure	Potdar *et al.* (2022)
5	Peel	AgNPs	Proteins, phenolic compounds	28 nm in size, face-centred cubic structure	Kokila *et al.* (2016)
6	Leaves	Fe_2O_3 NPs	Proteins, alcohols, phenolic compounds	Crystalline, 43 nm in size, agglomerated, spherical shape	Usha *et al.* (2022)
7	Leaves	AgNPs	Alcohols, phenolic compounds, amino acids	Crystalline, face-centred cubic structure, spherical shape, 25 – 50 nm size	Konjari *et al.* (2015)
8	Callus, Seed, Leaf, juice, peel	AgNPs		Nanorods, triangular shapes, agglomerated, polydispersed, < 100 nm size.	Jahangir *et al.* (2023)
9	Peel	Iron – doped ZnO NPs		Crystalline, spherical shape, 20.4 nm size	Al-Odayni and Abduh,(2023)
10	Leaves	AgNPs	Alcohols, phenolic compounds	Crystalline, spherical shape, face-centred cubic structure, 5 – 50 nm size	Banala *et al.* (2015)
11	Leaves	Cu – Ag NPs	Phenols, polyphenols, amino acids, proteins, carbohydrates	Polycrystalline, spherical shape, 20 – 50 nm size	Jacob *et al.* (2022)
12	Peel	AgNPs	Carboxylic acids, proteins, phenolic acids	Spherical shape, uniform distribution, 15 – 20 nm size	Balavijayalakshmi & Ramalakshmi, (2017)
13	Fruit	AgNPs	Ascorbic acid, phenolic compounds	Well dispersed, 35 – 50 nm size	Firdaus *et al.* (2017)
14	Leaves	AgNPs	Phenolics, carbohydrates		Patel & Singh, (2020)
15	Leaves	AgNPs		Crystalline, Spherical, 40.8 nm size	Syafiuddin *et al.* (2017)
16	Peel	AgNPs		Rod – like morphology, crystalline, 70 – 95 nm size	John *et al.* (2021)

2. Materials and Methods

2.1 Materials

The chemicals for the bench work were analytical grade (AR) reagents, hence, no further purification requirements. These include; silver trioxonitrate V ($AgNO_3$; 99.80% purity; by Merck, Germany), Iron (III) chloride ($FeCl_3$; 99% purity; Sigma – Aldrich, U.S.A) and Hydrochloric acid (HCl; 37% purity; Riedel – deHaen, U.S.A.). Other materials include *Carica papaya* (pawpaw) leaves, distilled water and natural clay.

2.2 Collection of *Carica papaya* Leaf and Extract Preparation

Fresh leaves of *Carica papaya* were collected from Uyo, Akwa Ibom State, Nigeria and identified by a taxonomist from the University of Uyo, Nigeria as shown in **Figures 1a** and **b**. The leaves were thoroughly washed with distilled water to remove impurities and air–dried to remove moisture before crushing into a fine powder

(Kormal & Anya, 2013). A 5.0 g of the leaf was weighed and boiled with 100 mL of distilled water for about 20 minutes at 70 °C and cooled at room temperature. The broth was separated from the leaves by filtration and the pure extract was refrigerated before synthesis (Jacob *et al*., 2022).

Figure 1. (a) *Carica papaya* tree and (b) *Carica papaya* leaves

2.3 Phytochemical Screening

Phytochemical screening of the *Carica papaya* leaves extract was done according to standard procedures, reported by Dubale *et al*. (2023). The presence of different phytochemicals were assessed by colour change or precipitate formation (Swapna *et al*., 2022).

2.4 Collection and Preparation of Clay material

The natural clay sample used in this study was sourced from Ikot Ebom Itam, Itu, Akwa Ibom State, Nigeria. It was washed, dried, pulverized and soaked in HCl for purification and separation of impurities for four hours (Hu *et al*., 2022). The soaked clay sample was washed with several times with distilled water, dried and pulverized before being used for the biosynthesis of the TCN.

2.5 Synthesis of Ternary Nanocomposite

The TCN was prepared in a similar method as described by Balachandar *et al*. (2019) and Magdalane *et al*. (2016). A 5.0 g each of the pulverized clay was washed, aged for 2 days and stirred for 6 hours with a 30 mL solution of the precursor (1 mM $FeCl_3$) and 30 mL of $AgNO_3$ to form slurry. About 100 mL of the *Carica papaya* leaves extract was then added to the slurry, stirred for 24 hours, allowed to age for 48 hours until a brown colour was observed before filtration. The residue was dried in an oven at 30 °C for 24 hours to form a cake and finally crushed into fine powder.

2.6 Characterization of the Ternary Clay Nanocomposite (TCN)

The absorbance spectra of the synthesized TCN was obtained using UV – visible spectroscopy while surface morphology as well as size and shape were determined using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) respectively. Also, surface and porousity characteristics, elemental composition as well as the crystallinity were determined using BET, EDX and XRD respectively. The Fourier – Transform infrared (FTIR) spectroscopy analysis was carried out using Nicolet 370 FT-IR spectrometer obtained at a transmittance mode operated at resolution of 2 cm^{-1} from 4000 cm^{-1} to 400 cm^{-1}

3. Results and Discussion

3.1 Physicochemical Analysis

Qualitative phytochemical screening of the *Carica papaya* leaves extract as represented in **Table 2** showed that phytochemicals like alkaloids, flavonoids, glycosides, saponins and tannins are responsible for the reduction of the metal precursors and subsequent stabilization of the ternary nanocomposite. This result is in agreement with the result of phytochemical screening of *Carica papaya* by Nandi *et al*. (2020) and Nduche *et al*. (2019).

