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Hematite Nanoparticle Synthesis and Its Tribological and Rheological Performance as a Lubricating Oil

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Abstract

Friction refers to the resistive forces generated between surfaces in relative motion. In engines, the primary sources of frictional losses are sliding and rotating components. The addition of nanoparticles to lubricating oils at an optimal concentration can effectively reduce the coefficient of friction and enhance overall lubrication performance. This research aims to synthesize hematite ($\alpha\text{-Fe}_2\text{O}_3$) nanoparticles using the co-precipitation method and evaluate their tribological and rheological performance as additives in 40-stock base oil to enhance its lubricating properties. Ferric chloride (FeCl_3) and ammonia solution were used as precursor and precipitating agents, respectively. The effect of the cationic surfactant CTAB on particle size and distribution was also studied. The synthesized samples were characterized using X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), atomic force microscopy (AFM), nitrogen adsorption (BET), and the Timken tester for load-carrying capacity.

The results confirmed the successful formation of uniform nanoparticles with sizes 25 nm. The use of CTAB increased the surface area and reduced the particle size. Vibrating sample magnetometer (VSM) analysis revealed that the nanoparticles exhibited ferromagnetic behavior. When added at an optimal concentration of 0.01 wt.%, the nano-hematite significantly improved the base oil's load-carrying capacity by 92% and reduced wear. However, at higher concentrations, particle agglomeration negatively affected the performance. The findings demonstrate the potential of nano-hematite as an efficient and sustainable additive for lubricating oils, contributing to improved mechanical performance and energy efficiency.

Keywords: Nano hematite, Base Oil, Nano-Lubricating oil, Surface Modification, Tribology and Rheology.

تصنيع مادة الهيماتيت النانوية وتأثيرها على أداء الاحتكاك والانسيابية كمضاف لزيت التزييت الخلاصة:

يشير الاحتكاك إلى القوى المقاومة التي تنشأ بين الأسطح المتلامسة أثناء حركتها النسبية. وتعد الأجزاء المتحركة الدوارة في المحركات المصدر الرئيسي للخسائر الناتجة عن الاحتكاك. يمكن تقليل معامل الاحتكاك بشكل فعال وتحسين أداء زيوت التزييت من خلال إضافة الجسيمات النانوية إليها. يهدف هذا البحث إلى تحضير جسيمات نانوية من الهيماتيت ($\alpha\text{-Fe}_2\text{O}_3$) باستخدام طريقة الترسيب المشترك، وتقييم خصائصها التريبولوجية والريولوجية عند إضافتها إلى زيت الأساس 40 stock لتحسين خواصه. تم استخدام كلوريد الحديد (FeCl_3) ومحلول الأمونيا كمصادر أولية في عملية التحضير، مع دراسة تأثير استخدام المادة المشتتة CTAB على حجم الجسيمات وتوزيعها. خضعت

العينات المحضرة لتحاليل مختلفة شملت: حيود الأشعة السينية (XRD)، مطيافية الأشعة تحت الحمراء (FTIR)، المجهر الذري للقوة (AFM)، ومقياس الامتزاز النيتروجيني (BET)، بالإضافة إلى اختبار Timken لدراسة مقاومة الحمل. أظهرت النتائج أن الجسيمات المحضرة تمتلك حجمًا نانويًا بحدود 25 نانومتر، مع تحسن في المساحة السطحية عند استخدام CTAB. كما أظهرت جسيمات الهيماتيت سلوكًا مغناطيسيًا (فيرومغناطيسيًا) عند قياسها باستخدام جهاز VSM. من خلال التجارب وبعد إضافة 0.01% وزني من الجسيمات النانوية إلى زيت الأساس أدت إلى تحسن كبير في قدرة الزيت على تحمل الأحمال بنسبة تصل إلى 92%، بالإضافة إلى تقليل واضح في آثار التآكل. إلا أن الأداء بدأ بالتراجع عند تركيزات أعلى نتيجة لتجمع الجسيمات (agglomeration)، مما قلل من فاعليتها. تشير هذه النتائج إلى إمكانية الكبيرة لاستخدام جسيمات الهيماتيت النانوية كإضافات فعالة وصديقة للبيئة في زيوت التزييت، مع إمكانية تطوير استخدامها في تطبيقات صناعية مستقبلية بعد تحسين آلية التحضير والتحكم في حجم وتوزيع الجسيمات.

1. Introduction

1.1. Overview

The term "tribology" originates from the Greek words "tribos," which translates to "rubbing," and "logos," meaning "study" or "science." Tribology involves studying the movement of surfaces that interact with each other, particularly focusing on aspects such as friction, wear, and lubrication. Wear represents a primary factor contributing to the failure of engineering components such as gears, piston rings, engines, undercarriages, bearings, and camshafts. These components play essential roles in ensuring the smooth and efficient operation of industries such as automotive, aerospace, mining, and machining [1-4]. The base oil, whether natural or synthetic, typically cannot achieve the properties of high-performance lubricating oil without the support of advanced additive technology. Lubricant additives, present in a few weight percent, are added to the base oil to significantly enhance lubricative properties. They are critical for the lubricant's overall performance and can affect particular lubricants and can influence specific features such as friction and wear, oxidation, foaming, and corrosion tendency [5]. The increasing severity of operations conditions, developments in equipment technology, higher lubrication demands, and stricter regulatory requirements across various markets are the key factors behind the search for novel types of additives and the optimization of their concentrations. Researchers have focused on enhancing base oil additives to address issues such as friction, oxidation, corrosion, and abrasion. The advancement of nanotechnology has led to the development of nano-additives for lubricating oil. Adding these nano-additives to base lubricants has resulted in substantial performance enhancements [6-8]. The main advantages to utilizing nano lubricants are their relative insensitivity to temperature, excellent tribological properties, and small-scale effects as compared to traditional additives. Nanoparticle additives can perform a variety of roles. Powder lubricants, made up of cohesive and soft particles, act as a third body between two surfaces, reducing friction and wear. Magnetic nanoparticles have unique magnetic properties, including superparamagnetic, high coercivity, low Curie temperature, and high susceptibility [9-11].

Researchers have discovered that nanoparticles, with their varied compositions and sizes, can significantly improve a lubricant's ability to reduce friction and wear and load-bearing capacity, resulting in energy savings, improved dynamic transmission efficiency, vibration dampening, and noise reduction. In particular, adding nanoparticles to the boundary lubrication regime has shown impressive results, with reductions in friction coefficient of up to 70% and wear volume of up to 75% [12]. Nanoparticulate additives can function through various mechanisms. In lubricants, nano-additives reduce friction and wear by employing processes such as colloidal stabilization, rolling, small-size effects, formation of protective layers, and acting as a third body during boundary lubrication [13]. Amorphous Fe_2O_3 particles were synthesized in sizes of 20-50 nm. Investigation revealed that adding ferric oxide to base oil SN500 enhanced wear resistance, increased load-carrying capacity, and reduced the friction coefficient [14].

