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Research Article

Enhancement of thermal efficiency of a wet cooling tower using magnetite nanofluid with different stabilizers

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ABSTRACT

Nanofluids have gained increasing attention because of their superior thermophysical properties compared to the base fluid. However, the environmental impact of the nanofluids has raised concerns together with their potential use in practical applications. This study aims to explore the impact of using Fe_3O_4 nanofluids stabilized by synthetic and natural stabilizers (CTAB and gelatin) to enhance thermal efficiency while minimizing environmental impact. The Fe_3O_4 nanoparticles were synthesized by using a hydrothermal method with an average particle size of 200 nm. The nanofluids were prepared by dispersing the nanoparticles (0.1 wt% Fe_3O_4) in the presence of the stabilizers with concentrations between 0.2 and 1.0 wt% in deionized water. The impact of stabilizer type and concentration on the nanofluids' stability was monitored through visual inspection. The thermal efficiency of the nanofluids was investigated experimentally on a laboratory-scale cooling tower at 45°C, with a 0.06 m^3/h volume flow rate, and between 0.02 and 0.07 kg/s air mass flow rates. The results show that nanofluid with 0.8 wt% gelatin achieves maximum stability for up to three weeks, significantly outperforming the nanofluid with the CTAB, which stabilized for only up to one week. The nanofluid with 0.8 wt% gelatin achieved a higher efficiency of 47 % at the air mass flow rate of 0.04 kg/s, consistently outperformed its CTAB counterpart. These results show that gelatin, a natural polypeptide, is more suitable than CTAB for nanofluid formulations, offering both thermal efficiency enhancement and environmental benefits due to its non-toxic and low-cost nature.

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INTRODUCTION

Energy efficiency has become a strong global focus in all industrial facilities, reducing energy demand in recent years. For most of these industries, the efficiency of production is limited by the effectiveness of the thermal management approaches. Most of the manufacturing processes and industrial chemical reactions produce heat that should be dissipated

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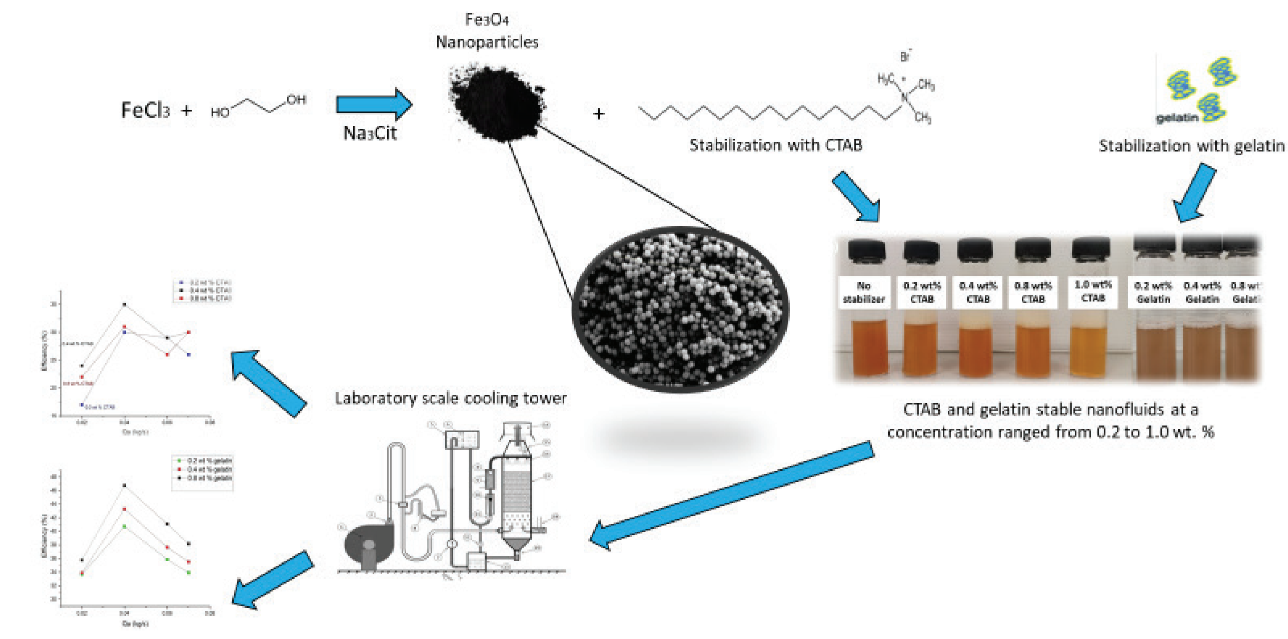
to maintain normal operating parameters without any malfunction and stoppages. As such, cooling towers are one of the most widely used systems to release excess heat loads from these processes into the atmosphere and therefore they play a vital role in the operation of industrial plants such as power stations, and chemical and steel plants [1,2] . Typically, cooling systems circulate water within a closed system across the cooling tower, and operating fans in forced draft units consume a significant amount of energy [3]. Therefore, environmentally friendly and sustainable cooling systems with more energy-efficient and sustainable solutions are necessary. These solutions would help to reduce the energy and water demand, and CO_2 emissions to the atmosphere [4,5]. Although water is used as the circulating fluid in most studies on cooling towers, recent studies have explored nanofluids instead of water. The nanofluid is a stable suspension of nanometer-sized materials such as nanoparticles, nanotubes, and nanorods in the base fluids such as water, ethylene glycol, and oil [6]. Nanoscale refers to a size regime of 1-100 nm. However, it is worth emphasizing that particles of size range between 100 and 500 nm are categorized as nanoparticles [7], which are expected to also constitute nanofluids as well.

