Kingdom of Saudi Arabia
Imam Mohammad Ibn Saud Islamic University (IMSIU)
Faculty of Science

Magnetic-Nanoparticles in Hyperthermia Application

A graduation project submitted to the Department of Physics in partial fulfillment of the requirements for the degree of Bachelor of Science in Applied Physics

By students

Dunya Mohammed Al-Osaimi

and

Omamah Hammad Hammad Alnaseef

In Supervision of

Dr./ Nawal Madkhali

IMSIU – Riyadh – KSA

January 2025

Contents

ACKNOWLEDGMENT

In the name of Allah, and peace and blessings be upon the best of messengers, our master and prophet Muhammad, and upon his family and companions and those who follow his guidance

I dedicate this research to my father, may Allah protect him, and to my teacher and first supporter, my mother, who supported me in all stages of my life until Allah took her soul after she was diagnosed with cancer. There is no doubt that she would have been proud of me and my achievement. May Allah have mercy on her.

I also extend my thanks and gratitude to Dr. Nawal Madkhali, who was keen to spread beneficial knowledge and devoted time and effort to helping and guiding me during my university period in general and in this project in particular.

I also thank my sisters, brothers, family and friends for their support and assistance during this difficult period. They have all my thanks and appreciation.

List of Figures

List of Tables

List of Abbreviation

Amplitude Modulated Frequency(AMF)
Superparamagnetic nanoparticles (NPs)
Vibrating Sample Magnetometer (VSM)
Magnetization field (M-H)
The saturation magnetization (M_s)
Remanence (M_r)
Coercivity (H_c)
Specific Absorption Rate (SAR)
Superparamagnetic Iron Oxide Nanoparticles (SPIONs)

Abstract

This study investigates the heating abilities of two types of iron oxide nanoparticles: maghemite (Fe_2O_3) and (Fe_2O_3-NH_2) for magnetic hyperthermia applications. The nanoparticles were characterized using vibrating sample magnetometry (VSM). Magnetic measurements demonstrated that both samples exhibited superparamagnetic behavior, which is crucial for effective hyperthermia. Additionally, the influence of nanoparticle concentration and amplitude modulated frequency parameters on heating efficiency was examined, providing insights into optimizing these variables for enhanced paving the way for future investigations into medical and electronic applications.

الملخص

تبحث هذه الدراسة في قدرات التسخين لنوعين من جسيمات أكسيد الحديد النانوية: الماغيميت (Fe_2O_3) و (Fe_2O_3-NH_2) لتطبيقات فرط الحرارة المغناطيسية. تم توصيف الجسيمات النانوية باستخدام مغناطيسية العينة المهتزة .(VSM) أظهرت القياسات المغناطيسية أن كلتا العينتين أظهرتا سلوكًا فائقًا مغناطيسيًا، وهو أمر بالغ الأهمية لفرط الحرارة الفعال. بالإضافة إلى ذلك، تم فحص تأثير تركيز الجسيمات النانوية ومعاملات التردد المعدل بالسعة على كفاءة التسخين، مما يوفر رؤى حول تحسين هذه المتغيرات لتحسين تمهيد الطريق لتحقيقات مستقبلية في التطبيقات الطبية والإلكترونية.

1 Introduction

1.1 Concept of Heat

Thermodynamics is the branch of physics in which we study the relationship between the heat energy and mechanical energy or in general, any other form of energy. In thermodynamics we consider only the microscopic properties of the substance.

According to the Zeroeth Law, if two systems are separately in thermal equilibrium with a third system then they both are also in thermal equilibrium with each other. Also, the temperature is the quantity which determines the direction of flow of heat when the two systems are kept in contact, if there is no exchange of heat energy between the two systems kept in contact, the systems are said to be in thermal equilibrium. But if there is a transfer of heat energy from one system to the other system, the system imparting heat energy is said to be at a higher temperature and the system which receives the heat energy is said to be at a lower temperature. Temperature is thus the thermodynamic property which controls the state of thermal equilibrium of the system.

The quantity of heat flowing into a system was expressed in terms of calories .1 calories was being defined as the heat flow into 1gm of water in a process in which its temperature increased by 1 Celsius degree is the heat flow into 1 pound mass of water when its temperature increased by 1 Fahrenheit degree.

For many years, it was thought that heat was a substance contained in material. The first conclusive evidence that it was not was given by Count Rumford (1753-1814) he observed the temperature rise of the chips produced while boring cannons. He concluded that heat flow into the chips was caused by the work of boring. However, the precision measurement of the mechanical equivalent of heat were made by Joule. The experiments were performed in a period from 1840 to 1878, and although, Joule expressed his results in English units, they are equivalent to the remarkable precise value of 1 calorie = 4.19 joules.

(The energy unit, 1 joule, was not introduced or named until after Joule's death and the standardizer 15-degree calorie had not been agreed on at the time of Joule's work).

However, the true significance of Joule's work went for beyond a mere determination of the mechanical equivalent of heat. By means of such above mentioned experiment, and other of similar nature, Joule concluded that there was in fact a direct proportion between "work" and “heat” and he succeeded in dispelling the belief, prevalent at that time that “heat” was an invisible, weight less fluid known as “caloric”. It may be said that joule not only determined the value of mechanical equivalent of heat but also provided the experimental proof that such an equivalence actually existed.

It is a will known fact that friction produces heat. Friction forces also gradually rob mechanical systems of their energy and eventually bring them to rest. It is a will known that the heat Q is a thermal energy in transit, and work W is mechanical energy in transit.

Objects have no capacity for heat. Also, heat transfer from the hot body to a cold body and not in reverse direction. There are some cases where the reverse direction of heat flow happens like the freezer. The heat transfer in reverse never occurs in isolation.

