

OPTIMIZING HIGH-IMPACT UV AND VISIBLE LIGHT-INDUCED BIO DEGRADABLE MULCH FILMS FROM PARTICLE SIZE AND MORPHOLOGY-CONTROLLED SYNTHESIS OF COAT BUTTON PLANT (TRIDAX PROCUMBENS) LEAVES EXTRACT CAPED IRON OXIDE NANO FILMS

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Abstract

Pure Iron Oxide Nanoparticles and Tridax procumbens extract capped Iron Oxide Nanostructures were synthesised by chemical co-precipitation route for mulch film applications. Using XRD, SEM, EDAX, TEM, and UV-VIS Spectra the crystallinity nature, size, shape and Ultraviolet and visible light absorption were studied. The particle size of pure IONPs and capped IONPs calculated from XRD is 24.46 nm and 48.26 nm respectively. The structure morphology was observed as spherical shape for pure IONPs and cubical shape for capped IONPs with the help of SEM and TEM analysis. The particle size also calculated from SEM image and the value of IONPs and capped IONPs is 26.76 nm and 49.26 nm respectively. The changes in particle size and structural morphology was observed when Tridax procumbens extract was capped. The chemical composition was quantified using EDAX analysis. The light absorption range was found from 250 nm to 650 nm using UV-Visible studies.

Keywords: Iron Oxide, Tridax Procumbens, Mulch Films.

1. INTRODUCTION

Studies on nanomaterials in agricultural applications have exploded in last few years, with uses ranging from crop germination to yield [1]. For example, iron oxide nanoparticles (IONPs) are having many uses in the field of Iron fertilization, protein purification, enhanced nutrient uptake, and novel diagnostics, etc, because of their special qualities includes low cytotoxicity, tuneable surface chemistry, and cost-effectiveness.

And also having excellent colloidal stability, compact in size overall particle size distributions (PSDs), and strong magnetic saturation all of which can be tuned by adjusting their synthesis techniques to be suitable for usage in aforementioned applications.

Fe deficiency is a common issue in crops affecting growth and yield. Traditional iron fertilizers have limitations, but α -Fe₂O₃ NPs offer an alternative [2,3]. α -Fe₂O₃ NPs increased root length, plant growth, biomass, and chlorophyll content (measured by SPAD values) in plants. These nanoparticles promoted growth by regulating phytohormone levels and antioxidant enzyme activity.

Fe content in plants treated with $\alpha\text{-Fe}_2\text{O}_3$ NPs was higher than in the control group. $\alpha\text{-Fe}_2\text{O}_3$ NPs adsorbed onto sandy soil, improving Fe availability to plants. Overall, $\alpha\text{-Fe}_2\text{O}_3$ NPs show promise as an iron fertilizer. They serve as a biologically available Fe pool in soil, benefiting plant growth and metabolism. Applying $\alpha\text{-Fe}_2\text{O}_3$ NPs at a rate of 10 mg/kg in soil significantly improved various traits like increased sprouting percentage, number of leaves, and plant biomass. Green leaves extract capped iron oxide nanoparticles (GLONPs) have drawn a lot of interest in the field of agriculture. One of the examples is mulch films which is commonly using to improve crop yield because of their special properties like biodegradable, facile surface functionalization, colloidal stability, and UV absorbance rate.

Among various strategies, capping of IONPs with organic material, in particular plant leaves extract, is an alternative method for sharp tuning their size and shape by controlling interparticle relations. In addition, a green leaves extract capping gives possibilities to further functionalize their surfaces with many biomarkers by exploiting the silanol groups on the surface [4,5,6,7]. The size and shape of these particles depend on several factors, including the catalyst concentration, solvent type, and green leaf extract precursor concentration. For GLIONPs, however, another factor is the concentration of the IONPs and the functional groups on their outer surface.

There are few reports address the function of the aforementioned reaction parameters in the synthesis of GLIONPs, even though numerous types of research address their functions in regulating the sizes of IONPs [8]. Curiously, none of the publications have specifically addressed how and why these characteristics influence the final morphologies instead, they have just looked at the impacts within a small range of the parameters.

Furthermore, these investigations identify two primary particle morphologies for IONPs and GLIONPs are spherical and aggregated [9,10]. However, nothing is known about how these morphologies affect the UV characteristics that result. Understanding the relationship between the size, morphology, and physical properties of GLIONPs as a function of different reaction conditions is essential for the successful application of GLIONPs [11,12]. Fertilization, nutrient uptake and UV absorption rates of nanoparticles are key features for agriculture applications [13,14].