The incorporation of exfoliated nanographene (XG Np) and Fe_2O_3 into paraffin base oil was investigated to evaluate its effects on viscosity and tribological performance [15]. The study revealed a wear scar diameter (WSD) reduction of approximately 24.45% with the addition of 0.4 wt.% and a reduction of 38.60% with the addition of 0.8 wt.% [15]. The nano-lubricant demonstrated optimal anti-friction and anti-wear properties when the nanoparticles had a diameter of 20 nm and the additive concentration was maintained at 8 wt%. This study indicates that Fe_3O_4 nanoparticles enhance the adsorption stability of lubricants on metal surfaces. This effect is more pronounced on metals with higher relative atomic mass, resulting in better surface quality of rolled metal samples. Thus, incorporating Fe_3O_4 nanoparticles into lubricants can significantly improve their performance, especially on heavier metals [6]. Fe_3O_4 nanoparticles modified with oleylamine and formulated lubricants synthesized with different mass concentrations of nanoparticles. Oleylamine-modified Fe_3O_4 nanoparticles were effectively dispersed in lubricating oil, maintaining stability at concentrations up to 20 wt.% for 12 months. Initially, increasing the nano- Fe_3O_4 content decreased the lubricants' dynamic and kinematic viscosity, which then increased at higher concentrations. The tensile curve test indicated that the lubricants' tackiness and stickiness followed a similar pattern. Notably, at a 5 wt.% concentration of Fe_3O_4 nanoparticles, the Fe_3O_4 /mineral oil composite nano lubricants exhibited significantly enhanced tribological properties, achieving a wear volume reduction of up to 93.8% compared to base oils [16].

1.2. Role of nanoparticles in lubricating oil

Nanoparticles play a crucial role in friction zones, particularly in the limit lubrication regime

where wear and friction margins are at their highest. The mechanism of nano-lubrication can be regarded as having four major effects ball bearing/ rolling mechanism, protective film, repair effects, and polishing, as shown in Figure (1).[17]

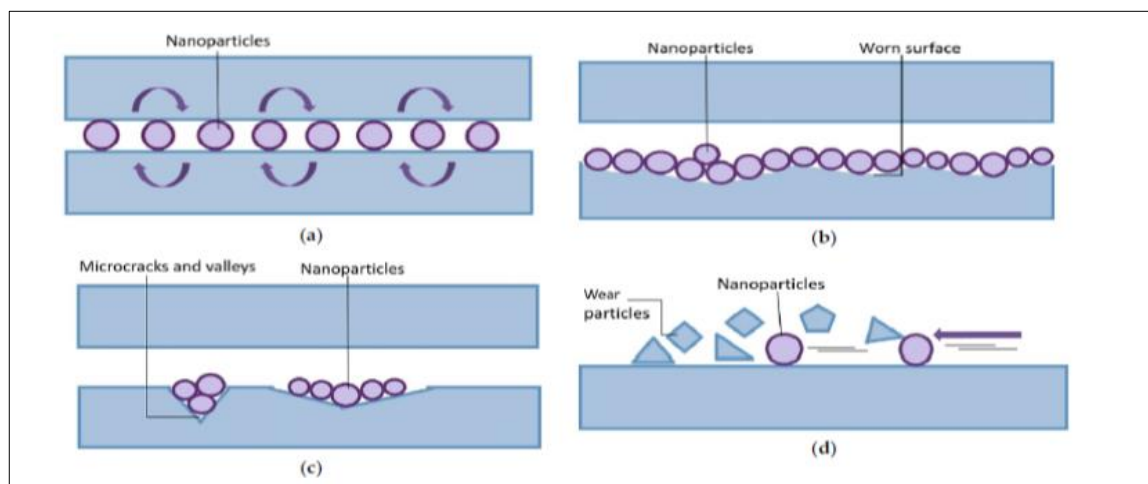


Fig. (1): Nano-lubrication mechanism (a) Rolling/ball bearing mechanism; (b) protective film/tribo-film formation; (c) mending effect; and (d) polishing/smoothing effect.[18]

Nano lubrication mechanism can be classified into two parts indirect and direct effect, Examples of direct lubrication mechanisms involving nanoparticles suspended in lubricating fluid include rolling ball bearings and protective film mechanisms, where nanoparticles act as ball bearings between frictional surfaces, forming a coating that shields these surfaces. Indirect lubrication methods encompass polishing and mending effects. The mending effect reduces abrasion by accumulating nanoparticles on friction surfaces, forming protective layers. The polishing effect, also known as surface smoothing, involves nanoparticles filling gaps on rough surfaces to reduce friction and wear.[19], [20]

2. Material and methods

2.1. Materials:

Ferric chloride (FeCl_3) 98.0% Assay (Thomas Baker Chemicals PVT. LTD. Co.) was used as a precursor of iron, Ammonia solution (NH_4OH) 25 % (Central drug hous LTD.) as a source of hydroxide ions, Ethanol absolute 99.8% (Romil LTD), Cetyl tri methyl ammonium bromide (CTAB) 99% assay (HiMedia Laboratories PVT. LTD. Co.), deionized water, The 40-stock base oil was provided by Al-Dura Refinery, Middle Refineries Company, Baghdad, Iraq, and oleic acid, required for the surface modification of the hematite nanoparticles, was purchased from Alpha Chemika, India. The properties of the Base oil are presented in Table (1).

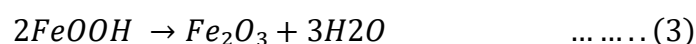
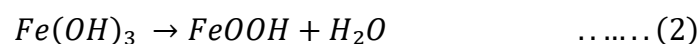
Table (1): Properties of base oil 40 stock

SPECIFICATION	BASE OIL (40 STOCK)
KINEMATIC VISCOSITY @ 40 °C(CST)	20.55
KINEMATIC VISCOSITY @ 100 °C (CST)	4.225
VISCOSITY INDEX	109
DENSITY @15 (G/CM ³)	0.863

2.2. Experimental Procedure of Preparation:

2.2.1. Synthesis of nano hematite

Nano hematite (α -Fe₂O₃) was synthesized as seen in equations 1,2 and 3:



A separating funnel was filled with 1 molar of ferric chloride, and another was filled with 5 molar of ammonia solution. Both solutions were permitted to dropwise in (0.02 M) CTAB (which used as a surfactant) solutions as the reaction medium referred as (H2). A second reaction was conducted without surfactant, referred to as (H1) as seen in Table (2). These reactions were continuously stirred with a magnetic stirrer for two hours at room temperature. PH value was adjusted to 8-9 by adding a nitric acid solution. Consequently, a Fe(OH)₃ precipitate would form, leaving it for aging overnight. Filtration and washing with deionized water and ethanol were used to wash the precipitate. Filtration was then repeated and dried for 12 hours at 60 C°. After calcining powder for two hours at 500 C° at a rate of 10 C°/min, nano hematite was produced. [21-23].