There are two ways to transfer heat (1) by adding heat from the outside. for example, Fireplace. (2) by done some work. Like exercising. The SI unit of heat is joules(J). The rate of heating has the units of watts(W). Where 1 W=1 J/s.

$$\boldsymbol{Q = mc\,\Delta T} \qquad \textbf{(1−1)}$$

Q: heat transfer (J)
m : mass (g)
c $(\frac{J}{-}K)$: specific heat capacity
$\Delta T(K)$: change in temperature

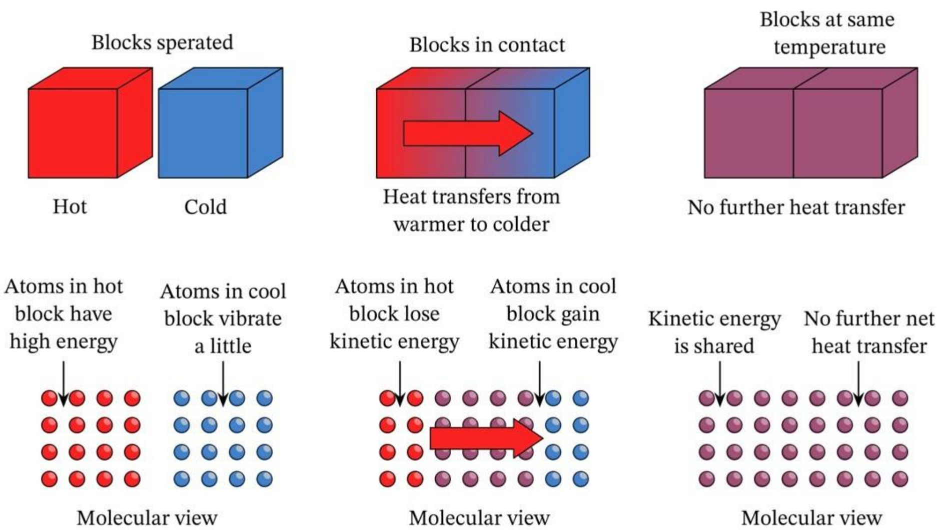

Figure 1.1 Heat transfer energy

Heat capacity C is the amount of heat required to raise the temperature of an object by a small amount dT and it is equal to the ratio of heat supplied to it to the rise in its temperature.

$$\boldsymbol{C} = \frac{\boldsymbol{dQ}}{\boldsymbol{dT}} \qquad \textbf{(1-2)}$$

Where the SI unit of heat capacity is J K^{-1}

Second low of thermodynamic is a statement about the direction of heat In the nineteenth century physicists as Carnot, Clausius kelvin was developing their different own statements of the second law of thermodynamics.

Therefore, there is two statements of the second low of thermodynamics:

***1- Clausius statement**:* "No process is possible whose sole result is the transfer of heat from a colder to hotter body." It is easy to change energy from one form to another in particular from work to heat. On the other hand, convert the heat into work is so hard. actually, completing the conversion is impossible

2-Kelvin's statement: "No process is possible whose sole result is the complete conversion of heat into work." This meaning that actually completing the conversion is impossible.

Carnot engine

The definition of engine is a system operating a cyclic process that converts heat into work. It should be cyclic so that it can be continuously operating, producing a steady power.

1.2 The Nanoparticles Application

1.2.1 Nanotechnology

Nanotechnology is a branch of science and engineering focused on designing, producing, and utilizing structures, devices, and systems by manipulating atoms and molecules at the nanoscale, specifically with dimensions of 100 nanometers or less. This field represents one of the key scientific advancements of the 21st century, ushering in a new era of innovation and technology across various sectors, including medicine, electronics, energy, and environmental science.

Research has demonstrated that incorporating metallic and non-metallic nanoparticles, such as TiO_2, CuO, Cu, and SiO_2, can significantly enhance the thermal conductivity of fluids compared to their base counterparts. Generally, liquids used for heat transfer exhibit lower thermal conductivity than solids; however, the inclusion of these nanoparticles boosts their efficiency. The unique properties of nanomaterials, which differ markedly from traditional materials, open up a multitude of possibilities for practical applications.

In the medical field, nanotechnology is leading the way in developing advanced methods for drug delivery and disease treatment. In the energy sector, it plays a crucial role in improving the efficiency of solar cells and energy storage solutions. Furthermore, nanotechnology acts as a bridge between fundamental sciences and practical applications, contributing to enhanced quality of life and promoting environmental sustainability. As research and development in this area continue, nanotechnology is poised to revolutionize numerous industries, making it an integral component of our technological future.

1.2.2 Nanoparticles Properties

A nanoparticle, or ultrafine particle, is defined as a particle of matter with a diameter ranging from 1 to 100 nanometers (nm). In some cases, the term can also refer to larger particles, extending up to 500 nm, as well as fibers and tubes that measure less than 100 nm in two dimensions. Particles smaller than 1 nm are typically referred to as atom clusters, distinguishing them from nanoparticles.

Nanoparticles are distinct from microparticles (1-1000 µm), fine particles (100 to 2500 nm), and coarse particles (2500 to 10,000 nm) due to their significantly smaller size, which imparts unique physical and chemical properties. These properties include colloidal characteristics and ultrafast optical and electrical effects. Because nanoparticles are more susceptible to Brownian motion, they tend not to sediment, unlike colloidal particles, which are generally considered to range from 1 to 1000 nm.

The unique attributes of nanoparticles, such as their high surface area relative to their volume, enhance their chemical and physical reactivity. At nanoscale dimensions, conventional materials exhibit altered properties, including changes in color, electrical conductivity, and magnetism. For instance, gold nanoparticles, which typically appear golden in bulk form, take on a red hue when reduced to the nanoscale.

These distinctive properties make nanoparticles highly valuable across various fields, including medicine, environmental science, and industry, leading to increased interest in their utilization and potential applications.

1.2.3 Types of Nanoparticles

Types of Nanoparticles can be classified based on their constituent material or composition

- Carbon-based NPs.
- Metal NPs.
- Ceramics NPs.
- Semiconductor NPs.
- Polymeric NPs.

1.2.4 Application of Superparamagnetic Magnetic Nanoparticles

The heat and power applications of nanoparticles, particularly magnetic nanoparticles (MNPs), are extensively explored in the context of biomedical and engineering uses:

- Magnetic particles play a crucial role in memory devices, particularly in magnetic storage systems such as hard disk drives, magnetic random-access memory, and emerging spintronic memory technologies. Their unique properties, such as high coercivity, remanence, and superparamagnetic behavior, make them ideal for storing digital data efficiently.

- Superparamagnetic Iron Oxide Nanoparticles (SPIONs) enhance MRI contrast, improving the visibility of organs and tissues. Used in detecting tumors, liver disorders, and vascular diseases.
- Magnetic beads can bind to toxins, bacteria, or heavy metals in the blood and remove them via a magnetic field. Used for treating sepsis (blood infections) by capturing bacterial toxins.

Heat production by MNPs is governed by Brownian and Néel relaxation mechanisms, which depend on particle size, composition, and interaction with external fields. These dynamics are crucial for understanding and optimizing their performance in specific applications.

1.3 Hyperthermia Néel And Brownian Relaxation

Magnetic nanoparticles (MNPs) possess fascinating properties that can be exploited in several engineering and biomedical application. with typical diameters of their magnetic core on the order of 5-30 nm, MNPs are magnetic mono-domain particles and therefore show superparamagnetic behavior. Relaxation time is the time it takes for the nanoparticles to lose their magnetization.