There are many preparation techniques, including ion exchange, sol-gel, aerosol pyrolysis, ion implantation, melt quenching and chemical co-precipitation method have been reported for the synthesis of iron oxide nanoparticles (IONPs) [15]. Among these, the chemical co-precipitation method is well-liked because of its low processing temperature and pressure. In this work, we have synthesised *Tridax procumbens* extract capped IONPs for mulch film applications since *Tridax procumbens* is a common weed in agricultural fields. We have methodically examined how the types of solvent, IONP mass ratios to green extract precursors, ammonium hydroxide concentration, and IONP surface chemistry affect the sizes, morphologies, and ultimately the UV characteristics of GLIONPs. Our comprehension will direct the development of more customized physicochemical features through improved particle design.

Tridax procumbens is a common weed in agricultural fields. Its antimicrobial and insect-repellent properties could be harnessed to reduce input costs in agriculture. It is standing guard, keeping pests at bay without synthetic chemicals. In regions where groundwater has high fluoride levels (including India), *Tridax procumbens* steps in. It's an inexpensive way to defluorinated water. Traditional plastic mulch films have been widely used in agriculture to improve yields and crop traits [16-20]. However, their environmental impact is a concern. These films offer an eco-friendly alternative. They break down naturally, reducing plastic waste. They can increase air and soil temperatures, protect plants from various stressors, improve water management, suppress weed growth, and reduce reliance on agrochemicals.

2. EXPERIMENTAL SECTION

2.1. Materials

For this fact-finding, iron (III) chloride anhydrous ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$, $\geq 99\%$) from Merck, ammonium hydroxide solution (NH_4OH) 25 weight percent, and ammonia buffer solution purchased from Nice Chemicals. None of these compounds were modified or purified; they were all utilized exactly as supplied by the suppliers. All solutions were made with double de-ionized water, from Ensign Aqua labs (India). *Tridax procumbens* (Coat button) leaves are collected from my agricultural land located in a rural village in Tamil Nadu (India).

2.2. Preparation of IONPs by Synthesis

The synthesis procedure is modified from our previously published articles. Chemical co-precipitation was used to create IONPs. For that 300 ml of double de-ionized taken in a 1-litre volume capacity beaker to create a product. In a volumetric beaker, 12.25 g of $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ were weighed and dissolved. Then the setup is arranged with vigorous magnetic stirring on ambient atmospheric conditions over 6 hours. The pH value is measured every 30 minutes and it starts from 1 to reach 6. Then 1 M ammonia solution was added and the reaction was maintained. In addition to increasing the reaction rate ammonia buffer solution was added dropwise through a pipet as a catalyst and further stirring the pH reached 10. Through ten washing cycles with double de-ionized water and filtered to generate the final IONPs. In order to get dry product, the sample was kept in a hot air oven for over 4 hours at 150°C followed by grounding with mortar pestle. Finally, to increase crystallinity and softening, the sample was kept in muffle furnace for 4 hours at 400°C to get final product for further studies.

2.3. Preparation of GLIONPs with *Tridax Procumbens* Extract

In order to synthesis green leaves extract capped iron oxide nanoparticles (GLIONPs), the coprecipitation process can be further altered. For that 300 ml of double de-ionized water was taken in a 1-litre volume capacity beaker to create a product. In a volumetric beaker, 12.25 g of $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ were weighed and dissolved. Then the setup is arranged with vigorous magnetic stirring on ambient atmospheric conditions over 6 hours. The pH value is measured every 30 minutes and it starts from 1 to reach 6. Then 1 M ammonia solution was added and the reaction was maintained. In addition to increasing the reaction rate ammonia buffer solution was added dropwise through a pipet as a catalyst and further stirring the pH reached 10. Through ten washing cycles with double de-ionized water. The fresh *Tridax procumbens* (Coat button) leaves are collected and washed with double de-ionized water and then dried in the open air without droplets. Further, the sample was grinded using mortar without any additives and then twisted by using cotton cloth the pure extract was obtained. For capping purposes, 10 ml extract was added to the washed solution then stirred over 2 hours and filtered to generate the final capped GLIONPs.

To create a dry product, it was kept in a hot air-oven for over 4 hours at 150°C Finally to increase crystallinity and softening of the sample using a muffle furnace for 4 hours at 400°C then grinded fine powder GLINOPs with purple colour has been obtained.

3. CHARACTERIZATION TECHNIQUES

3.1. X-ray Diffraction (XRD)

Both types of IONPs and GLINOPs employed in this study had their crystallographic structures examined using X-ray powder diffraction (XRD) on a BRUKER-binary V4 (.RAW) with 2θ starts from 10.0000 to ends 80.4800. The pattern is compared with JCPDS data card No.89-8103 and concludes the system as a Rhombohedral crystal structure [21]. The primary peak values obtained from the

experimental results are mentioned in the **Table 1** and the experimental XRD results of synthesized α - Fe_2O_3 and Tridax procumbens capped α - Fe_2O_3 is shown in **Fig. 1** and **Fig. 2** respectively.