Table (2): Experimental Procedure

	FeCl ₃ Molarity	NH ₄ OH	CTAB Molarity
H1	0.1	5	----
H2	0.1	5	0.02

2.2.2. Surface Modification of Nanoparticles

To modify the surface of nanoparticles (NPs), 2 grams of oleic acid (OA) were dissolved in 100 mL of anhydrous ethanol. Hematite nanoparticles were then added to the solution. The mixture was heated to 75°C and stirred magnetically for two hours to ensure a complete reaction. The resulting product was filtered to remove ethanol and any unreacted oleic acid. It was then placed in an oven

for four hours to completely eliminate any residual ethanol. This procedure was repeated once to obtain oleic acid surface-modified hematite nanoparticles, designated as H/OA as seen in Figure (2). [24-28]. The modified samples were added to base oil and mixing for 4 hour using magnetic stirrer with 700 rpm.

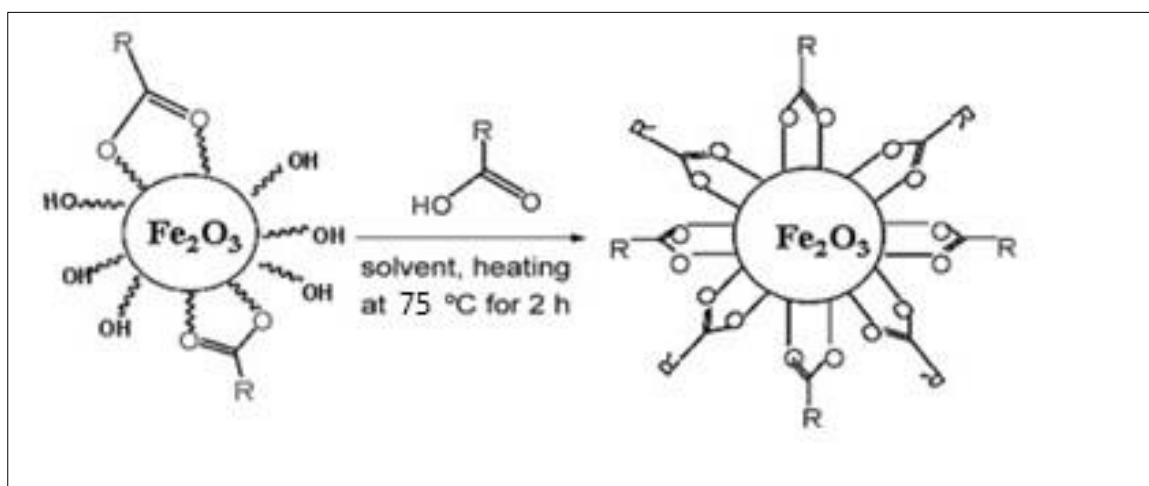


Fig. (2): Surface modification of nano hematite. [28]

2.2.3. Measuring and Analyzing Apparatus

BET (Brunauer, Emmet, and Teller), AFM (atomic force microscope), and Fourier transform infrared spectroscopy (FTIR-8400S, Shimadzu, Japan) were used to characterize the synthesized materials. It appears that spherical nano-sized particles with a mean diameter of 30 nm were obtained. Contact pressure (load-carrying capacity) of nano-lubricating oil were measured using portable Timken machine (Chongqing top oil Purifier Co., Ltd, china).

3. Results and Discussions

3.1. Surface area and Pore volume

The surface area and pore volume of the synthesized hematite were evaluated through nitrogen adsorption–desorption measurements at 77 K. Prior to analysis, the samples were degassed at 523 K (250 °C) to remove adsorbed species. Subsequently, liquid nitrogen was used to cool the samples to 77 K, and nitrogen gas was gradually introduced. The partial pressure of nitrogen was increased incrementally up to near saturation, followed by a gradual decrease to low pressure to complete the adsorption-desorption cycle.

As shown in Table (3), the use of a cationic surfactant during synthesis significantly enhanced both the surface area and pore volume of the hematite. This improvement is attributed to the ability of

surfactants to reduce surface tension by decreasing intermolecular attraction. Consequently, particle aggregation is minimized, leading to a more porous structure with increased surface accessibility.

Table (3): Hematite Surface Morphology

	Surface area (m ² /g)	pore volume (cm ³ /g)
H1	29	0.0358
H2	42	0.0415

3.2. Atomic Force Characterization

AFM is a powerful and versatile microscopy technology used to study the samples at a nanoscale. AFM can generate images at an atomic resolution. In metal oxide, AFM can measure the roughness and other properties of the surface. From Figure (3) we saw that the mean particle size reduced by 24% from 33 nm to 25 nm according to using CTAB surfactant.

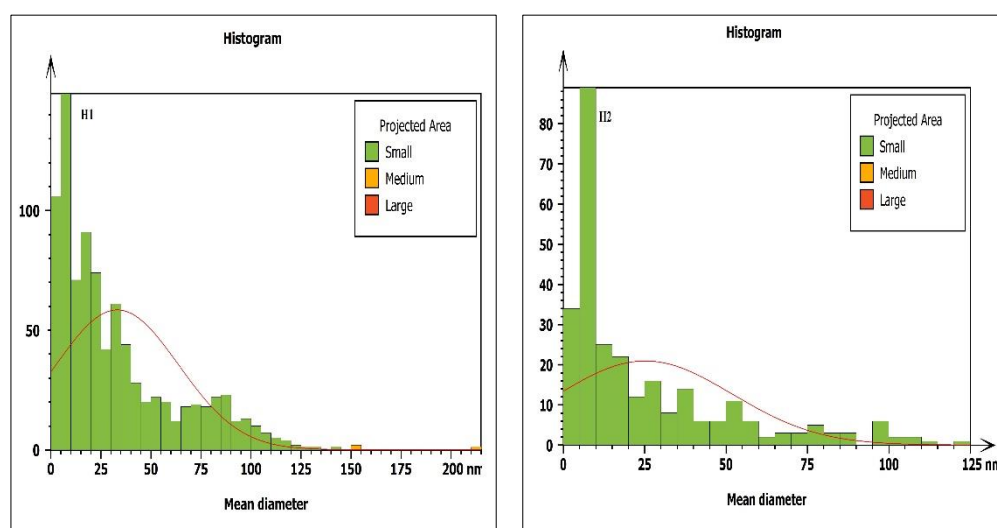


Fig. (3): AFM particle size distribution of synthesized hematite (H1 without surfactant and H2 with surfactant).