Nanofluids can be prepared by dispersing metals, metal oxides, or carbon nanotubes in a base fluid [8]. They possess unique properties owing to nano regime size, large surface area, and excellent heat capacity. These properties enable them to improve heat transfer and thermophysical properties for a range of variables such as flash point, viscosity, thermal conductivity, heat and mass transfer coefficients, pour point, cooling rate [9,10]. Therefore, they have been searched to improve heat transfer in a variety of applications, including cooling and refrigeration systems, process engineering, combustion engines, HVAC (heating, ventilation, and air-conditioning), power generation, and mechanical tools [8,9,11,12]. Since nanofluids promise to be an efficient heat transfer fluid, they are expected to replace cooling and heating water. Their use in industrial cooling is expected to contribute great energy savings and reductions in the emission of carbon dioxide, nitrogen oxides, and sulfur dioxide [13]. Because of their relevant importance in the practical applications in industry, there are many works in the literature that address the heat transfer efficiency of nanofluids in cooling systems. For instance, Rahmati et al. and many other researchers studied the heat transfer performance of natural draft Wet Cooling Towers (WCT) under crosswind and windless conditions [14–20]. The results showed that the tower characteristics, cooling range, and tower effectiveness increase by using nanofluids. Xie et al. concluded that the Al_2O_3 nanoparticles enhanced the heat transfer coefficient, mass transfer coefficient, and cooling efficiency of WCT. At 0.5 wt % of nanofluids, the results were 20, 17, and 19% higher than water as a circulating fluid [21]. Fares et al. studied graphene flakes nanofluids on WCT and found improved cooling range, thermal efficiency, and heat transfer characteristics as they were 6.5 °C, 0.16, and 0.65 respectively. The tower characteristics, cooling range, and the tower effectiveness were shown to increase with increasing concentrations of nanofluids [22]. Mousavi et al. studied Fe_3O_4 - Carbon Quantum Dot nanocomposites prepared by hydrothermal method on the WCT and found a 12% increase in effectiveness compared to base fluid [23]. Siricharoenpanich et al. studied Ag/Fe_3O_4-Water nanofluids as a coolant for electronic devices and their experiment resulted in an 11.94% increase in thermal dissipation efficiency [24]. Afshari et al. also used surface-modified Fe_3O_4-Water nanofluids ($Fe_3O_4@SiO_2@(CH_2)_3IM$) to cool the Peltier cooling system and the performance of the system significantly increased [25].