Table 1: 2θ values versus Miller indices of crystal structures

2θ	24.216	33.243	35.740	40.980	49.607	54.218	57.631	62.632	64.212	72.483	75.717
hkl	(012)	(104)	(110)	(113)	(024)	(116)	(122)	(214)	(300)	(119)	(220)

The average particle size of pure α - Fe_2O_3 and capped α - Fe_2O_3 has been calculated from the diffraction peaks from the XRD profile by the Debye-Scherrer formula [22].

$$t = 0.9\lambda / \beta \cos \theta \text{ nm}$$

where t is the average particle size, λ is the X-ray wavelength (0.1542 nm), β is full width at half maximum (FWHM) and θ is the Bragg angle

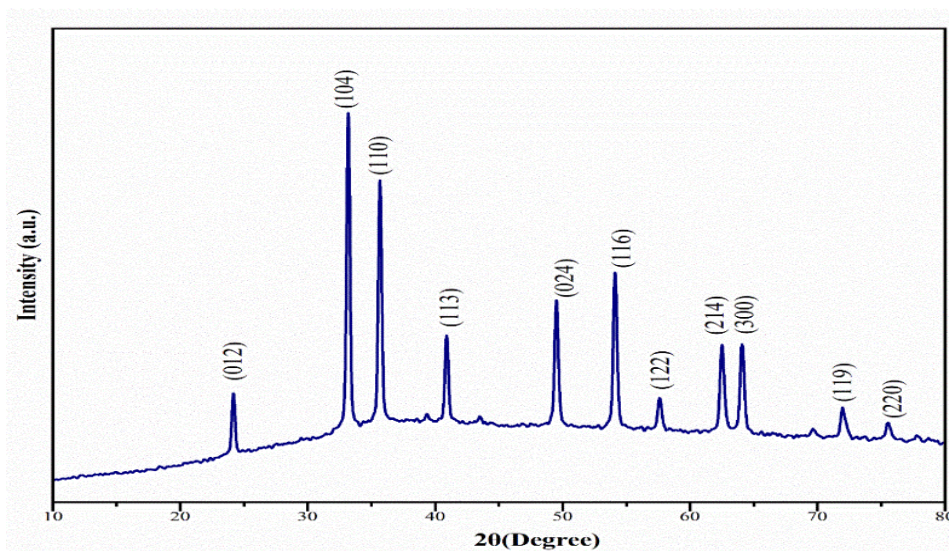


Fig 1: XRD pattern for pure synthesized α - Fe_2O_3 nanoparticles

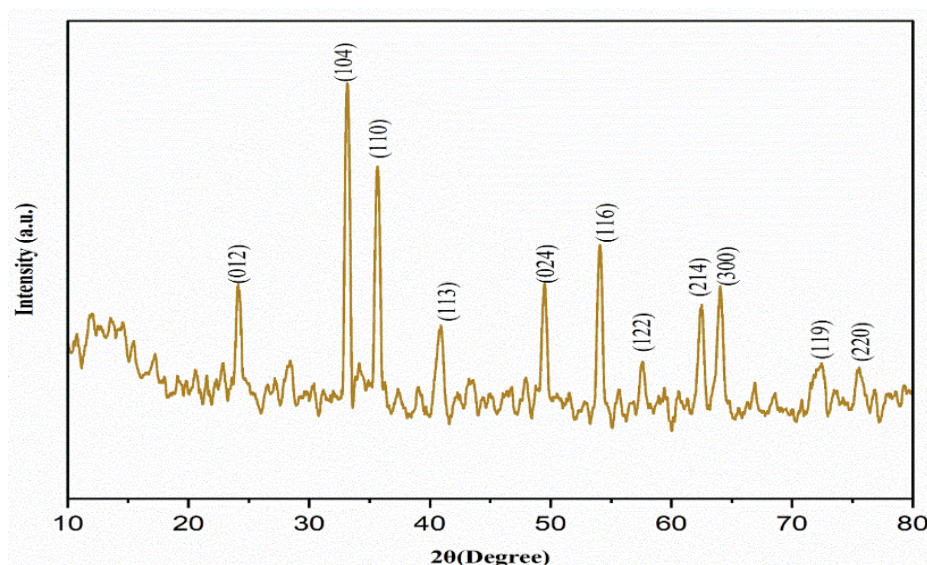


Fig 2: XRD pattern for Tridax procumbens capped α - Fe_2O_3 nanostructures

The average particle size is calculated in the XRD profile as pure α -Fe₂O₃ - 24.46 nm and capped α -Fe₂O₃ - 48.26 nm. The presence of organic materials in the plant leaf extract may have induced particle aggregation or agglomeration, which could be the cause of the increase in particle size shown in XRD. The existence of organic compounds could result in larger particle sizes by stabilizing or capping the particles. Additionally, the surface properties of the nanoparticles may interact with the extract, modifying their XRD patterns and apparent particle size.