3.3. Identification Results from XRD

XRD observations on hematite samples are depicted in Figure (4). Data obtained from X-ray diffraction (XRD) involves the analysis of phase distinction by measuring the angle 2θ and intensity (University of Kashan/Iran). This identification is referenced in the ICDD (International Center for Diffraction Data) The analysis was performed by comparing the experimental results with the ICDD database. The findings from the XRD analysis indicate that the predominant phase present is crystalline hematite (Fe_2O_3) as in ICDD card No. 01-084-0308 and 01-084-0310 with identical scores of 81% and 76% respectively. The peaks appear in the 2θ range 24.26° , 33.33° , 35.78° , 41.05° , 49.70° , 54.36° , 57.93° , 62.74° , 64.30° , 72.40° , and 75.83° for H1 sample was matched by

$\pm 0.006^\circ$ while the 2θ range 24.42, 33.38, 35.82, 41.13, 49.71, 54.32, 57.85, 62.74, 64.22, 72.17, and 75.66 for H2 sample was identical by ± 0.02 . The average crystalline size of the synthesized hematite nanoparticles has been calculated from the full width at half maximum (FWHM) and Debye-Sherrer formula from HighScore software of Malvern Panalytical company:

$$D = \frac{0.89\lambda}{B \cos \theta} \quad \dots\dots\dots (5)$$

Where;

0.89 is the shape factor.

λ is the x-ray wavelength.

B is the line broadening at half the maximum intensity (FWHM).

θ is the Bragg angle.

The mean crystalline size of α -Fe₂O₃ nanoparticles was around 29 nm and 23 nm for H1 and H2 samples respectively.

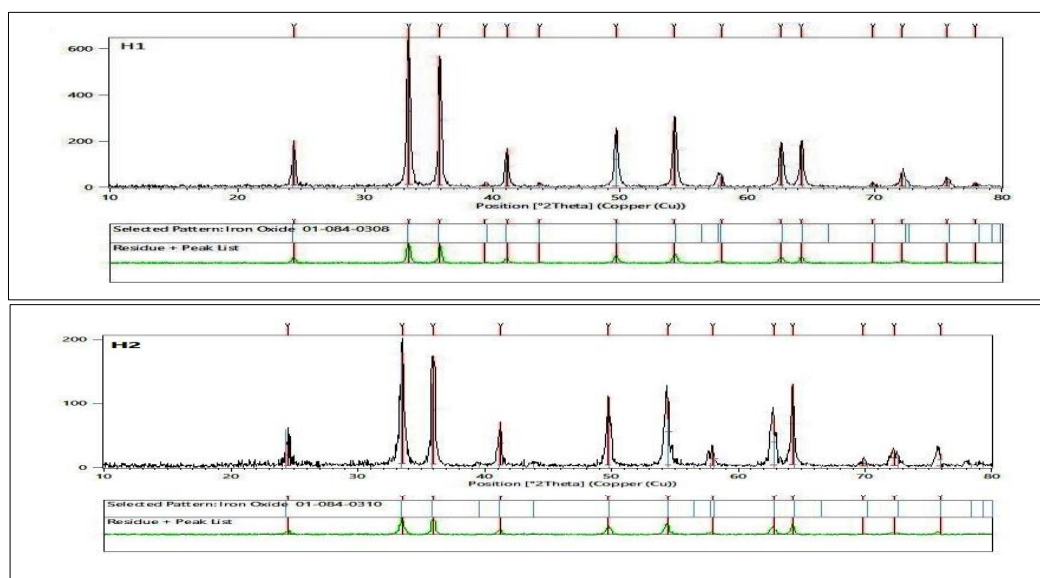
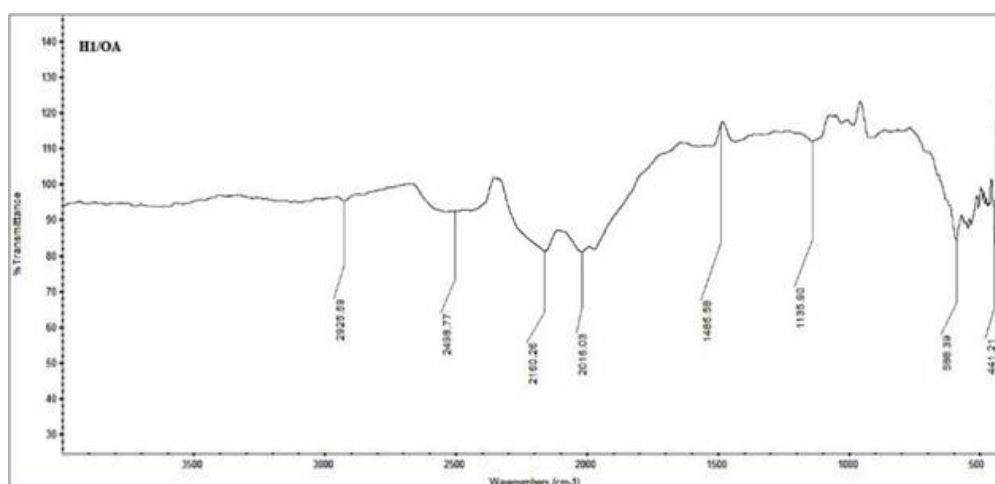
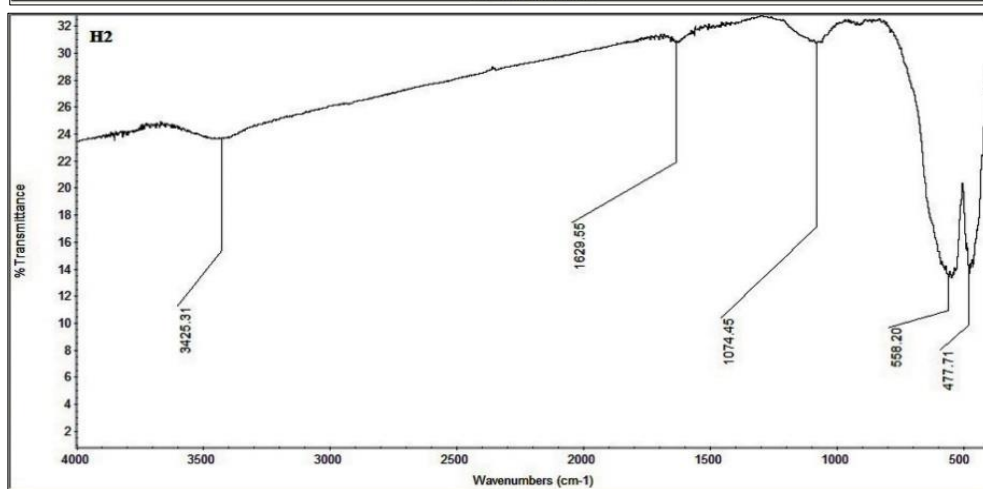
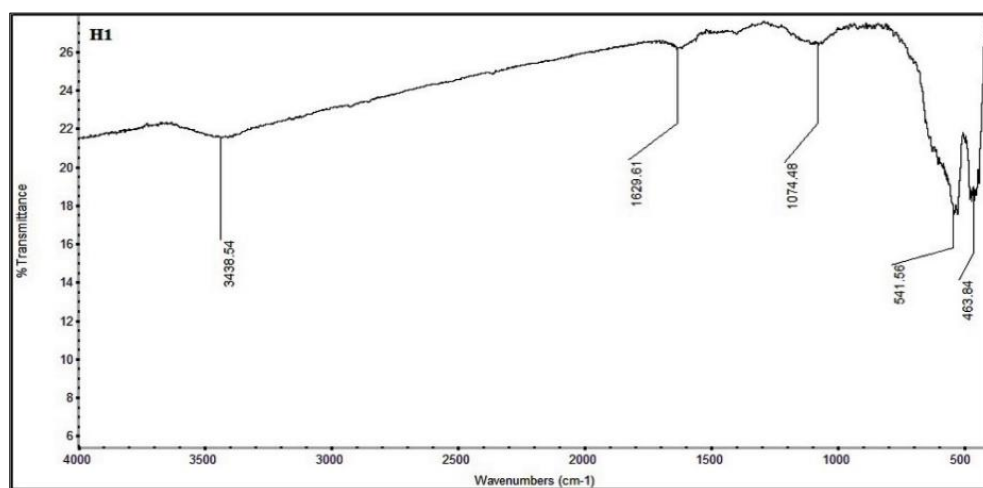