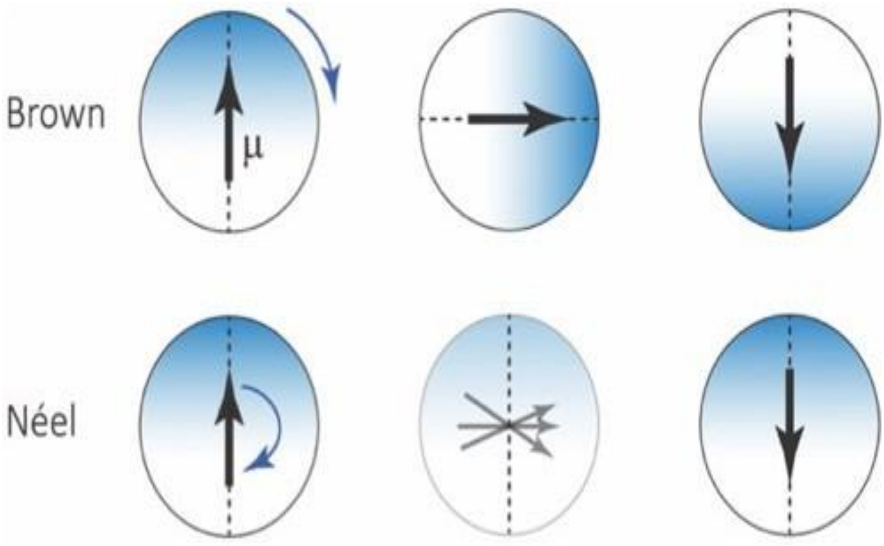

Figure 1.2 Mechanisms of heat generation by magnetic nanoparticles

There are two basic mechanisms govern the magnetization relaxation of MNPs:

1-Internal magnetization relaxation with in the MNP, Néel relaxation, on time scale,
2- Brownian relaxation on time scale by rotational diffusion of the whole MNP when the particle is suspended in a viscous liquid.

The relative contribution of Brownian and Néel relaxation is crucial for optimal use of MNPs in many technical as well as biomedical applications such as hyperthermia.

Therefore, methods for determining their relative importance are currently being explored, helping to find the optimal colloids for the given application. For ferrofluids, where MNPs are suspended in a non-magnetic carrier fluid, Rosensweig assumed that both relaxation process occur independently so that the corresponding rates can be added up to yield an effective relaxation given by:

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_B} + \frac{1}{\tau_N} \quad (1-3)$$

Equation (1.3) is fundamental for ferrofluid research and is used in numerous textbooks and research articles. However, one should bear in mind that the equation was originally suggested for non-interacting MNPs in the absence of external fields.

Since t_N grows almost exponentially with the magnetic volume of the nanoparticle, while tB grows only linearly with its hydrodynamic volume, different ratios t_N/t_B can realized for core shell particles with the same magnetic material by different sizes of the magnetic core and different thickness of the nonmagnetic shell. The dependence of t_B and t_N on the strength of an external magnetic field has recently been determined experimentally by comparing the field-dependent magnetic susceptibility in the fluid and freeze-dried state for very dilute conditions. In another set of very recent experiments, the concentration dependence of the magnetization relaxation has been measured and the Brownian and Néel contributions have been identified. While the effective Brownian relaxation time was found to increase with increasing concentration, a weaker, opposite behavior was observed for the effective Néel relaxation time.

Furthermore, the corresponding dynamic magnetic susceptibility deviates strongly from the Debye law for noninteracting MNPs and the effective relaxation time is not sufficient to describe the behavior. Intriguingly, some experiments suggest that Brownian effects seem to play a role under conditions where only Néel relaxation was expected. In addition, hysteresis measurements pointed out the importance of dipolar interactions for magnetic losses that are relevant e.g in hyperthermia applications.In order to obtain the characteristic hysteresis loop It is necessary for the magnetization induced in the nanoparticles by the magnetic field to be conserved over the time frame of the measurement If it’s not the case the magnetization of the nanoparticles is said to have relaxed during the AC field circle. Relaxation time is the time it takes for the nanoparticles to lose their magnetization.

1 Néel relaxation

Can occur when the thermal energy of the surroundings far exceeds the magnetic anisotropy energy of the particle. The smaller particles have lower anisotropy energies and that's means

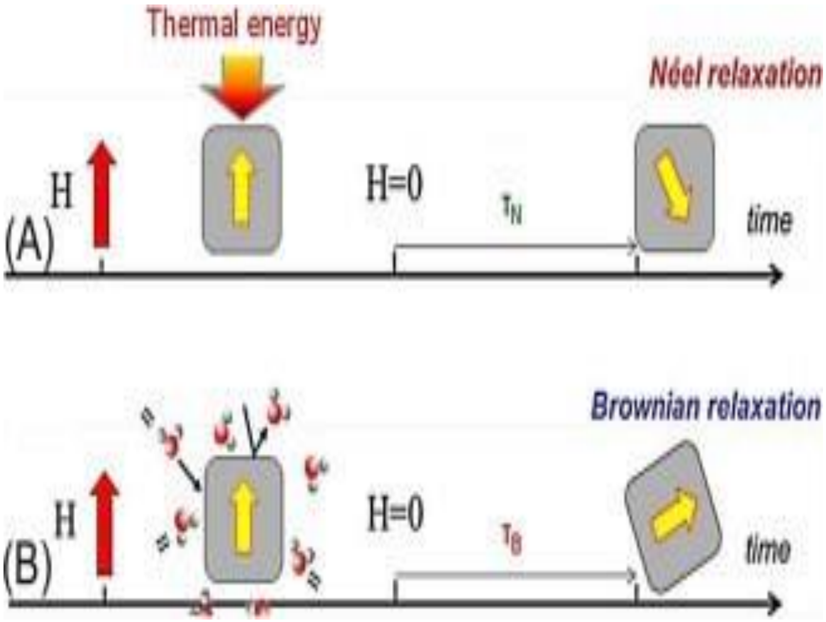

Figure 1.3 (A) Neel relaxation and (B) Brownian relaxation

that the anisotropy energy act to preserve the magnetization direction of the particle and is proportional to the particle size.Néel relaxation time, reflects the competition between two energy terms which is thermal and anisotropy and describes how long the particles remain magnetized after the magnetic fields has been removed. Néel relaxation time depends on volume and magnetic anisotropy. Néel relaxation is more dominant in the case of particles with smaller sizes.

Superparamagnetic state: when the particles are sufficiently small the Néel relaxation time became shorter than the measurement time.

2 Brownian Relaxation:

Brownian relaxation varies linearly with the volume and the media viscosity. Large particles relax in liquid medium mainly by a Brownian mechanism. A reverse superparamagnetic magnetization curve rather than A hysteresis loop is obtained, as the magnetization of the particle is no longer preserved when the magnetic field is removed.