Table 2. Phytochemical screening of *Carica papaya* leaves extract

S/N	Phytochemical	Test	Result
1	Alkaloids	Mayer's Test	+
		Iodine Test	+
2	Anthraquinones	Borntrager's Test	-
3	Flavonoids	Shinoda Test	+
4	Glycosides	Salkowski's Test	+
5	Phenolics	Lead acetate Test	+
		Iodine Test	+
6	Saponins	Frothing test	+
7	Tannins	Ferric chloride Test	+
		Braymer's Test	+

(-) Indicates absence (+) indicates presence

3.2 Surface plasmon resonance of TCN

The spectra of clay shows minimal absorption around 250 nm while that of the synthesized TCN shows enhanced absorption peaked around 350 nm and 450 nm for iron and silver nanoparticles respectively in the clay matrix depicted in **Figures 2a** and **b**. This highlights how incorporating nanoparticles like silver and iron into clay materials significantly alters their optical properties, enhancing their absorption in specific regions of the UV-visible spectrum.

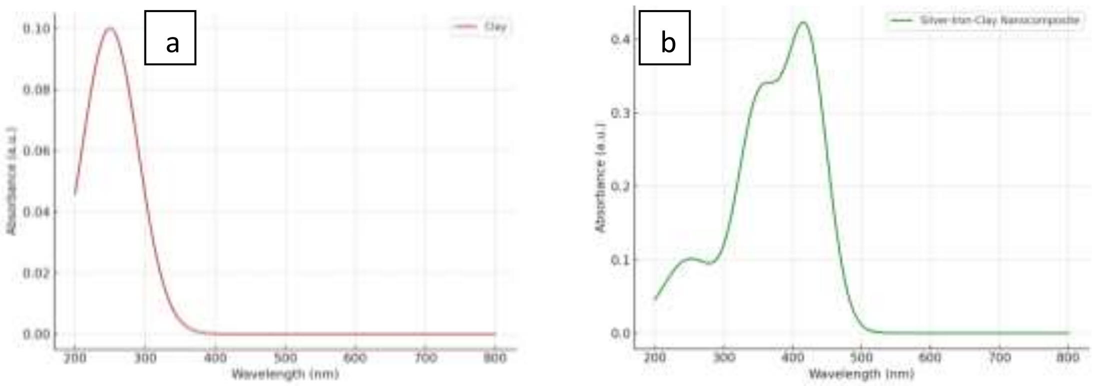

Figure 2: Uv-vis spectra of (a) natural clay (b) TCN

3.3 Surface morphology, shape and particle size of TCN

The SEM images of the clay and ternary (Fe – Clay – Silver) nanocomposite prepared from the leaves extract of Carica papya are shown in **Figures 3a** and **b** respectively. The TEM image of the ternary nanocomposite is presented in **Figure 3c** while the particle distribution is in **Figure 3d**. An improved morphology was seen when comparing the SEM images of the natural clay and the TCN. The natural clay shows extensive agglomeration of the particles in a lumpy form while the particles of the TCN were found to be well dispersed with minimal aggregation basically due to the capping and stabilization by the biomolecules from the extract. The slight aggregation is due to the iron–based magnetic interactions as reported by Bhuiyan *et al*. (2020) and agglomeration of clay particles, which is typical in nanocomposites due to strong Van der Waals forces between the clay layers (Jacob *et al*., 2022). Similarly, the particles exhibit an irregular, granular structure with a non-uniform size distribution as supported by the TEM image. The TEM micro-graph in **Figure 3d**, shows the grains and grain boundaries oriented in different plane outlines indicating the polycrystallinity of the TCN with an average particle size of 33.5 nm. The Light region in the TEM images indicates the porosity of the TCN. More so, some of the grains appear darker than others due to diffraction contrast as a result of the different orientations of the particles. These observations are in agreement with the findings of Aswiri *et al*. (2024) and, Mohamad & Hawar, (2022). The possibility of the TCN having more than one geometric shape is primarily due to the different bioactive components in the extract (Obadimu *et al*., 2024). **Figure 3d** shows the particle size distribution of a TCN, where the majority of particles fall within the 30 - 40 nm range, indicating a narrow distribution that may result from precise synthesis conditions.

3.4 FTIR Analysis

Molecular vibrations were studied using FTIR spectra as presented in **Figure 4a** and **b** for clay and TCN respectively and used to identify the interaction of functional groups in biomolecules with the precursors and clay material in other to evaluate the efficacy of the synthesis and stabilization of TCN. The spectrum for natural clay in **Figure 4a** shows major absorption peaks at 3693.71 cm^{-1}, 3622.34 cm^{-1}, 1625.04 cm^{-1}, 1093.64 cm^{-1} and 910.40 cm^{-1}. Peaks 3693.71 cm^{-1} and 3622.34 cm^{-1} represent –OH vibrations typical of clay while absorption at 1625.04 cm^{-1} indicates possible adsorbed water on the clay material (Rezender *et al*., 2018). Peaks at 1093.64 cm^{-1} and 910.40 cm^{-1} represent Si – O in-plane stretching and Al – OH – Al bending vibrations of the clay material respectively. This is in agreement with the previous submissions of Oguz *et al*. (2016) and Rezender *et al*. (2018). The spectrum of the TCN in **Figure 4b** shows sharp and intense bands at 3428.81 cm^{-1}, 2921.63 cm^{-1}, 2852.20 cm^{-1}, 1681.62 cm^{-1}, 1384.6 cm^{-1}, 1047 cm^{-1}, 790 cm^{-1} and 694 cm^{-1} aside from the ones observed in the clay material. The prominent peaks of TCN are highlighted in **Table 3** depicting the influence of different phytochemicals from the *Carica papaya* extract on the TCN functionalities (Nandini *et al*., 2020).