3.2. Surface morphology characteristics

To prepare samples for SEM analysis, a sample was cleaned using a plasma cleaner both samples IONPs and GLIONPs were scanned using an FEI scanning electron microscope (SEM). The SEM images are shown in **Fig.3** and **Fig.4**. These SEM images were used to assess the size structure and particle size distribution (PSD) of the IONPs and GLIONPs using ImageJ software. The average particle size is calculated in the SEM profile as pure α -Fe₂O₃ - 26.76 nm and capped α -Fe₂O₃ - 49.26 nm and capped α -Fe₂O₃ - 49.26 nm. For similar way the morphology of nanostructures as pure α -Fe₂O₃ – Spherical and capped α -Fe₂O₃ – Cubical.

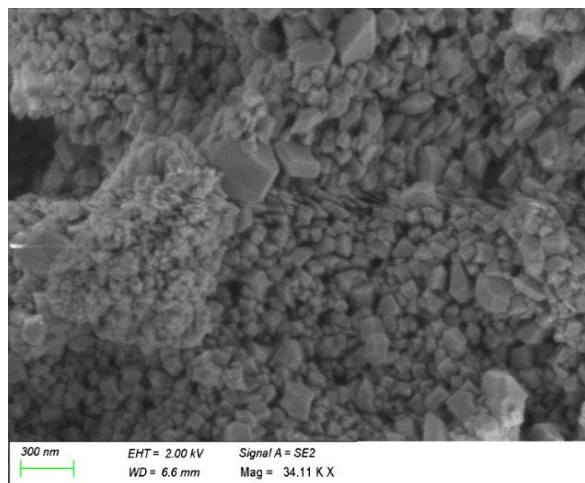
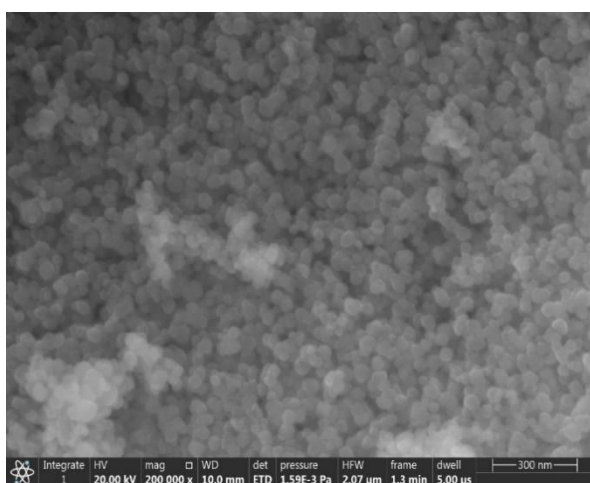
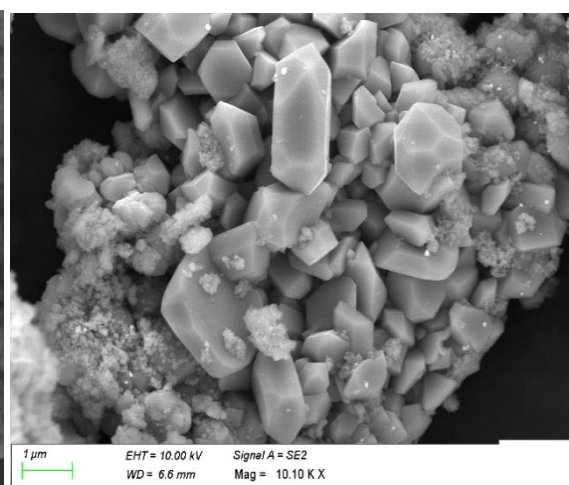
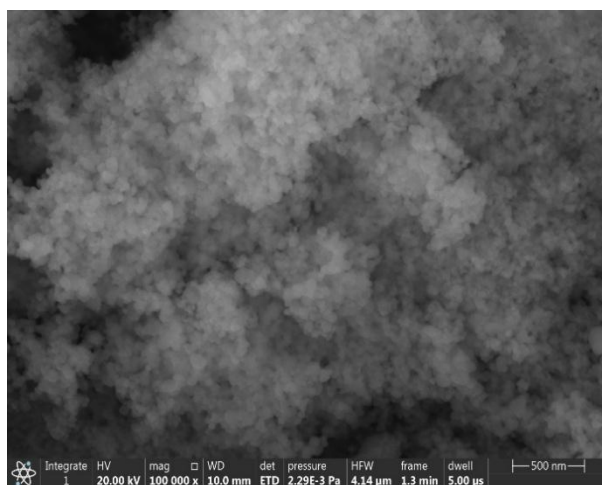


Fig.3: SEM image for pure α -Fe₂O₃

Fig.4: SEM image for capped α -Fe₂O₃

The change in morphology from spherical to cubical structure observed in SEM images could indicate a significant alteration in the material's composition or arrangement [23].