If the particles become immobilized (through their interaction with cells then only Néel relaxation is possible. For particles dispersed in liquid media, both Néel and Brownian relaxation modes are possible.

1.4 Specific Absorption Rate (SAR)

We can define the specific absorption rate as the power turns into heat per unit of mass of nanoparticles. the SAR value, also known as Specific Loss Power (SPL). It depends entirely on several parameters like the intensity of the applied magnetic field and frequency, also there is an internal parameter such as size, shape, material, build up state and properties of the scattering medium. And we can use the SAR to measure the heat efficiency of the magnetic nanoparticles in the attendance of an AC magnetic field.

The SAR value is measured by the given formula:

$$SAR = \frac{\rho C_w}{M_{MNP}(\frac{\Delta T}{\Delta t})} \qquad (1-6)$$

C_W: specific heat capacity, for water =4.185 J/g.k.

ρ: the density of the colloid.

M_{MNP}: the concentration of the magnetic nanoparticles in the suspension.

ΔT/Δt :is the heating rate. By performing a linear fit of temperature increases versus time at the initial time interval (1 to 30 s), the slope is obtained.

2.1Vibrating Sample magnetometer (VSM) experiment.

The VSM machine is based on the faraday's Law, and we can identify it as changing magnetic field induced an electric current in a conductor. It's discovered by Micheal Faraday; this principle highlights the dynamic relationship between magnetism and electricity.

When the magnetic field around a conductor changes, it produces an electromotive force that drives an electric current. Our goal from doing this experiment is to check the magnetization property for the material we choose. Remanence and coercivity tells how much a material can resist demagnetization But what is the deference between these two, the material that is still very magnetic after the magnetizing field withdraws has high remanence. On the other hand coercivity measures how much magnetic intensity is needed to demagnetize a magnet.

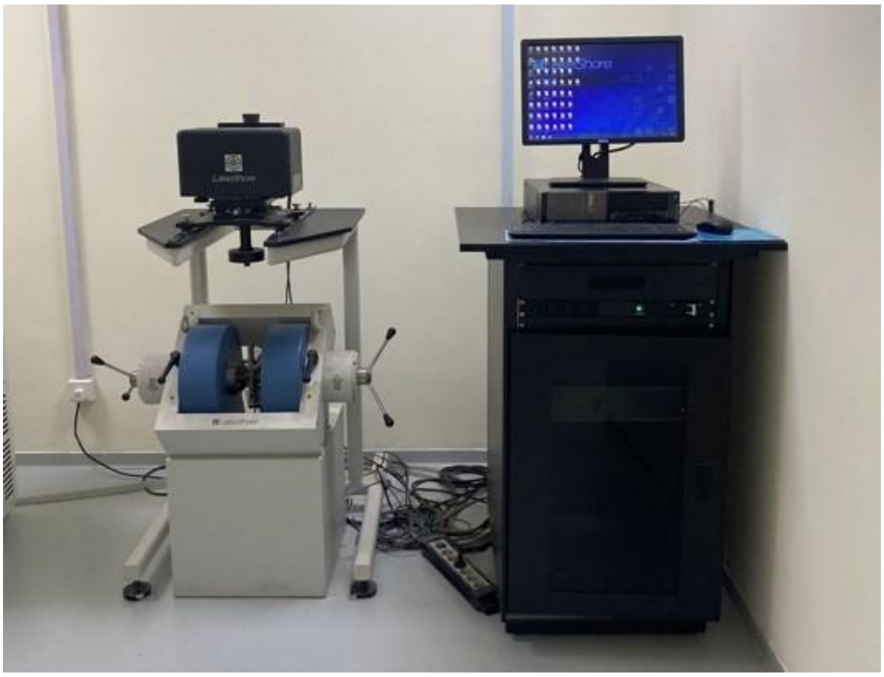

Figure 2.1: Vibration Sample Magnetometer (VSM, 7400 model, Lakeshore Westerville-OH)

Now, we work on the steps of the experiment:

- In the beginning we measured 30 mg of Fe_2O_3 and the $Fe_2O_3{-}NH_2$ by using the scale.
- After that we added each material into the VSM holder respectfully and measure

the magnetization properties by using a vibrating sample magnetometer from -10,000 to +10,000 O_e at room temperature (300 K) for each one.

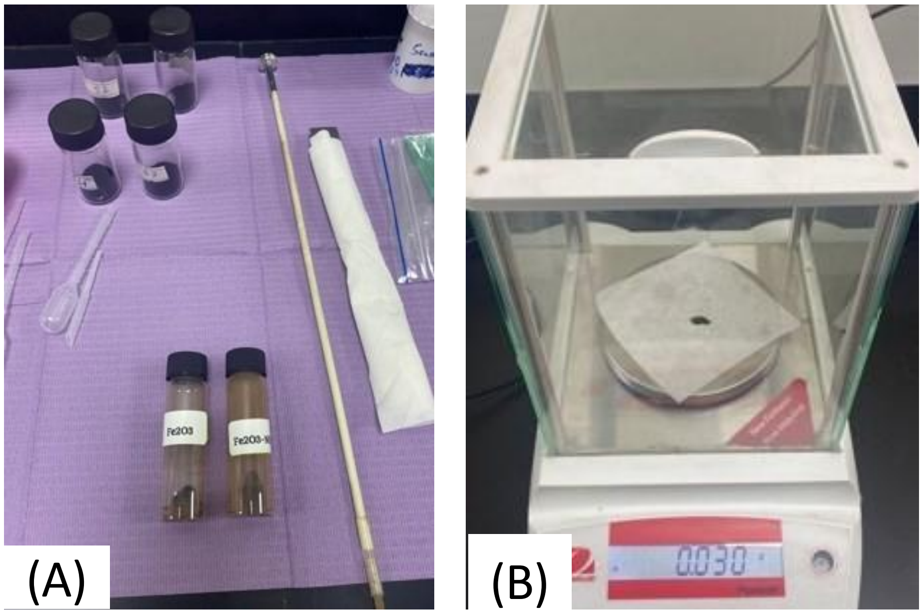

Figure 2.2 (A) samples of the experiments, we have Fe_2O_3, and on the right we have $Fe_2O_3{-}NH_2$ and (B) : weighing the material in analytical balance

Table 2.1: Magnetic parameters in hysteresis loop

Sample	M_s (eum/g)	M_r (eum/g)	H_C (O_e)	M_r/M_S
Fe_2O_3	88.85	14	118.47	0.16
$Fe_2O_3-NH_2$	67.66	9.28	105.35	0.14