Fig. (4): H1 and H2 samples XRD patterns of synthesized hematite compared with blank XRD patterns.

3.4. FTIR analysis

The FT-IR spectra of the α -Fe₂O₃ nanoparticles were analyzed using a Thermo Fisher Nicolet 380 instrument. The wave numbers of vibrational infrared extended from 400 to 4000 cm⁻¹. The bands at 3438, 1070, and 1629 cm⁻¹ in Figure (4 H1) aligned with the stretching and bending vibration of hydroxyl groups (O-H), while two sharp peaks at 541.8 and 463.8 cm⁻¹ contributed to the stretching and bending vibration of (Fe-O) vibrations. A similar observation is seen in Figure (5 H2).[29]

In decorated hematite in Figure (4 H1/OA and 4 H2/OA) three additional peaks were also investigated, four peaks were observed due to surface modification with oleic acid around 2500 cm^{-1} corresponding to the asymmetric and symmetric (CH_2) stretch, 2000 cm^{-1} refer to (CH) group, and about 1400 cm^{-1} for carboxyl group. [22]



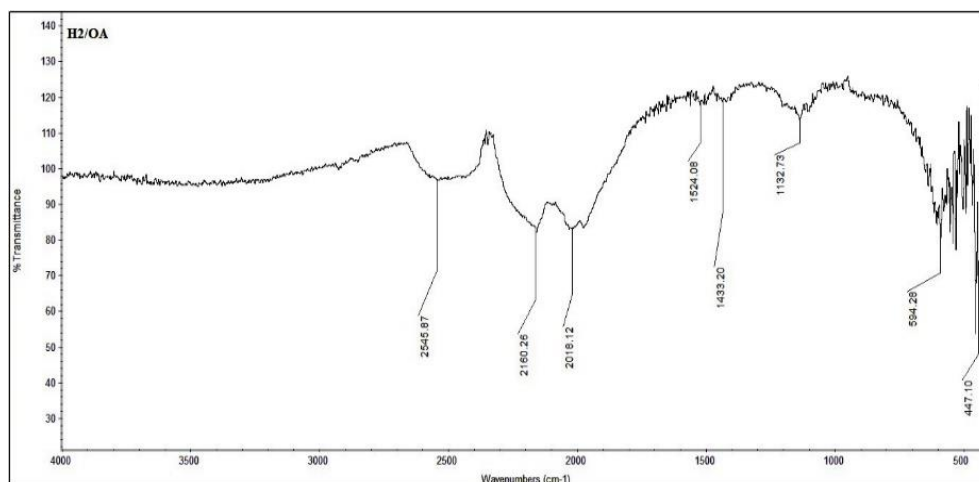


Fig. (5): FTIR for H1, H2, H1/OA, and H2/OA patterns of synthesized hematite

3.5. Effect of α -Fe₂O₃ NPs on the contact pressure (load carrying capacity) of base oil:

The most significant rheological parameter for lubricants is viscosity, which has a direct impact on tribological properties such as friction between surfaces and wear. The kinematic viscosity is calculated at 40 °C and 100 °C using Viscometer (Anton Paar SVM 3000), There is a slight increase in viscosity with an increase in nano hematite concentrations added for both samples. A commercial portable Timken tester (procured from Chongqing TOP Oil Purifier CO., LTD, China), as illustrated in Figure (6) was employed to compare the contact pressure of the formulated nano-lubricating oil with that of the base oil. The contact pressure was measured following the Timken method specified by ASTM D-2782, and the corresponding equation was utilized for its calculation.[30]

$$C, PSI = \frac{[L(X+G)]}{YZ} \dots\dots (6)$$

Where;

C = contact pressure (load-carrying capacity) psi

L = mechanical advantage of the load-lever arm, 1

X = mass (weight) placed on the weight, Ib

G = load-lever constant, (weight of the long arm and short arm)