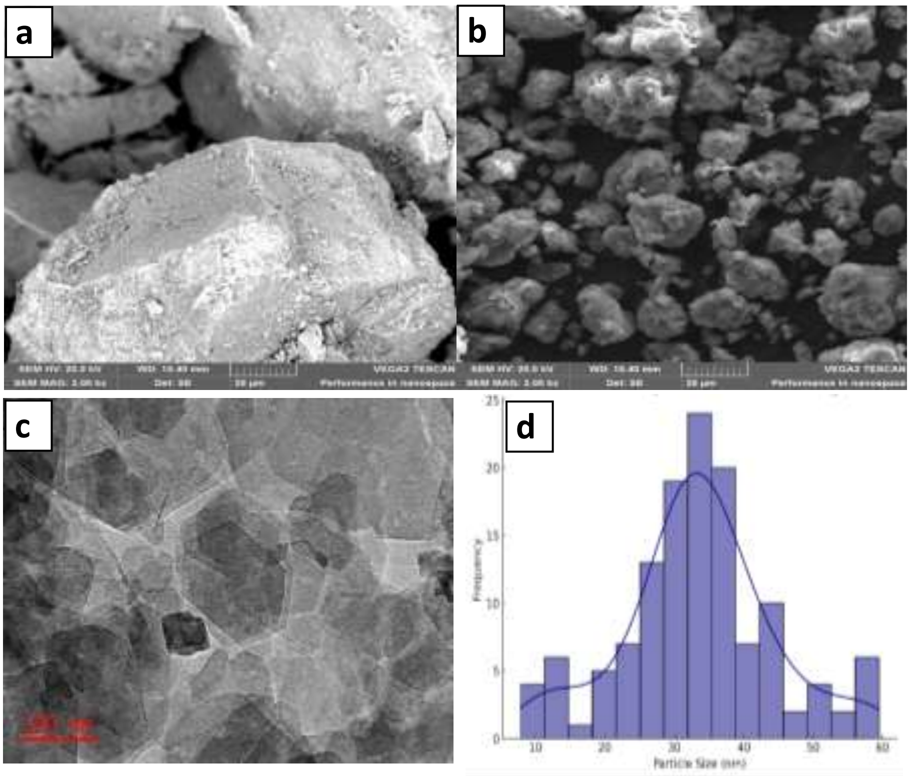

Figure 3. (a) SEM image of natural clay mineral (b) SEM image of synthesized TCN (c) TEM image of TCN (d) particle size distribution of TCN