This alteration might be attributed to the interaction of the extract with the material leading to a transformation in its physical characteristics.

3.3. Energy Dispersive and X-Ray Analysis

EDX (also known as Energy-Dispersive X-ray Analysis or Energy-Dispersive Spectroscopy) is a powerful analytical technique used to identify and quantify the elemental composition of materials.

Each element emits a different set of X-ray frequencies as their vacated lower energy states are refilled. Measuring these emissions provides both qualitative and quantitative information about the near-surface makeup of the sample.

From **Fig.5** and **Fig.6** EDX helps identify and quantify elements in nanoparticles, ensuring their purity and functionality.

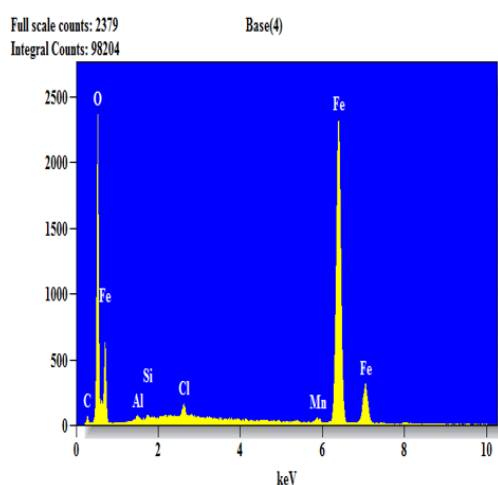


Fig.5: EDAX image for pure α - Fe_2O_3

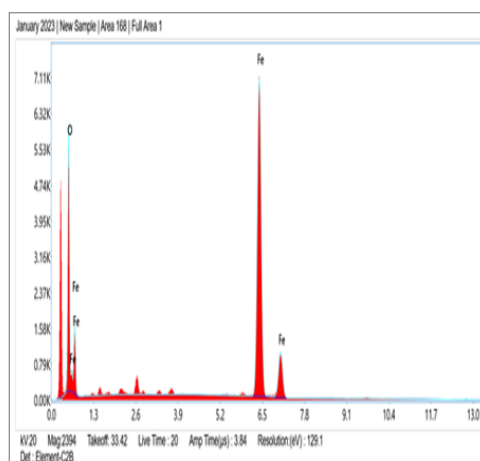


Fig.6: EDAX image for capped α - Fe_2O_3

Table 2: Elemental percentage of α - Fe_2O_3 and capped α - Fe_2O_3 using EDAX with a weight percentage of both nanostructures

Nano structure	Elements	Weight (%)
Pure α - Fe_2O_3	Fe	72.72
	O	23.61
Caped α - Fe_2O_3	Fe	80.36
	O	19.64

The observed elemental percentage of α - Fe_2O_3 and capped α - Fe_2O_3 is listed in **Table 2**. The interaction between the material and the extract from *Tridax procumbens* leaves appears to have led to the build-up or deposition of metal components, as indicated by the increase in weight concentration of metal seen through the EDAX (Energy Dispersive X-ray study) study. The observed morphological transition in the SEM pictures from spherical to cubical structure may be further clarified by this modification.

3.4. Transmission Electron Microscopy

TEM shows us the shapes and contours of things like a cosmic cartographer mapping out the landscape of nanoscale worlds. TEM helps us understand the morphology (shape) and composition of nanomaterials. Whether it's a nanowire, a quantum dot, or a layered material, TEM provides crucial insights. TEM image of α - Fe_2O_3 and capped α - Fe_2O_3 is shown in **Fig. 7** and **Fig.8** respectively.

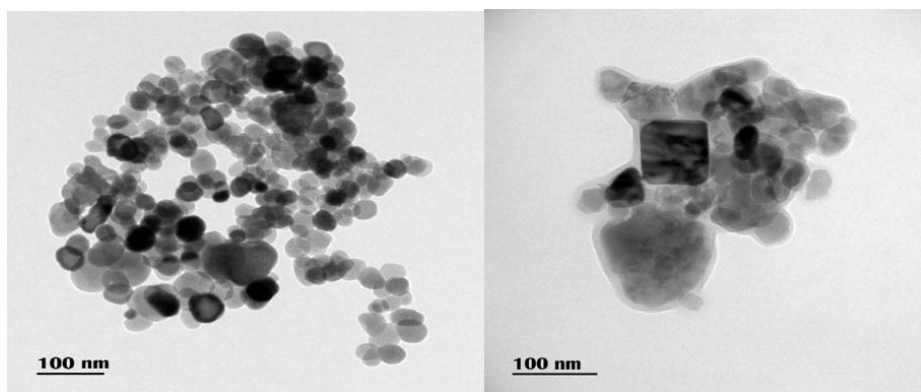


Fig.7: TEM image for pure α -Fe₂O₃

Fig.8: TEM image for capped α -Fe₂O₃

The average particle size is calculated in the TEM profile using ImageJ software as

Pure α -Fe₂O₃ - 29.65 nm

Caped α -Fe₂O₃ – 51.67nm

Morphology of nanostructures as

Pure α -Fe₂O₃ - Spherical

Caped α -Fe₂O₃ –Cubical

The change in morphology from spherical to cubical structure observed in TEM images could indicate a significant alteration in the structure with additional surface. This makes the interaction between extract and material which leads to various functional effects.