Y = length of test scar, inch

Z = average width of test scar, inch

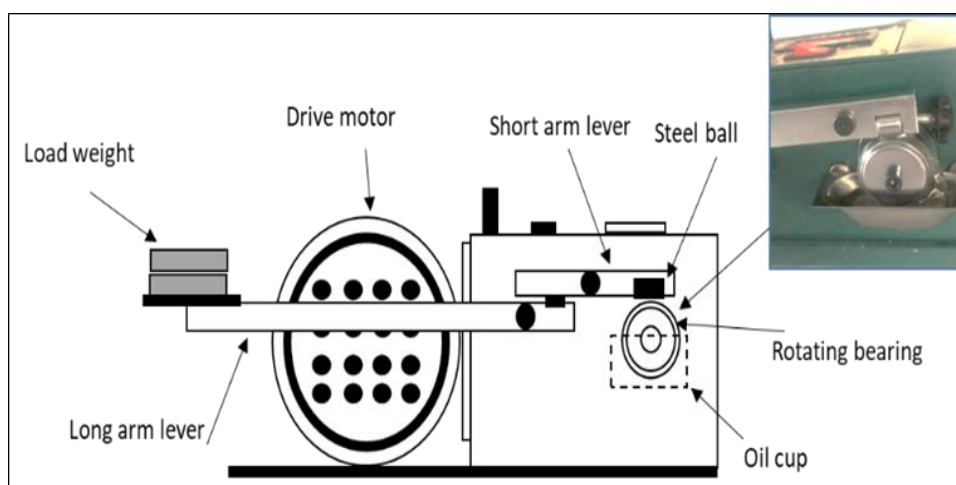


Fig. (6): Portable Timken tester

A stationary block was pressed against a rotating roller operating at a speed of 800 rpm. The test cup held 25 ml of lubricating oil, maintained at a temperature of 40°C. The load was applied using a lever system with a 1:10 mechanical advantage by adding weights. Each test, conducted by the ASTM D2782 standard, lasted for 10 minutes, followed by an inspection for scars. If no scar was detected (Figure 7) the load was increased, and the test was repeated for another 10 minutes until a scar was observed as seen in Table (4).



Fig. (7): image of rolling element scar test.

Table (4): Scar dimensions observed.

	Nano hematite percent %	Length of scar (Y mm)		Width of scar (Z mm)		Viscosity @40 c mm ² /s H1&H2
		H1	H2	H1	H2	
1	0.005	1.79	2.07	1.48	1.49	4.29
2	0.01	1.58	1.34	1.33	1.1	4.3
3	0.05	1.83	1.68	1.39	1.28	4.35
4	0.1	2.11	2.28	1.47	1.62	4.39
5	0.15	2.14	1.57	2.3	1.7	4.45
Rolling E.	zero	5.8		3.2		4.22

The α - Fe_2O_3 nano-lubricants exhibited a markedly improved load-carrying capacity compared to the base oil. This improvement was evidenced by an increase with increase of nano α - Fe_2O_3 concentration and the highest value was obtained at 0.01 % attributed to the formation of a tribo-film on the sliding surface. This tribo-film effectively minimized friction between the steel ball and the roller bearing under a 1.1-pound load. Additionally, scar damage showed reduction with the initial increase in α - Fe_2O_3 nano additives concentration. However, at higher concentrations, the performance began to decline due to nanoparticle agglomeration. As the concentration rose, van der Waals forces and magnetic interactions caused the nanoparticles to aggregate, reducing their ability to form a stable and uniform protective coating on contact surfaces[7]. This phenomenon led to diminished performance, as illustrated in Figure (8).

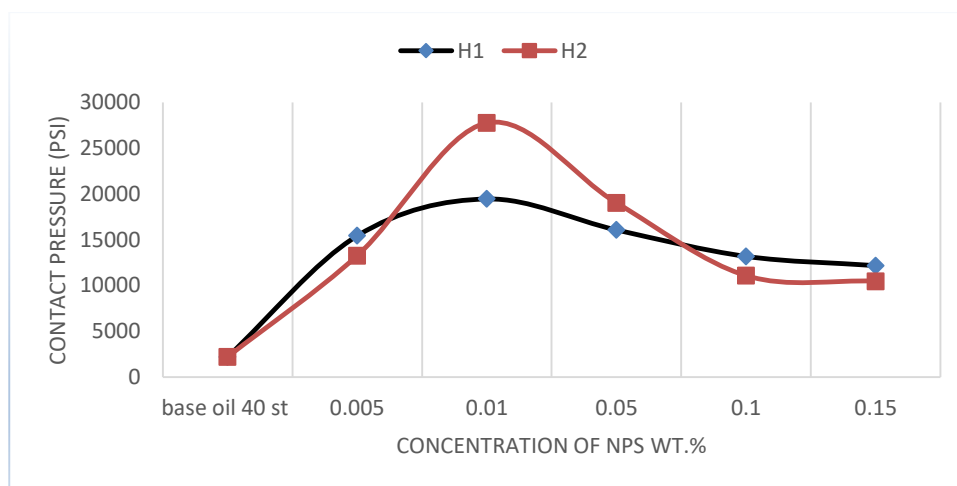


Fig. (8): Load-carrying capacity of modified 40-base oil

3.6. Vibrating Sample Magnetometer (VSM):

Many researchers used magnetite (Fe_3O_4) as lubricant additives due to their magnetic properties while hematite (Fe_2O_3) was antimagnetic [30], [31]. We made a magnetism comparison between the two samples of synthesized nano hematite and bulk commercial one (> 100 nm) by VSM. When a ferromagnetic material is exposed to an alternating magnetic field, a characteristic relationship is observed between (magnetic induction) and (magnetic field strength)[32]. The magnetic behavior of nanoparticles influences their dispersion in base oil, alignment under magnetic fields, interaction with metal surfaces, While Fe_2O_3 is more abundant and less expensive. Figure (9) shows hysteretic loop investigations of the magnetic characteristics of the samples.

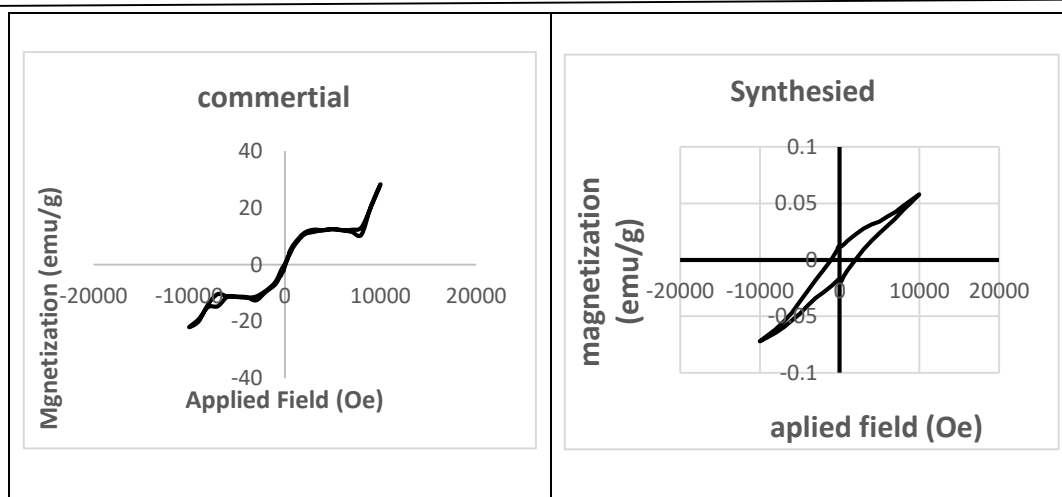


Fig. (9): Magnetic hysteresis loop for commercial and synthesized hematite.