The material acts like Superparamagnetic because of M_r/M_s is less than 1

2.2The Hyperthermia Experiment

- First, we measured 5 mg of and Fe_2O_3 and the $Fe_2O_3-NH_2$ in the scale,
- and add 1ml of distilled water to each compound,
- after that we put it in the ultrasonic machine that vibrate using high frequency for 10 minutes to heat up the sample so the elements mix will together before,
- We insert the samples in the hyperthermia machine and insert the sensor into the sample to determine the temperature to time relation and then calculate the specific absorption rate SAR.
- In the program, we set the frequency at 470 kHz and the magnetic field at 16 mT for about 15 minutes,
- After that we change the time to 30 minutes, for the Fe_2O_3 and the $Fe_2O_3-NH_2$ respectfully.
- And then we change the concentration to 10 mg/ml and repeat the same steps,
- and we change the concentration to 15 mg/ml and do the same steps we did before,
- finally, we take the data that gives the best result for SAR and change the capacitor to give frequency equal to 626 kHz and the magnetic field at 12 mT.

Figure 2.3: Ultrasonic machine

Chapter 3 : Results and Discussion

3.1Results and Discussion

In hyperthermia experiment we studied the effect of different concentrations (5mg/ml,10mg/ml and 15 mg/ml) of two samples Fe_2O_3 and the $Fe_2O_3{-}NH_2$ at varies parameters such as: concentration, frequency, time period of experiment we use MagneTherm system .As show in Figure 3.1 show the exponentially relation between the time in second and increased of temperature from the samples. The relation between the concentration is inversely relation and Fe_2O_3 is show higher temperature comparing with the $Fe_2O_3{-}NH_2$. Fe_2O_3 sample reach 37C^0 at concentration 5mg/ml comparing with same concentration of $Fe_2O_3{-}NH_2$ sample at the same frequency (470kHz) and magnetic field (16mT).

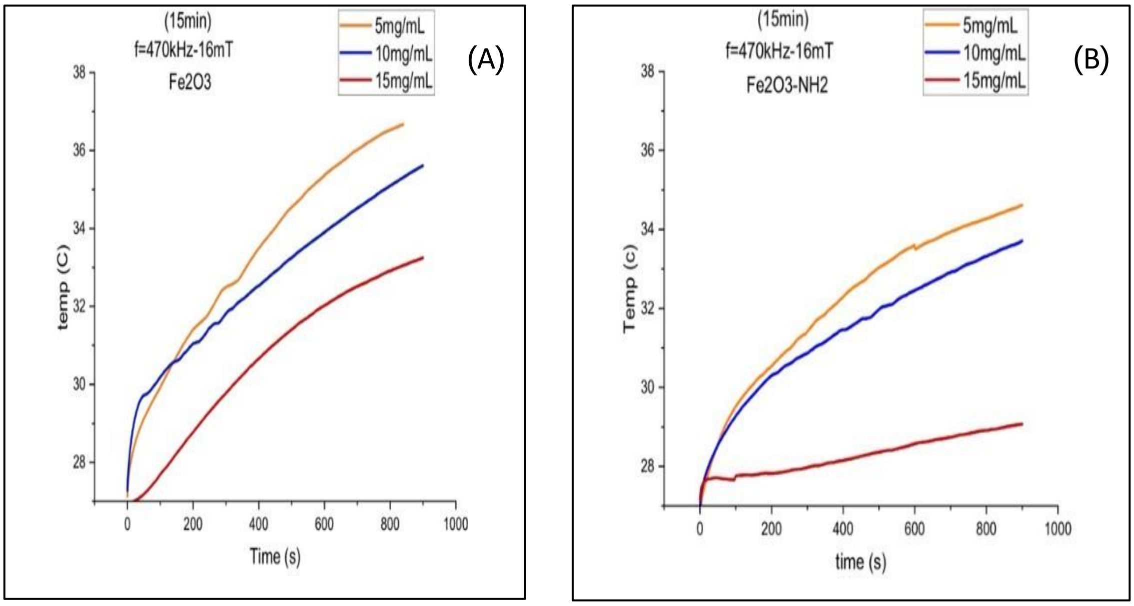

Figure 3.1 of A) Fe_2O_3 and the (B) $Fe_2O_3{-}NH_2$ using 5, 10 and 15 mg/mL concentration

Specific Absorption Rate (SAR) was calculated for both samples in three period time by use formula :

$$SAR = \frac{\rho C_w}{n_{MNP}}\left(\frac{\Delta T}{\Delta t}\right)$$

Where : ρ *and* C_w *is the density and specific heat capacity of water* (*solvent*)