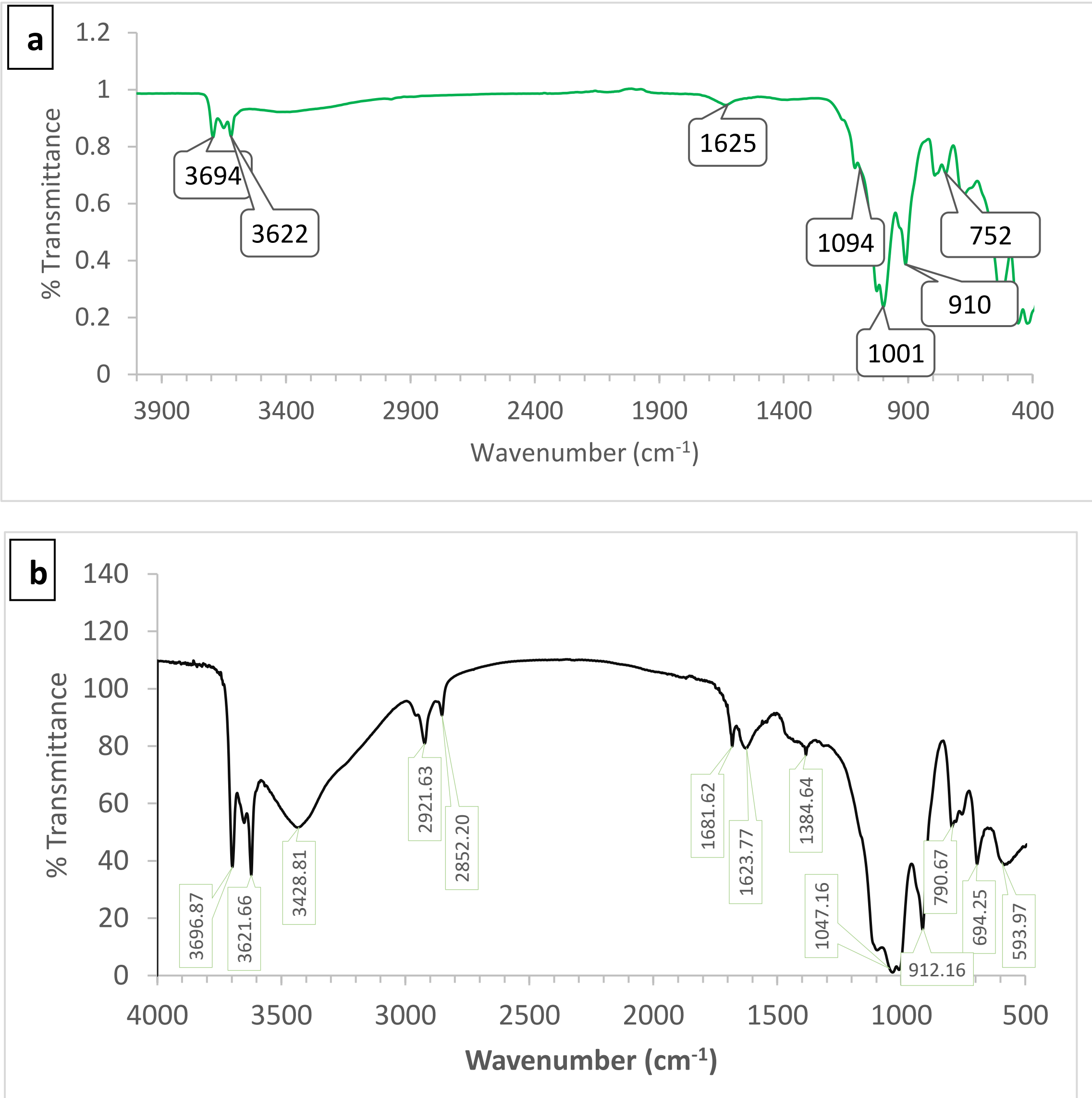

Figure 4. FTIR Spectra of (a) natural clay (b) TCN

3.5 EDX Analysis

The elemental analysis of the clay and the TCN using energy dispersive X – ray spectroscopy is as shown by the spectra in **Figure 5a** and **b**. The EDX spectrum of natural clay (fig.3 a) shows the dominant elements; silicon (Si), oxygen (O) and aluminum (Al). Silicon (40.2%) and aluminum (26.1%) are key constituents of aluminosilicate minerals (quartz, kaolinite and montmorillonite), which form the structural basis of the clay material and is consistent with result of Sabbagh *et al*. (2019). The high silicon content confirms the presence of silica (SiO2), a primary component of clays and other silicate-based materials. Oxygen and aluminum in the clay sample indicates the presence of oxide compounds, particularly silicates and aluminates. This finding supports the identification of the sample as clay, specifically in the form of aluminum silicates such as kaolinite or montmorillonite. These compounds are common in natural clays and contribute to the material's thermal stability, plasticity and ion-exchange properties (Singh *et al*., 2019; Irabor & Unuigbe, 2023). The spectrum shows no significant impurities, suggesting that the sample is a relatively pure form of aluminosilicate clay. The spectrum of the synthesized TCN using *Carica papaya* leaf extract (**Figure 5b**) highlights the presence of silicon (Si), oxygen

(O), aluminum (Al) as typical constituents of the clay matrix, silver (Ag) and iron (Fe) from the bio-synthesized silver and iron nanoparticles in the TCN. The presence of carbon (C) is due to organic components from the *Carica papaya* leaf extract or carbon-based compounds formed during the synthesis process.

Table 3. Functional groups observed from FTIR analysis of TCN

S/N	Observed Peak (cm^{-1})	Functional Groups	References
1	3428	–OH stretching vibration of alcohols and phenols	Banala *et al.* (2015)
2	2921	–CH stretching vibrations of alkyls	Jacob *et al.* (2022)
3	2852	–CH stretching vibrations of alkyls	Datkhile *et al.* (2023)
4	1681	–C=C stretching of aromatic functional group	Manikandan *et al.* (2022)
5	1384	–CN stretch of amines	Balavijayalakshim *et al.* (2017)
6	1047	–C–OH stretching vibration	Mahalingam *et al.* (2023)
7	790	–CH out – of – plane bending vibrations of aromatic phenols	Ullah *et al.*, (2024)
8	694	–CX weak vibration of alkyl halides	Alghthaymi *et al.* (2021)

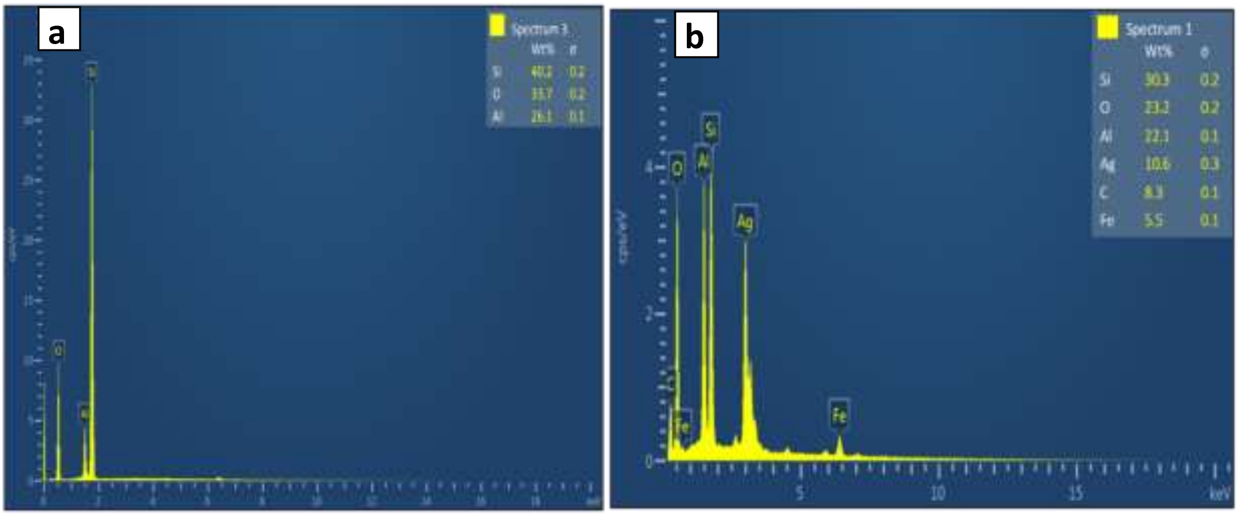

Figure 5. EDX spectra of (a) Clay and (b) TCN

3.6 Phase purity and Crystallinity of TCN

The XRD diffractogram of the clay and TCN, **Figures 6a** and **b** as compared with the reflection patterns of the Joint Committee on Powder Diffraction Standards (JCPDS) card no. 04-0783 and 06–0696 reveals key information about its mineralogical composition and crystallinity. The most prominent peak, occurring around 25° (2θ), is characteristic of quartz (SiO_2) with high intensity suggesting that quartz is a major phase in the sample. Other smaller peaks between 5° and 10° (2θ) may indicate the presence of montmorillonite or illite, which are typical clay minerals. Montmorillonite, in particular, often shows peaks in this region due to its layered, expandable structure. Additional peaks observed around 12° (2θ) are likely attributed to kaolinite, it is known for its characteristic peaks at both 12° and 25° (2θ) as also seen in the result of Obot *et al*. (2021) and Shaibu *et al*. (2022).

The TCN diffractogram in **Figure 5b**, shows significant peaks at around 38.1° (2θ) and 44.1° (2θ) corresponding to the (111) and (200) planes of face-centered cubic (FCC) silver (Ag), clearly visible while a peak observed near 44.7° (2θ), corresponds to the (110) plane of body-centered cubic (BCC) α-Fe (zerovalent iron). However, the peak at 35.5° (2θ) corresponds to the (311) reflection of magnetite (Fe_3O_4), indicating partial oxidation of the iron nanoparticles (Dadashi *et al.*, 2015; Shaibu *et al.*, 2014).