4. Conclusions

This study successfully synthesized hematite ($\alpha\text{-Fe}_2\text{O}_3$) nanoparticles via the co-precipitation method and demonstrated their effectiveness as nano-additives in lubricating oil. Detailed characterization confirmed the formation of nanoparticles with reduced particle size and increased surface area, particularly when synthesized with a cationic surfactant (CTAB). The incorporation of these nanoparticles at an optimal concentration (0.01 wt.%) significantly enhanced the rheological and tribological properties of the base oil most notably, improving the load-carrying capacity by up to 92% and the kinematic viscosity is slightly increased by 1.6 %.

The performance enhancements were primarily attributed to the formation of a tribo-film, the ball-bearing effect of nanoparticles, and their ability to fill surface asperities. However, performance declined at higher concentrations due to particle agglomeration caused by van der Waals and magnetic interactions, which hindered uniform dispersion and film formation.

Additionally, magnetic characterization showed that the synthesized hematite nanoparticles exhibit ferromagnetic behavior, contributing further to their tribological performance by promoting better adherence to metal surfaces under dynamic conditions.

For future research, it is recommended to optimize the synthesis parameters to achieve better control over particle size, distribution, and stability of nano-hematite in lubricating oils. Further studies should also explore the long-term performance of these additives under real engine or industrial operating conditions and assess their compatibility with various base oil types such as base oil 60 stock to broaden their application potential in commercial lubricant formulations.

Author Contributions Statement: Mustafa H. Flayyih contributed to the Conception of the study; Methodology; Investigation and experimental work; Data interpretation; Writing – Original Draft; and Writing – Review & Editing. Mustafa R. Fahad Conception of the study; Methodology; Investigation and experimental work; Data interpretation; Writing – Original Draft; and Writing – Review & Editing. Haider J. Saiwan contributed to the Conception of the study; Methodology development; Data interpretation, and manuscript review and editing. All authors have read and approved the final version of the manuscript.

References

- [1] W. J. Bartz, “Tribology, lubricants and lubrication engineering — a review”, *Wear*, vol. 49, no. 1, pp. 1-18, 1978. [https://doi.org/10.1016/0043-1648\(78\)90019-4](https://doi.org/10.1016/0043-1648(78)90019-4).
- [2] P. V. Babu, S. Ismail, and B. S. Ben, “Experimental and numerical studies of positive texture effect on friction reduction of sliding contact under mixed lubrication”, *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, vol. 235, no. 2, pp. 360–375, Jun. 2020. <https://doi.org/10.1177/1350650120930911>.
- [3] M. S. Gemsprim, N. Babu, and S. Udhayakumar, “Tribological evaluation of vegetable oil-based lubricant blends”, *Materials Today: Proceedings*, vol. 37, no. 2, pp. 2660–2665, 2020. <https://doi.org/10.1016/j.matpr.2020.08.521>.
- [4] D. Demydov, A. Adhvaryu, P. McCluskey, and A. P. Malshe, “Advanced lubricant additives of dialkyldithiophosphate (DDP)-functionalized molybdenum sulfide nanoparticles and their tribological performance for boundary lubrication”, *ACS Symposium Series, In Nanoscale Materials in Chemistry: Environmental Applications*, Chapter 8, pp. 137-163, Aug. 2010. <https://doi.org/10.1021/bk-2010-1045.ch008>.
- [5] S. Shahnazar, S. Bagheri, and S. B. Abd Hamid, “Enhancing lubricant properties by nanoparticle additives”, *International Journal of Hydrogen Energy*, vol. 41, no. 4, pp. 3153–3170, 2016. <https://doi.org/10.1016/j.ijhydene.2015.12.040>.
- [6] Y. Zhu, H. Zhang, N. Li, and Z. Jiang, “Friction and Wear Characteristics of Fe₃O₄ Nano-Additive Lubricant in Micro-Rolling”, *Lubricants*, vol. 11, no. 10, Oct. 2023. <https://doi.org/10.3390/lubricants11100434>.
- [7] M. R. Fahad and B. A. Abdulmajeed, “Surface Modification of TiO₂-Al₂O₃ Nanoparticles for the Enhancement of the Rheological Properties of Lubricating Oil”, *Journal of applied research and technology*, vol. 20, no. 1, pp. 37–47, 2022. <https://doi.org/10.22201/icat.24486736e.2022.20.1.1556>.
- [8] M. Raad and B. A. Abdulmajeed, “Effect of Modified Hybrid Nanoparticles on the Properties of Base Oil”, *Iraqi Journal of Chemical and Petroleum Engineering*, vol. 23, no. 1, pp. 1–7, Mar. 2022. <https://doi.org/10.31699/IJCPE.2022.1.1>.
- [9] M. I. H. C. Abdullah, M. F. bin Abdollah, H. Amiruddin, N. Tamaldin, N. R. M. Nuri, and M. Hassan, “Improving engine oil properties by dispersion of hBN/Al₂O₃ nanoparticles”, *Applied Mechanics and Materials*, vol. 607, pp. 70–73, 2014. <https://doi.org/10.4028/www.scientific.net/AMM.607.70>.
- [10] M. K. A. Ali and H. Xianjun, “Improving the tribological behavior of internal combustion engines via the addition of nanoparticles to engine oils”, *Nanotechnology Reviews*, vol. 4, no. 4, pp. 347–358, 2015. <https://doi.org/10.1515/ntrev-2015-0031>.