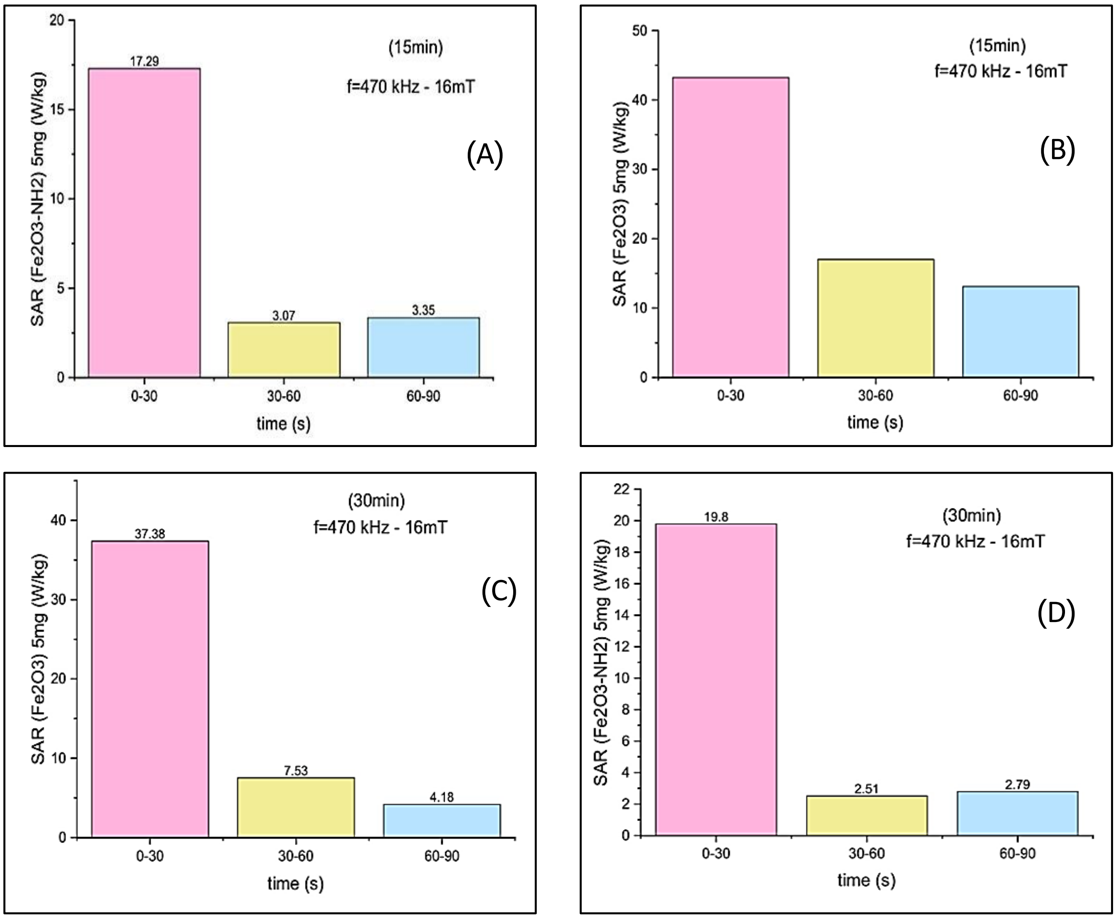

Figure 3.2 data of SAR of A) ,(B) Fe_2O_3 and the (C) , (D) $Fe_2O_3{-}NH_2$ in Magnetic field (16 mT) of Concentration (5 mg/ml).

Table 3.1 data of SAR of Fe_2O_3 and the $Fe_2O_3{-}NH_2$ in Magnetic field (16 mT) of Concentration (5 mg/ml).

Sample	**Time (min)**	**SAR (W/Kg)**		
		0 – 30 (s)	**30 – 60 (s)**	**60 – 90 (s)**
Fe_2O_3	15	43.24	17.02	13.11
	30	37.38	7.53	4.18
$Fe_2O_3{-}NH_2$	15	17.29	3.07	3.35
	30	19.80	2.51	2.79

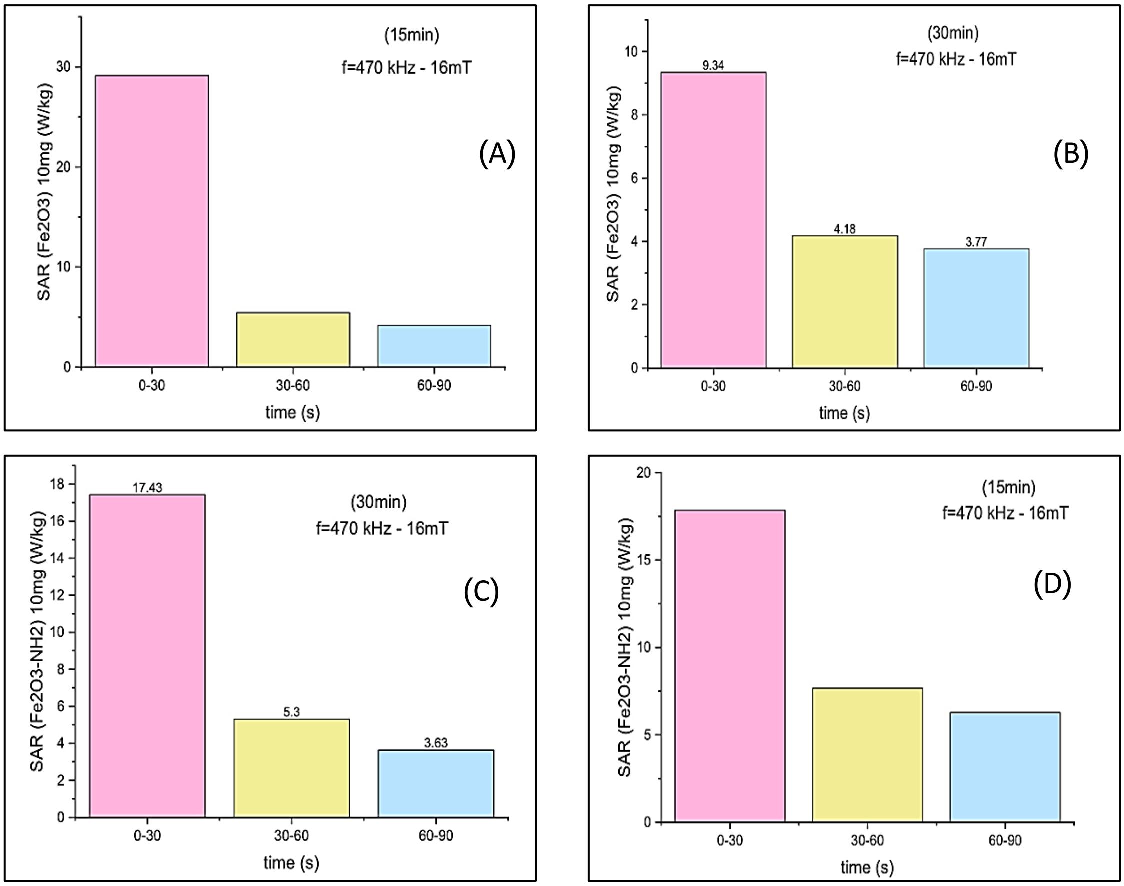

Figure 3.3 SAR of (A) ,(B) Fe_2O_3 and the (C) , (D) Fe_2O_3−NH_2 in Magnetic field (16 mT) of Concentration (10 mg/ml)

Table 3.2 data of SAR of Fe_2O_3 and the Fe_2O_3−NH_2 in Magnetic field (16 mT) of Concentration (10 mg/ml)

Sample	**Time (min)**	**SAR (W/Kg)**		
		0 − 30 (s)	**30 − 60 (s)**	**60 − 90 (s)**
Fe_2O_3	15	29.15	5.44	4.18
	30	9.34	4.18	3.77
Fe_2O_3−NH_2	15	17.85	7.67	6.28
	30	17.43	5.30	3.63