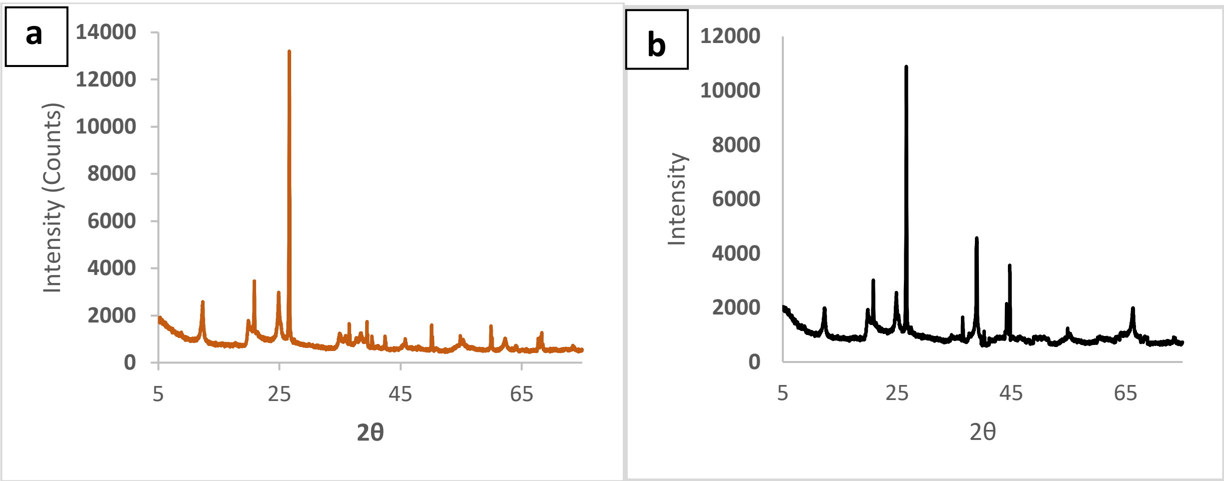

Figure 6: XRD diffractogram of (a) clay and (b) TCN

3.7 Surface Area Determination

BET Analysis was done to determine the surface characteristics like surface area, pore size and pore volume and the result is presented in **Figure 7**. The plain clay has a surface area of 44.23 m^2/g, a pore volume of 0.1032 cm^3/g and a pore size of 91.177 Å typical for natural clays. The iron-clay-silver ternary composite exhibits significant changes, with a surface area of 112.03 m^2/g, a pore volume of 0.3208 cm^3/g and a pore size of 182.004 Å. This sharp increase in surface area and pore volume highlights the synergistic effects of incorporating both iron and silver into the clay, resulting in improved performance in applications requiring high surface area and porosity.

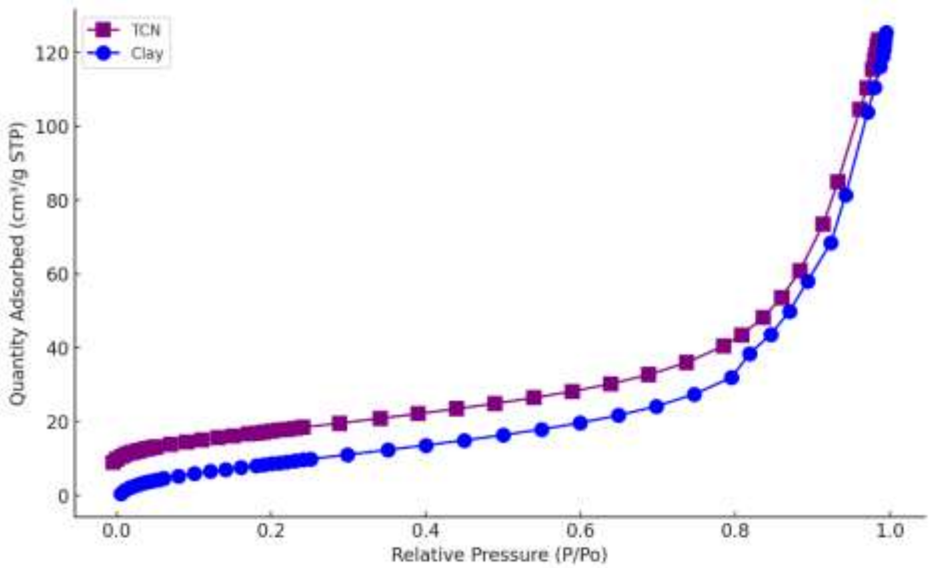

Figure 7: N_2 adsorption desorption plot of clay and TCN

4. Conclusion

The synthesis of ternary clay nanocomposite using *Carica papaya* leaves extract, metal precursors and clay as the matrix material was successfully carried out as confirmed by the extensive characterization results. Biological compounds like alkaloids, flavanoids, phenolics, saponins and tannins were found to be present in the extract and perform the roles of reduction, capping and stabilization. The nanocomposite was composed of well-dispersed silver and iron nanoparticles over the clay matrix, which was made up of major quartz, kaolinite and montmorillonite minerals. Further characterization of the synthesized TCN revealed its highly crystalline nature with excellent surface characteristics like surface area, pore volume and pore size. The combination of these materials has offered enhanced properties, such as optical and improved adsorption efficiency, due to the synergistic effects of both silver and iron nanoparticles. The TCN therefore has great potential for various applications, especially in environmental remediation owing to its simple and cost-effective synthesis method and excellent properties.

Acknowledgements: Authors express appreciation to TETFUND, Nigeria, for providing support for this study through the Institutional Based Research (IBR) Programme 2023 set.

References

Adebayo, G. B., B. B. Balogun, S. E. Shaibu, W. Jamiu, E. U. Etim, F. Oleh, N. E. Efiong and B. S. Ogboo. (2019). Comparative study on the adsorption capacity and kinetics of xylene onto rice husk and cassava peel activated carbon. *International Journal of Current Resesrch* 11: 8282-8288.