- [11] W. Wu, Q. He, and C. Jiang, "Magnetic iron oxide nanoparticles: Synthesis and surface functionalization strategies", *Nanoscale research letters*, vol. 3, no. 11, pp. 397–415, Nov. 2008. <https://doi.org/10.1007/s11671-008-9174-9>.
- [12] Y. Chen, P. Renner, and H. Liang, "Dispersion of nanoparticles in lubricating oil: A critical review", *Lubricants*, vol. 7, no. 1, p. 7, 2019. <https://doi.org/10.3390/lubricants7010007>.
- [13] Deepika, "Nanotechnology implications for high performance lubricants", *SN Applied Sciences*, vol. 2, no. 6, Art. no. 1128, 2020. <https://doi.org/10.1007/s42452-020-2916-8>.
- [14] Z. S. Hu, J. X. Dong, and G. X. Chen, "Study on antiwear and reducing friction additive of nanometer ferric oxide", *Tribology International*, vol. 31, no. 7, pp. 355-360, 1998. [https://doi.org/10.1016/S0301-679X\(98\)00042-5](https://doi.org/10.1016/S0301-679X(98)00042-5).
- [15] F. S. A. Majeed, N. B. M. Yusof, M. A. Suhaimi, and N. M. Elsiiti, "Effect of paraffin oil with XGnP and Fe₂O₃ nanoparticles on tribological properties", *Materials Today: Proceedings*, vol. 27, no. 2, pp. 1685–1688, Jan. 2020. <https://doi.org/10.1016/j.matpr.2020.03.576>.
- [16] X. Wang, H. Liu, Q. Zhao, X. Wang, and W. Lou, "Viscosity Variations and Tribological Performances of Oleylamine-Modified Fe₃O₄ Nanoparticles as Mineral Oil Additives", *Lubricants*, vol. 11, no. 3, p.149, Mar. 2023. <https://doi.org/10.3390/lubricants11030149>.
- [17] M. Garcia Tobar, R. W. Contreras Urgiles, B. Jimenez Cordero, and J. Guillen Matute, "Nanotechnology in Lubricants: A Systematic Review of the Use of Nanoparticles to Reduce the Friction Coefficient", *Lubricants*, vol. 12, no. 5, p. 166, May 2024. <https://doi.org/10.3390/lubricants12050166>.
- [18] A. Morshed, H. Wu, and Z. Jiang, "A comprehensive review of water-based nanolubricants," *Lubricants*, vol. 9, no. 9, p. 89, Sep. 01, 2021. <https://doi.org/10.3390/lubricants9090089>.
- [19] K. Maharaja, S. N. Vijayan, and S. Karthik, "Tribological Effect of Size, Shape and Structure of Nanoparticle in Lubricant Oil-A Review", *International conference on systems, science, control, communication, engineering and technology (ICSSCET 2016)*, pp. 730–734, 2016.
- [20] P. D. Srivyas and M. S. Charoo, "A review on tribological characterization of lubricants with nano additives for automotive applications", *Tribology in Industry*, vol. 40, no. 4, pp. 594–623, 2018. <https://doi.org/10.24874/ti.2018.40.04.08>.
- [21] M. H. Flayyih and M. S. Theib, "Effect of Cationic Surfactant in the Synthesis Process of Nano γ -Alumina for Petroleum Industry Application", *Journal of Petroleum Research and Studies*, vol. 12, no. 4, pp. 92-103, Dec. 2022. <https://doi.org/10.52716/jprs.v12i4.578>
- [22] M. Khalil, J. Yu, N. Liu, and R. L. Lee, "Hydrothermal synthesis, characterization, and growth mechanism of hematite nanoparticles", *Journal of Nanoparticle Research*, vol. 16, no. 4, Art. no. 2362, 2014. <https://doi.org/10.1007/s11051-014-2362-x>.
- [23] N. Angelova, S. Koleva, and G. Yordanov, "Synthesis and characterization of nanostructured hematite for wastewater treatment Synthesis and characterization of nanostructured hematite for wastewater treatment", *Industry 4.0*, vol. 7, no. 6, pp. 232-233, December 2022.
- [24] T. Pinnarat and P. E. Savage, "Noncatalytic esterification of oleic acid in ethanol", *The Journal of Supercritical Fluids*, vol. 53, no. 1–3, pp. 53–59, Jun. 2010. <https://doi.org/10.1016/j.supflu.2010.02.008>.
- [25] L. N. Okassa, H. Marchais, L. Douziech-Eyrolles, K. Hervé, S. Cohen-Jonathan, E. Munnier, M. Soucé, C. Linassier, P. Dubois, and I. Chourpa, "Optimization of iron oxide nanoparticles encapsulation within poly(d,l-lactide-co-glycolide) sub-micron particles", *European Journal of Pharmaceutics and Biopharmaceutics*, vol. 67, no. 1, pp. 31–38, Aug. 2007. <https://doi.org/10.1016/j.ejpb.2006.12.020>.

- [26] W. Aadinath and V. Muthuvijayan, "Influence of oleic acid coating on the magnetic susceptibility and Fenton reaction-mediated ROS generation by the iron oxide nanoparticles", *Nano Express*, vol. 5, no. 1, Art. no. 015017, Mar. 2024. <https://doi.org/10.1088/2632-959X/ad2b7f>.
- [27] V. M. Mello, G. P. A. G. Pousa, M. S. C. Pereira, I. M. Dias, and P. A. Z. Suarez, "Metal oxides as heterogeneous catalysts for esterification of fatty acids obtained from soybean oil", *Fuel Processing Technology*, vol. 92, no. 1, pp. 53–57, Jan. 2011. <https://doi.org/10.1016/j.fuproc.2010.08.019>.
- [28] Y. J. Lee, K. W. Jun, J. Y. Park, H. S. Potdar, and R. C. Chikate, "A simple chemical route for the synthesis of γ -Fe₂O₃ nano-particles dispersed in organic solvents via an iron-hydroxy oleate precursor", *Journal of Industrial and Engineering Chemistry*, vol. 14, no. 1, pp. 38–44, Jan. 2008. <https://doi.org/10.1016/j.jiec.2007.08.009>.
- [29] M. Zhu, Y. Wang, D. Meng, X. Qin, and G. Diao, "Hydrothermal synthesis of hematite nanoparticles and their electrochemical properties", *Journal of Physical Chemistry C*, vol. 116, no. 30, pp. 16276–16285, Aug. 2012. <https://doi.org/10.1021/jp304041m>
- [30] C. D. Powell, A. W. Lounsbury, Z. S. Fishman, C. L. Coonrod, M. J. Gallagher, D. Villagran, J. B. Zimmerman, L. D. Pfefferle, and M. S. Wong, "Nano-structural effects on Hematite (α -Fe₂O₃) nanoparticle radiofrequency heating", *Nano Convergence*, vol. 8, no. 1, Art. no. 8, Dec. 2021. <https://doi.org/10.1186/s40580-021-00258-7>.
- [31] J. B. Lee, H. J. Kim, J. Lužnik, A. Jelen, D. Pajić, M. Wencka, Z. Jagličić, A. Meden, and J. Dolinšek, "Synthesis and magnetic properties of hematite particles in a 'nanomedusa' morphology", *Journal of Nanomaterials*, vol. 2014, Art. no. 902968, 9 pages, 2014. <https://doi.org/10.1155/2014/902968>
- [32] G. Hübschen, I. Altpeter, R. Tschuncky, and H.-G. Herrmann, *Materials characterization using nondestructive evaluation methods*, Woodhead Publishing, an imprint of Elsevier, 2016. <https://doi.org/10.1016/C2014-0-00661-2>.