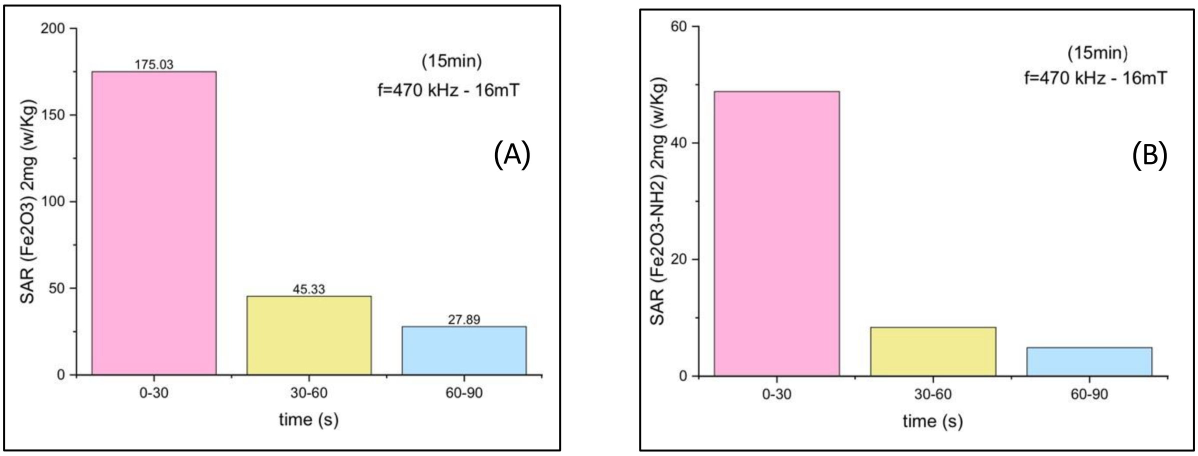

Figure 3.4 SAR of (A) Fe_2O_3 and the (B) $Fe_2O_3-NH_2$ in Magnetic field (16 mT) of Concentration (2 mg/ml)

Table 3.3 data of SAR of Fe_2O_3 and the $Fe_2O_3-NH_2$ in Magnetic field (16 mT) of Concentration (2 mg/ml)

Sample	**Time (min)**	**SAR (W/Kg)**		
		0 – 30 (s)	**30 – 60 (s)**	**60 – 90 (s)**
Fe_2O_3	15	175.03	45.33	27.89
$Fe_2O_3-NH_2$	15	48.81	8.37	4.88

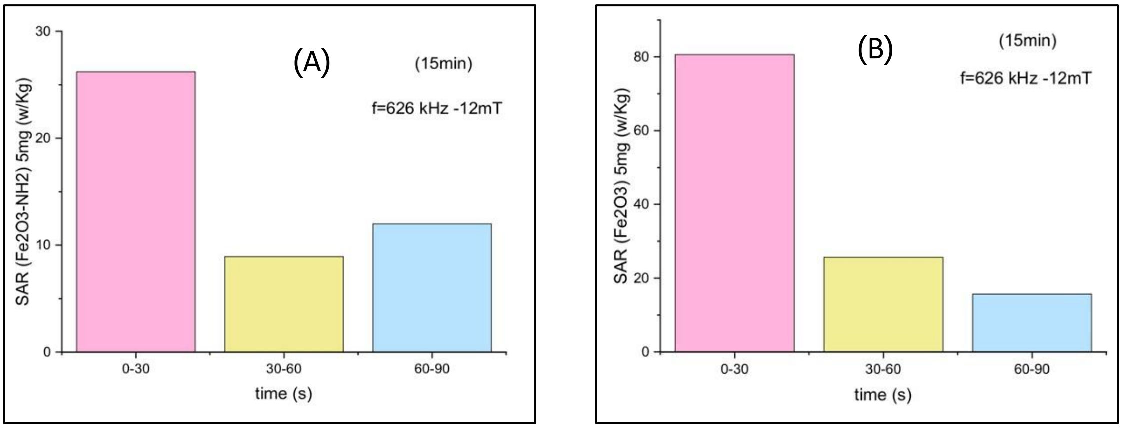

Figure 3.5 (A) Fe_2O_3 and the (B) $Fe_2O_3{-}NH_2$ in Magnetic field (12 mT) of Concentration (2 mg/ml)

Table 3.4 data of SAR of Fe_2O_3 and the $Fe_2O_3{-}NH_2$ in Magnetic field (12 mT) of Concentration (5 mg/ml)

Sample	**Time (min)**	**SAR (W/Kg)**		
		0 − 30 (s)	**30 − 60 (s)**	**60 − 90 (s)**
Fe_2O_3	15	80.61	25.66	15.62
$Fe_2O_3{-}NH_2$	15	26.22	8.93	11.99

3.2 Effect of concentration

In our experiment we started off with three concentration 5,10 and 15 mg/ml we notice that the best SAR is when the concentration is in the lowest so we decided to make another sample with concentration equal to 2 mg/ml to reach the goal faster.

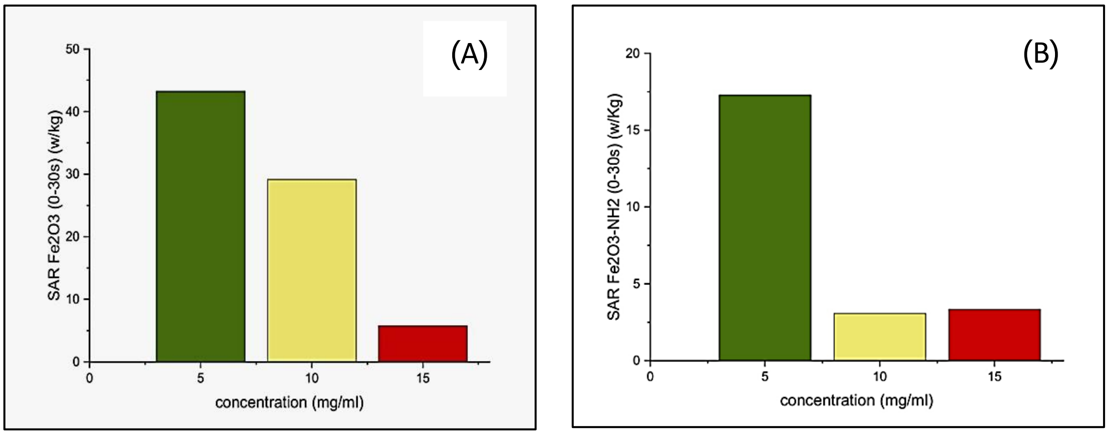

Figure 3.6: Effect of concentration on SAR for A) Fe_2O_3 and the (B) Fe_2O_3–NH_2