3.5.UV-Vis Absorbance Characteristics

Ultraviolet-visible (UV-Vis) spectroscopy is a technique used to analyze how a material absorbs or transmits light across different wavelengths. In UV-Vis spectroscopy, we measure the absorbance of light energy or electromagnetic radiation by a compound. When light interacts with a sample, it can excite electrons from their ground state to higher energy levels (such as the first singlet excited state). The UV-Vis region of the electromagnetic spectrum covers wavelengths from approximately 200 nm (ultraviolet) to 800 nm (visible light). The observed UV-Vis spectra of α -Fe₂O₃ and capped α -Fe₂O₃ are shown in **Fig.9** and **Fig.10**.

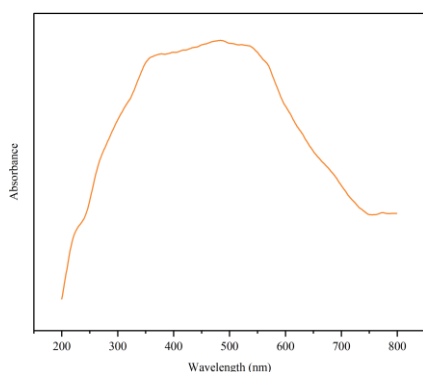


Fig.9:UV-Vis spectra for pure α -Fe₂O₃

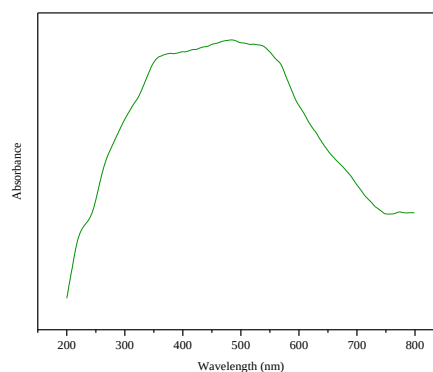


Fig.10: UV-Vis spectra for capped α -Fe₂O₃

From the Fig.9 and Fig.10, we conclude both structures have high absorbance rates in the range from UV to Visible region. The absorbance peaks indicate specific wavelengths at which the compound absorbs light most strongly. These peaks correspond to electronic transitions within the molecule. A higher absorbance value at a particular wavelength means that more light of that wavelength is being absorbed. The position of the peak provides valuable information about the compound's electronic structure and the energy levels involved.

4. EFFECT OF NANOPARTICLES ON MULCH FILMS

Mulch films are thin plastic sheets placed on the soil surface to enhance crop growth and productivity. Biodegradable Mulch Films are growing interest in replacing conventional plastic mulch films with biodegradable alternatives. These films break down naturally, reducing plastic waste. Biodegradable mulch films can be more expensive than traditional plastic films. Ensuring that biodegradable films provide adequate weed control, moisture retention, and temperature regulation is crucial. Large-scale adoption requires efficient production and distribution systems. Besides *Tridax procumbens*, other natural additives like chitosan, starch, and cellulose have been explored for mulch films. When IO-NPs are incorporated into biodegradable materials (such as extract-based films), they enhance the film's properties without compromising its eco-friendliness. When it comes to mulch films, UV-Vis testing helps us assess their transparency, light-blocking capabilities, and potential UV protection for crops. UV-Vis-absorbing mulch films can protect crops from harmful UV radiation. Excessive UV exposure can lead to plant stress, reduced yield, and even DNA damage. The reduced light transmittance due to UV absorption helps suppress weed growth, which is essential for maintaining a weed-free environment around crops [24]. By considering both UV protection and transparency, researchers aim to develop mulch films that optimize crop health while minimizing environmental impact [25].