Al-Odayni, A. B. and Abduh, N. A. Y. (2023). *Carica papaya* Peel extract – induced Iron – doped zinc oxide nanostructures: synthesis, characterization, hemolysis and antibacterial properties. *Biomass Conversion and Biorefinery*, 6: 04980.

Alam, M. W., Qahtani, H. S. A., Aamir, M., Abuzir, A., Khan, M. S., Albuhulayqah, M., Mushtaq, S., Zaidi, N. and Ramya, A. (2022). Phyto synthesis of manganese-doped zinc nanoparticles using *Carica papaya* leaves: structural properties and its evaluation for catalytic, antibacterial and antioxidant activities. *Polymers*, *14*(9): 211-230.

Alghuthaymi, M. A., Rajkuberan, C., Santhiya, T., Krejcar, O., Kuca, K., Periakaruppan, R. and Prabukumar, S. (2021). Green Synthesis of Gold Nanoparticles Using *Polianthes tuberosa* L. Floral Extract. *Plants*, 10, 2370.

Al-Mutairi, N. H., Mehdi, A. H. and Kadhim, B. J. (2022).Nanocomposites Materials Definition, Types and some of their Applications.: A Review. *European Journal of Research Development and Susutainability,* 3(2): 102-108.

Aswiri, R., Jothiman, K., Pothu, P., Shanmugam, P., Boddula, R., Radwan, A. R., Periyasami, G., Karthikeyan, P. and Al – Qahtani, N. (2024). *Carica papaya* leaves infused metal oxide nanopcomposite: a green approach towards water treatment and anti – bacterial applications. *Environmental Geomistry Health*, 46: 334.

Balachandar, R., Gurumoorthy, P., Karmegam, N., Barabadi, H., Subbaiya, R., Anand, K. and Saravanan, M. (2019). Plant – mediated synthesis, characterization and bactericidal potential of emerging silver nanoparticle using stem extract of *Phyllanthus pinatus*: A resent advance in phytonanotechnology. *Journal of Cluster Science,* 30(6): 1481 – 1488.

Balavijalakshmi, J. and Ramalakshmi, V. (2017). *Carica papya* peel mediated synthesis of silver nanoparticles and its antibacterial activity against human pathogens. *Journal of Applied Research and Technology,* 15 (5): 1 – 15.

Banala, R. R., Nagati, V. B. and Karnati, P. R. (2015). Green synthesis and characterization of *Carica papaya* leaf extract coated silver nanoparticles through x – ray diffraction, electron microscopy and evaluation of bactericidal properties. *Saudi Journal of Biological Sciences,* 22(5): 637 – 644.

Bhuiyan, M. H., Miah, M. Y., Paul, S. C., Aka, T. D., Saha, O., Rahaman, M. and Sharif, M. (2020). Green synthesis of iron oxide nanoparticle using *Carica papaya* leaf extract: application for photocatalytic degradation of remazol yellow dye and antibacterial activity. *Heliyon*, 6: 04603.

Dadashi, S., Poursalehi, R. and Delavari, H. (2015). Structural and optical properties of pure iron and iron oxide nanoparticles prepared via pulsed Nd:YAG laser ablation in liquid. *Prodedia Material Science*, 11: 722 – 726.

Datkhile, K. D., Durgawale, P. P., Chakraborty, S., Jegdale, N. J., More, A. L. and datil, S. R. (2023). Biogenic nanoparticles: synthesis, characterization and biological potential of gold nanoparticles synthesized using *Lasciosiphon eriocephalu* decne plant extract. *Pharmaceutical Nanotechnology*, 11(3): 303 – 314.

Dubale, S., Kebebe, D., Zeynudin, A., Abdissa, N. and Suleman, S. (2023). Phytochemical screening and antimicrobial activity evaluation of selected medicinal plants in ethiopia. *Journal of Experimental Pharmacology*, *15*, 51–62.

Enin, G. N., Antia, B. S., Shaibu, S. E. and Nyakno, I. (2023). Comparison of the chemical composition, nutritional values, total phenolics and flavonoids content of the ripe and unripe Solanum nigrum Linn. Fruits from Nigeria. *World Journal of Pharmacy and Pharmaceutical Sciences*, *12*(8), 1-18.

Enin, G. N., Shaibu, S. E., Ujah, G. A., Ibu, R. O. and Inangha, P. G. (2021). Phytochemical and Nutritive Composition of Uvariachamae P. Beauv. Leaves, Stem Bark and Root Bark. *ChemSearch Journal*, *12*(1), 9-14.

Firdaus, M., Andriana, S., Elvinawati, Alwi, W., Swistoro, E., Ruyani, A. and Sundaryono, A. (2017). Green Synthesis of Silver Nanoparticles Using *Carica papaya* Fruit Extract Under Sunlight Irradiation and their Colorimetric Detection of Mercury Ions. Journal of Physics: *Conference Series*, 817, 012029.

Hassan, T., Salam, A., Khan, A., Khan, S. U., Khanzada, H., Wasim, M., Khan, M. Q. and Kim, I. S. (2021). Functional nanocomposites and their potential applications: A review. *Journal of Polymer Research*, *28*(2):105 – 120.

Heriekar, M., Barve, S., Kumar, R. (2014). Plant-mediated green synthesis of iron nanoiparticles. *Journal of Nanoiparticles Research*, 2014: 1-9.

Hu, B., Zhang, C. and Zhang, X. (2022). The Effects of Hydrochloric Acid Pretreatment of Different Types of Clay Minerals. *Minerals,* 12 (12): 1167.

Irabor, E. E. and Unuigbe, C. A. (2023). Evaluation of some physico-chemical and mineralogical properties of clay mineral deposits in Ihievbe, Owan East Local Government Area, Edo State, Nigeria*. Chemsearch Journal,* 14(1): 33 – 38.

Iravani, S., Korbekandi, H., Mirmohammadi, S. V. and Zolfaghari, B. (2016). Green synthesis of metal nanoparticles using plants*. Green Chemistry,* 13(10):2638 – 2650.