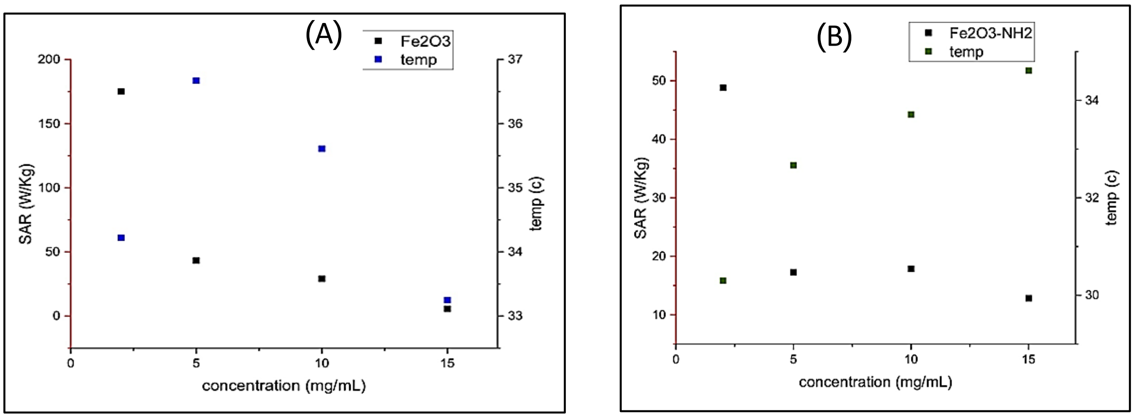

Figure 3.7: Effect of Temperature on SAR for A) Fe_2O_3 and the (B) Fe_2O_3–NH_2

3.3 Effect of frequency

At first, we set the device with new capacitor with frequency qual to 470 kHz. As shown in the figure below: both temperature and SAR increase with increasing applied frequency.

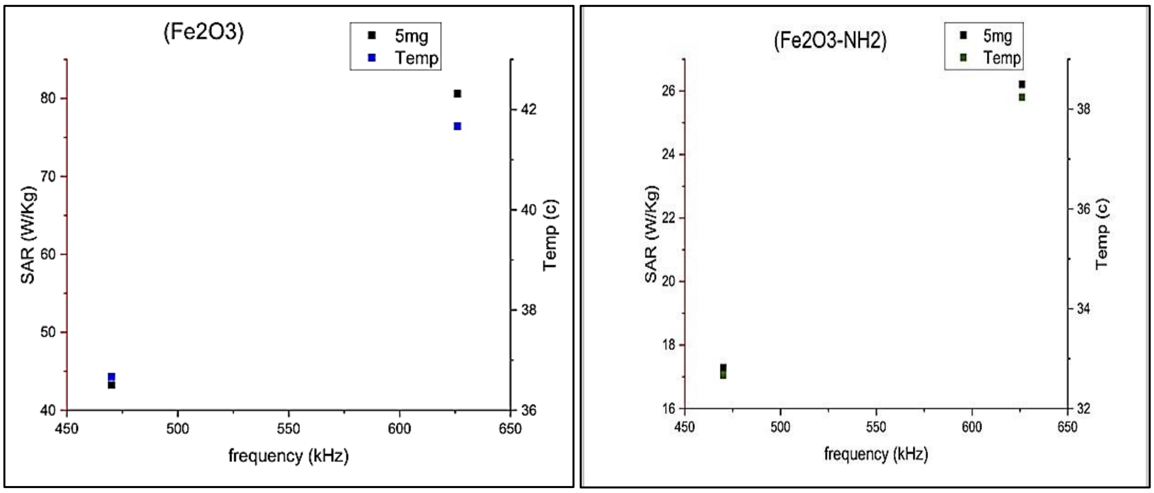

Figure 3.8 Effect of frequency on SAR for A) Fe_2O_3 and the (B) $Fe_2O_3-NH_2$

3.4 Effect of time period

After doing some experiment with time at 15and 30 min, we figured that as the time goes down the temperature becomes better and because of that we decided to keep the time at 15 minutes .

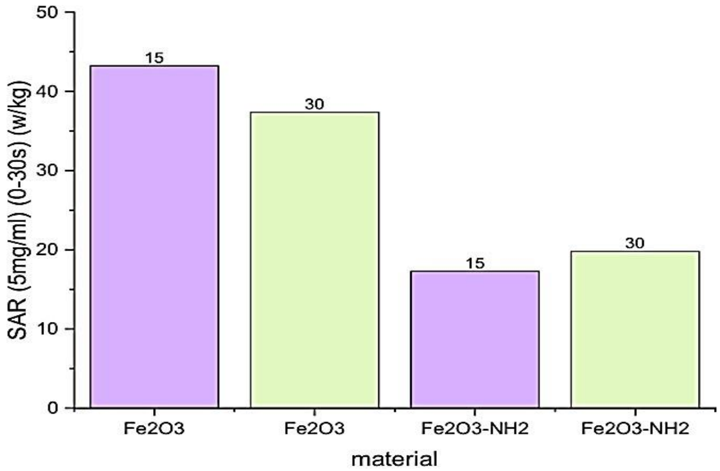

Figure 3.9: Effect of time period on SAR for Fe_2O_3 and $Fe_2O_3-NH_2$

Conclusion

In this study, we investigated the magnetic and thermal properties of iron oxide (maghemite) (Fe_2O_3) and the effects of its functional association with the amine group($Fe_2O_3-NH_2$). We utilized a Vibrating Sample Magnetometer (VSM) to determine the type of magnetism, which revealed a superparamagnetic nature.

In the second part of the research, we examined the heat generated by the samples under varying conditions. We analyzed the effects of concentration at 2, 5, 10, and 15 mg/ml over two-time intervals (15 and 30 minutes) and at two different frequencies (470 and 620 kHz). We also measured the rate of heat emission for all 32 samples and found that the Specific Absorption Rate (SAR) reached its peak at the lowest concentration and during the shortest time period in each experiment (from 0 to 30 seconds). The findings suggest the potential for using these materials in electronic and medical applications.

References

[1] D. L. Leslie-Pelecky and R. D. Rieke, "Magnetic Properties of Nanostructured Materials," 1996. [Online]. Available: https://pubs.acs.org/sharingguidelines

[2] K. Woo *et al.*, "Easy synthesis and magnetic properties of iron oxide nanoparticles," *Chemistry of Materials*, 2004, doi: 10.1021/cm049552x.

[3] O. G. Ellert *et al.*, "Structure, Magnetic and Photochemical Properties of Fe–TiO2 Nanoparticles Stabilized in Al2O3 Matrix," *Russian Journal of Inorganic Chemistry*, vol. 63, no. 11, pp. 1403–1413, Nov. 2018, doi: 10.1134/S0036023618110049.

[4] D. Reyes-Coronado, G. Rodríguez-Gattorno, M. E. Espinosa-Pesqueira, C. Cab, R. de Coss, and G. Oskam, "Phase-pure TiO2 nanoparticles: Anatase, brookite and rutile," *Nanotechnology*, vol. 19, no. 14, Apr. 2008, doi: 10.1088/0957-4484/19/14/145605.

[5] Madkhali, Nawal, et al. "Heating ability of amine functionalized Fe3O4 as a function of field amplitude and frequency for hyperthermia application." *Physica Scripta* 99.4 (2024): 045957.