5. RESULT AND DISCUSSION

By using the chemical co-precipitation process both IONPs and GLIONPs were created, and then their characterization data is presented here, together with the impact of reaction parameters on the size and shape of NPs, and a discussion of the resulting characteristics. The major changes occur in both particle size and structure morphology occur due to the addition of the common weed (*Tridax procumbens*). Using XRD, SEM, EDAX, TEM, and UV-VIS Spectrometry respectively, the crystallinity, size, shape, and Ultraviolet and visible light absorption of both IONPs and GLIONPs were assessed. The diffraction patterns of IONPs and GLIONPs are displayed in Figures 1 and 2. The reflections of the rhombohedral cubic structure of Fe_2O_3 are identified as the primary diffraction peaks for XRD patterns. These results demonstrate that the crystalline nature of the nanoparticles was unaffected by the extract capping applied to the IONP surface but size variation can be doubled due to addition of weed (*Tridax procumbens*) extract. From XRD data analysis we get average nano structure size for IONP's (24.46 nm) and it can be doubled for GLIONPs (48.26 nm). Alternative characterization analysis gives almost same results of both structures. The SEM tool reveals that the variation of nano structure size for IONP's (26.76 nm) and it can be doubled for GLIONPs (49.26 nm) and similar way TEM tool reveals that the variation of nano structure size for IONP's (29.65 nm) and it can be doubled for GLIONPs (51.67nm).

The spherical shape of iron oxide nanoparticles, which can be produced in a wide range of methods, is a common morphology. It frequently refers to controlled synthesis conditions, where nucleation and growth processes make well-defined spherical particles. Both structures IONP's and GLIOP's have different morphologies obtained from SEM and TEM tools the changes like spherical shape for pure state (Pure $\alpha\text{-Fe}_2\text{O}_3$) and cubical shape for impure state (Capped $\alpha\text{-Fe}_2\text{O}_3$). The compositional analysis EDAX gives the quantify of elements present in materials. The ratio for Fe atoms changes

incrementally from 72.72% to 80.36% and decremental from 23.61% to 19.64% for O atoms due to structural alterations. Ultimately, this approach uses UV-Vis spectroscopy to obtain the interaction between light and substance. The material's absorption rate as measured by the incident light's wavelength. The broad band absorption of both INOP's and GLINOP's nanostructures spans the ultraviolet to visible spectrum (about from 250 nm to 650 nm).

6. CONCLUSION

The addition of weed leaf extract creates the changes in structural size can be doubled and structural morphology from spherical to cubical shape. The spherical shape can have advantages in drug delivery applications, where uniform particle size enables consistent behaviour and interactions with biological systems. Compared to pure nanoparticles, the iron oxide nanoparticles produced with the help of *Tridax procumbens* leaf extract appear to have an additional surface structure, as can be seen by their capped structure. The capped morphology may improve the stability, biocompatibility, or functional qualities of the nanoparticles for particular applications. The existence of a cap or coating may suggest the adsorption of biomolecules from the leaf extract onto the surface of the nanoparticles. The wide band absorption stores sufficient light energies in the surface and it releases when it required. From the above discussions the pure INOP's and capped GLINOP's used in mulch films to satisfies all processes starts from seed germination to harvesting in agricultural domain.

Future Scope

Using *Tridax procumbens* leaf extract as a capping agent may also give the nanoparticles other characteristics that come from the natural components in the extract, which could lead to new possibilities for specific applications. Understanding the connection between quantum activities and nanoparticle shape can help develop advanced substances with unique characteristics for specific uses for instance, compared to their spherical replacements, cubical nanoparticles can show unique electrical, optical, or magnetic properties. the successful application of IO-NPs in mulch films depends on factors like film composition, nanoparticle concentration, and compatibility with specific crops. As research continues, we'll likely discover even more benefits and optimize their use in sustainable agriculture.

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References

- 1) P. Sangaiya & Jayaprakash, R. (2018) A review on iron oxide nanoparticles and their biomedical applications, *Journal of Superconductivity and Novel Magnetism*. 31(11), 3397-3413.
- 2) Seshadri Kannan, (2008) Problems of iron deficiency in different crop plants in India: Causative factors and control measures, *Journal of Plant Nutrition*, Pages 187-200.
- 3) Zuo, Y., Zhang, F. (2011) Soil and crop management strategies to prevent iron deficiency in crops. *Plant Soil* **339**, 83–95.
- 4) Kamath V, Chandra P, Jeppu GP. (2020) Comparative study of using five different leaf extracts in the green synthesis of iron oxide nanoparticles for removal of arsenic from water. *International Journal of Phytoremediation*. 22(12):1278-1294.
- 5) Huang L, Weng X, Chen Z, Megharaj M, Naidu R. (2014) Green synthesis of iron nanoparticles by various tea extracts: A comparative study of the reactivity. *Spectrochemical Acta Part A: Molecular and Biomolecular Spectroscopy*. 130:295-301.