Jacob, J., Prasad, T.,Vithiya, B. S. and M. Rosaline Athisa, M. R. (2022). Biosynthesis of bimetallic Cu-Ag nanocomposites and evaluation of their electrocatalytic, antibacterial and anti-cancerous activity. *Journal of Pure and Applied Microbiology,* 16(2):955-966.

Jahangir, G.Z.; Anjum, T.; Rashid, N.; Sadiq, M.; Farooq, R.; Akhtar, M.; Hussain, S.; Iftikhar, A.; Saleem, M.Z.; Shaikh, R.S. (2023). *Carica papaya* crude extracts are an efficient source of environmentally friendly biogenic synthesizers of silver nanoparticles. *Sustainability*, 15: 16633.

John, T., Parmar, K. A., Kotval, S. C. and Jadhav, J. (2021). Synthesis, characterization, antibacterial and anticancer properties of silver nanoparticles synthesized from *Carica papaya* peel extract. *International Journal of Nanoscience and Nanotechnology,* 17, 23 – 32.

Khan, S. A., Shahid, S. and Lee, C. S. (2020). Green synthesis of gold and silver nanoparticles using leaf extract of clerodendrum inerme; characterization, antimicrobial and antioxidant activities. *Biomolecules*, *10*(6):112 – 134.

Kianpour, S. , Ebrahiminezhad, A., Mohkam, M., Tamaddon, A. M., Dehshahri, A. and Heidari, R. (2017). Physicochemical and biological characteristics of the nanostructured polysaccharide-iron hydrogel produced by microorganism *Klebsiella oxytocaa*. *Journal of Basic Microbiology,* 57(2):132-140.

Kokila, T., Ramesh, P. S. and Geetha, D. (2016). Biosynthesis of AgNPs using papaya peel extract and evaluation of its anti-oxidant and antimicrobial activties. *Ecotoxicology and Environmental Safety,* 134(2): 467 – 473.

Komal, R. and Anya, V. (2013**)**. Biosynthesis and characterization of silver nanoparticles from aqueous leaf extracts of *Carica papaya* and its antibacterial activity. *International Journal of Nanomaterials Biostructures*, 3, 17–20.

Konjari, R. S., Jacob, A. A., Yayanthi, S., Ramalingam, C. and Ethiraj, A. S. (2015). Investigation of biogenic silver nanoparticles green synthesis from *Carica papaya. International Journal of Pharmacy and Pharmaceutical Sciences*, 7(3): 107 – 110.

Laurent, S., Bridot, J., Elst, L. V. and Muller, R. (2010). Magnetic iron oxide nanoparticles for biomedical applications. *Future Medicinal Chemistry*, 2(3):427-449.

Li, F., Li, Z., Zeng, C. and Hu, Y. (2017). Laccase-assisted rapid synthesis of colloidal gold nanoparticles for the catalytic reduction of 4-nitrophenol. *Journal of the Brazilian Chemical Society*, *28*(6), 960–966.

Madhavi, V., Prasad, T. N., Reddy, V. B., Ravindra, R. B. and Madhavi, G. (2013). Application of phytogenic zerovalent iron nanoparticles in the adsorption of hexavalent chromium. *Spectrochimica Acta A: Molecular and Biomolecular Spectroscopy*, 116: 17-25.

Magdalane, C. M., Kaviyarasu, K., Vijaya, J. J., Siddhardha, B. and Jeyaraj, B. (2016). Photocatalytic activity of binary metal oxide nanocomposites of CeO2/CdO nanospheres: Investigation of optical and antimicrobial activity. *Journal of Photochemistry and Photobiology B: Biology*, 163:77–86.

Mahalingam, S., Govindaraji, P. K., Solomon, V. G., Kesavan, H., Neelan, Y. D., Bakthavatchalam, S., Kuri, J. and Bakthavatchalam, P. (2023). Biogenic synthesis and characterization of silver nanoparticles. Evaluation of their larvicidal, antibacterial and cytotoxic activities. *ACS Omega*, 8: 11923 – 11930.

Mandal, D., Bolander, M. E., Mukhopadhyay, D., Sakar, G. and Mukherjee, P. (2006). The use of microorganisms for the formation of metal nanoparticles and their application. *Applied Microbiology and Biotechnology*, 69:485-496.

Manikandan, V., Packialakshmi, J. S., Bharti, B., Jayanthi, P., Dhandapani, R., Velmurugan, P., Elango, D., Paramasivam, R., Mohanavel, V., Syed, A. and Elgorban, A. M. (2022). Efficient One-Pot Synthesis of $TiO_2/ZrO_2/SiO_2$ Ternary Nanocomposites Using Prunus× Yedoensis Leaf Extract for Enhanced Photocatalytic Dye Degradation. *Oxidative Medicine and Cellular Longevity*, *2022*(1), 3088827.

Mohammed, G. M. and Hawar, S. N. (2022). Green Biosynthesis of Silver nanoparticles from *Moringa oleifera* leaves and its Antimicrobial and Cytotoxicity Activities. *International Journal of Biomaterials*, 2022: 4136641.

Mude , N., Ingle, A., Grade, A. and Rai, M. (2009). Synthesis of silver nanoparticles using callus extract of *Carica papaya* – A first report. *Journal of Plant Biochemistry and Biotechnology,* 18, 83 – 86.

Nahari, M. H., Ali, A. A., Asiri, A., Mahnashi, M., Shaikh, I. A., Shettar, A. and Hoskeri, J. (2020). Green Synthesis and Characterization of Iron Nanoparticles Synthesized from Aqueous Leaf Extract of *Vitex leucoxylon* and its Biomedical Applications. Nanomaterials, 12(14): 2404.

Nandini, G., Gopenath, T. S., Nagalambika, P., Murugesan, K., Ashok, G., Ranjith, M. S., Pradeep, P. and Kanthesh, M. B. (2020). Phytochemical analysis and antioxidant properties of leaf extracts of *Carica papaya*. *Asian Journal of Pharmaceutical and Clinical Research,* 13(11):58 – 62.