- 6) Saif S, Tahir A, Chen Y. (2016) Green synthesis of iron nanoparticles and their environmental applications and implications. *Nanomaterials*. 6(11):209.
- 7) Thirumalai, R., Kuaanan Techato, M. Chandrasekaran, K. Venkatapathy, and M. Seenivasan. (2021) "Experimental investigation during turning process of titanium material for surface roughness." *Materials Today: Proceedings* 45 1423-1426.
- 8) Dharmalingam, R., K. K. Sivagnanaprabhu, and R. Thirumalai. (2014) Nano materials and nanofluids: an innovative technology study for new paradigms for technology enhancement. *Procedia Engineering* 97: 1434-1441.
- 9) Q. Zhang, GQ L. A., Zhao, Z. Li, X. Xu, (2015) Morphology-modulations of TiO₂ nanostructures for enhanced photocatalytic performance, *Appl. Surf. Sci.* 332: 224–228.
- 10) Ebrahiminezhad A, Zare-Hoseinabadi A, Berenjian A, Ghasemi Y. (2017) Green synthesis and characterization of zero-valent iron nanoparticles using stinging nettle (*Urtica dioica*) leaf extract. *Green Processing and Synthesis*. 6(5):469-475.
- 11) P. Sangaiya & Jayaprakash, R. (2018) Tuning effect of Sn doping on structural, morphological, optical, electrical, and photocatalytic properties of iron oxide nanoparticles. *Materials Science in Semiconductor Processing*, 85, 40-51.
- 12) P. Sangaiya & Jayaprakash, R. (2020) Influence of annealing temperature and electrical conductivity of α -Fe₂O₃ nanoparticles for Schottky barrier diode. *Journal of materials science and materials in electronics*. 31(18) 15153-15174.
- 13) Carrapiço A, Martins MR, Caldeira AT, Mirão J, Dias L. (2023) Biosynthesis of metal and metal oxide nanoparticles using microbial cultures: *Mechanisms, antimicrobial activity and applications to cultural heritage*. *Microorganisms*. 11(2):378.
- 14) Murugan, K., S. Venkatesh, R. Thirumalai, and S. Nandhakumar. (2021) Fabrication and investigations of kenaf fiber and banana fiber reinforced composite material. *Materials Today: Proceedings* 37: 110-114.
- 15) P. Sangaiya & Jayaprakash et al, R. (2022) Hydrogen production and photocatalytic activity of HTAB assisted Titanium doped α -Fe₂O₃ nanoparticles treated by microwave irradiation process. *Inorganic Chemistry Communications*. Volume 144, Pages 109852.
- 16) Xinglin Li, Guanfeng Zheng, Zhiyu Li, Peng Fu, (2024) Formulation, performance and environmental/agricultural benefit analysis of biomass-based biodegradable mulch films: A review. *Journal*, Volume, 19 January 2024, 112663.
- 17) Qiansen Wang, Yujia Duan, Ying Huang, Yilin Teng, Chao Li, Yehan Tao, Jie Lu, Jian Du, Haisong Wang (2024) Multifunctional soybean protein isolate-graft-carboxymethyl cellulose composite as all-biodegradable and mechanically robust mulch film for "green" agriculture. *Carbohydrate Polymers*, Volume 323, 1 January 2024, 121410.
- 18) Qiansen Wang, Louyu Wang, Chao Li, Cong Jiang, Jinwen Hu, Yanna Lv, Yehan Tao, Jie Lu, Gaofeng Pan, Jian Du, Haisong Wang. (2024) Biodegradable and multifunctional black mulch film decorated with darkened lignin induced by iron ions for "green" agriculture, *International Journal of Biological Macromolecules*, Volume 265, Part 2, April 2024, 130981.
- 19) Youming Xu, Qiang Li, Liping Man (2021) Bamboo-derived carboxymethyl cellulose for liquid film as renewable and biodegradable agriculture mulching, *Macromolecules*, Volume, 1 December 2021, Pages 611-617.
- 20) Liang Chen, Taotao Qiang, Xuejun Chen, Wenqi Ren, Hui Jie Zhang (2021) Fabrication and evaluation of biodegradable multi-cross-linked mulch film based on waste gelatin, *Chemical Engineering Journal*, Volume 419, 1 September 2021, 129639.
- 21) Krispin, M., Ullrich, A. & Horn, S. (2012) Crystal structure of iron-oxide nanoparticles synthesized from ferritin. *J Nanopart Res* 14, 669.

- 22) P. Mallick, B. N. Dash, (2013) X-ray Diffraction and UV-Visible Characterizations of α -Fe₂O₃ Nanoparticles Annealed at Different Temperature, *Nanoscience and Nanotechnology*, 3(5): 130-134.
- 23) Siddiqi, K.S., ur Rahman, A., Tajuddin *et al.* (2016) Biogenic Fabrication of Iron/Iron Oxide Nanoparticles and Their Application. *Nanoscale Res Lett* **11**, 498.
- 24) Sharma, R., Garg, R., Bali, M. *et al.* (2023) Potential applications of green-synthesized iron oxide NPs for environmental remediation. *Environ Monit Assess* **195**, 1397.
- 25) Esfanddarani, H.M., Panigrahi, M. (2024) Photosynthesis of transition (Ni, Fe, Co, Cr, and Mn) metals and their oxide nanoparticles for biomedical applications: a review. *J Mater Sci* **59**, 10677–10723.