Nduche, M. U., Nkaa, F. A. and Onyebinime A. (2019). Phytochemical screening and microbial activity of *Carica papaya* L, *Citrus paradisi* L, *Citrus sinensis* L and *Vernonia amygdalina* Del. C. *Diary and Veterinary Science Journal*, 9(4): 555768

Obadimu, C. O., Shaibu, S. E., Enin, G. N., Ituen, E. B., Anweting, I. B., Ubong, U. U., Ekwere, I. O., Adewusi, S. G., Adeoye, T. J., Fapojuwo, D. P. and Ofon, U. A. (2024). Aqueous phase adsorption of phenothiazine derivative onto zinc oxide doped activated carbon. *Scientific Reports*, *14*(1), 21611.

Obot, O. W., Odeh, E., Okon, A. and Obot, M. (2021). Mineralogy of clays from Ikot Ebom Itam, Akwa Ibom State, Nigeria. *International Journal of Innovative Research in Sciences and Engineering Studies (IJIRSES)*, 1(2): 28 – 34.

Oguz, M., Usher, H., Uzunoglu, D. and Ozer, A. (2016). Green synthesis of clay/silver nanocomposite for adsorption of harzardous dyestuffs. *Desalination and Water Treatment,* 93: 309 – 317.

Ohiduzzaman, M., Khan, M. N. and Khan, K. A. (2024). Green Synthesis of *Carica papaya* mediated Silver Nanoparticles: Characterization, Antibacterial Activity and Bioelectricity Generation for Sustainable Application in Nanotechnology. *Journal of Molecular Structure*, 1317, 139141.

Oluwafemi, O. S., Sakho, E. M., Parani, S. and Lepebe, T. C. (2021). Ternary quantum dots: synthesis, properties and application. Woodhead Publishing series in electronic and optical materials, pp. 77-115.

Patel, N. and Singh, S. (2020). Green Synthesis and Characterization of Silver Nanoparticles Using Banana and Papaya Leaves Extract and Their Application. *International Journal of Agriculture Innovations and Research,* 8(6): 2319 – 1473.

Potdar, C. K. Jain, H. and Dixit, R. B. (2022). *Carica papya* leaves extract for biosynthesis of nanoparticles and their application. *Journal of Environmental Science and Pollution Research,* 8(2): 471 – 474.

Rezender, J., Ramos, V., Herbet, O. A., Oliveira, R. M. and Esmevalda, D. J. (2018). Removal of Cr(VI) from aqueous solutions using clay from calumbi geological formation, N, Sra Socorro, SE State, Brazil. *Material Science Forum,* 912: 1 – 6.

Sabbagh, F., Khatir, N. M., Karim, A. K., Omidvar, A., Nazari, Z. and Jaberi, R. (2019). Mechanical properties and sweling behaviour of acrylamide hydrogels using montmorillonite and kaolinite as clays. *Journal of Environmrntal Treatment Techniques,* 7(2):211 – 219.

Saka, A., Shifera, Y., Jule, L. T., Badassa, B., Nagaprasad, N., Shanmugam, K., Dwarapudi, L. P., Seenivasan, V. and Ramaswamy, K. (2022). Biosynthesis of TiO_2 nanoparticles by caricaceae (Papaya) shell for antifungal application. *Scientific Reports,* 12: 15960.

Shaibu, S. E., Adekola, F. A., Adegoke, H. I. and Ayanda, O. S. (2014). A comparative study of the adsorption of methylene blue onto synthesized nanoscale zero-valent iron-bamboo and manganese-bamboo composites. *Materials*, *7*(6), 4493-4507.

Shaibu, S. E., Inam, E. J. and Moses, E. A. (2022). Biogenic silver-kaolinite nanocomposite for the sequestration of lead and cadmium in simulated produced water. *Journal of Material and Environmental Sustainability Research*, *1*(2), 13-25.

Sidhu, A. K., Verma, N. and Kaushal, P. (2022). Role of biogenic capping agents in the synthesis of metallic nanoparticles and evaluation of their therapeutic potential. *Frontiers in Nanotechnology*, 3: 1–17.

Singh, S. K., Ngaram, S. M. and Wante, H. P. (2019). Determination of thermal conductivity for adobe (clay soil). *International Journal of Research – Granthaalayah*, 7(3): 335 – 345.

Swapna, B., Chandrasekhar, K. B., Madhuri, D. and Sumathi, G. (2022). Biological synthesis and characterization of silver nanoparticles of *Carica papaya* and evaluation of its biological activity. *Journal of Pharmaceutical Negative Results*, 13(9): 902 – 911.

Syafiuddin, A., Salmaiti, Hadibarata, T., Salim, M. R., Kueh, A. B. and Sari, A. A. (2017). A purely green synthesis of silver nanoparticles using *Carica papaya*, *Manihot esculenta* and *Morinda citrifolia*: synthesis and antibacterial evaluation. *Bioprocess and Biosystems Engineering,* 40, 1349 – 1361.

Ullah, Z., Iqbal, J., Gul, F. Abbasi, A. B., Kanwal, S., Elsadek, M. F., Ali, M. A., Iqbal, R., Elsalahy, H. H. and Mahmood, T. (2024). Biogenic synthesis, characterization, and in vitro biological investigation of silver oxide nanoparticles (AgONPs) using *Rhynchosia capitata, Scientific Reports,* 14, 1048.

Usha, V., Amutha, E., Pushpalaksmi, E., Jenson, S., Rajaduraipandian, S., Gandhimathi, S. and Annadurai, G. (2022). Green synthesis and characterization of antibacterial studies by iron oxide nanoparticles using *Carica papaya* leaf extract. *Journal of Applied Science and Environmental Management,* 26(3): 421 – 427.

Yehia, B.S. and Ali, A. M. (2020). Biosynthesis and Characterization of Iron Nanoparticles produced by *Thymus vulgaris* L. and their Antimicrobial Activity. *Acta Botanica Croatica,* 79 (2): 114 – 1.