The thermal efficiency of nanofluids depends on two main factors which are the thermal conductivity of the selected nanoparticle with a particular size and morphology, and the stability of the particles in dispersed phase. Due to the capability of nanofluids to replace conventional heat transfer fluids in the future, long-term colloidal stability is of crucial importance for related applications [26,27]. Surface passivation or coating is therefore an important issue for increasing the dispersive characteristics and colloidal stability of the nanofluids. Shima et.al [28] studied the effect of aggregation formation on the thermal heat transfer in stable and unstable nanofluids. The aggregation was shown to have a prominent role in the enhancement of thermal conductivity and therefore, surface coating or passivation to avoid aggregation is of crucial importance for the performance of the nanofluids. Dispersion characteristics of the nanoparticles in the colloids are usually followed by coating or modifying the nanoparticle surface with stabilizers. Stabilizing agents are grouped as either synthetic or natural. There are various types of synthetic stabilizers, which are also known as surfactants, that are frequently chosen for the stabilization of nanofluids. These include SDS, CTAB, TX-100, and SDBS. Surfactants are attracted by the highly active surface of the nanoparticles utilizing weak interactions including electrostatic or Van der Waals interactions thus preventing nanoparticles from being agglomerated [29]. According to literature reviews, the cationic surfactant, CTAB is reported to contribute to a higher degree of stabilization [30,31] and influences the morphology of nanoparticles. It is also reported that the coloration of nanoparticles is significant due to CTAB concentration, which can be determined by visual observation over time [30]. Considering heat transfer enhancement of nanofluids, some studies in the literature show better results for CTAB [32]. Lei et. al [33] compared various surfactants such as SDS, PVP, CA, CTAB, TMAH and found that the CTAB surfactant gave better results after TMAH regarding the zeta potential value (25), and average particle size (>300) which leads to higher stability. Arora et. al [34], studied CTAB at different weight concentrations (0.01, 0.05, 0.1, and 0.3 wt%) and also assessed its viscosity, resulting in better thermo-physical properties and stability of multi-walled carbon nanotubes (MWCNT)/water nanofluids.

Apart from synthetic stabilizers, natural biopolymers such as starch, chitosan, and gelatin have received increased

Graphical Abstract



attention as stabilizers especially in biomedical applications due to their non-toxicity, benign nature, and lower cost. Gelatin is a natural polypeptide, and it is also a better candidate for the stabilization of iron oxides [35,36]. Sirivat et. al [37] utilized gelatin to synthesize Fe_3O_4 nanoparticles with sizes between 25-80 nm via chemical co-precipitation method for cancer drug loading. Bahaya et. al [38] used gelatin as a surfactant to prevent sedimentation during their thermal conductivity measurements on graphene based nanofluids.

Nanofluids cost more than conventional working fluids, and their long-term durability and environmental impact have been assessed as one of the major concerns in the research area [39]. The heat transfer efficiency of nanofluids has been extensively studied considering many parameters. As a result, the suitability of using nanofluids for specific thermal applications must be determined on a case-by-case basis, considering the unique requirements of that application. [40]. These requirements should not only aim at lowering operating expenses and promoting superior heat transfer performance but also consider mitigating toxicity and environmental impacts. The environmental impacts for nanofluids mainly arise from used nanoparticles. Magnetite (Fe_3O_4) nanoparticles have been extensively studied in recent years due to their intrinsic features such as low toxicity and magnetic effect. Additionally, magnetite nanofluids also possess interesting thermal properties which can be tuned under magnetic field, making them beneficial to heat transfer applications. Even in the absence of external magnetic field, thermal properties of magnetite nanofluids have been of current interest as a function of many parameters such as, concentration, nature of the stabilizer, particle size and morphology, temperature and method of preparation. However, the correlation of these parameters to thermal properties still remains a subject of debate owing to conflicting reports, which arise from highly dependence of thermo-physical properties of magnetite nanofluids on material composition [41–45].

Using environmentally friendly, cost-efficient, and safe stabilizers is of significant importance in the reduction of environmental impacts. For this reason, gelatin presents advantages over synthetic stabilizers like CTAB due to its low cost, non-toxicity, and naturally occurring abundant nature. This study aims to investigate the impact of using Fe_3O_4 nanofluids stabilized by synthetic and natural stabilizers (CTAB and gelatin) to enhance thermal efficiency, and offers a novel comparison of stabilizers, demonstrating how gelatin -a natural and environmentally friendly stabilizer- outperforms the synthetic alternatives like CTAB in terms of both stability and thermal performance. To the best of our knowledge, concerning the environmental impacts of nanofluids, there are no such comparative reports that deal with the effect of both natural and synthetic stabilizers on the thermal heat transfer of magnetite nanofluids on WCTs. For this purpose, Fe_3O_4 nanoparticles were synthesized and nanofluids were prepared using a two-step method. Nanofluids were prepared by dispersing Fe_3O_4 nanoparticles (0.1 wt%) in deionized water with gelatin (MNF@gelatin) and CTAB (MNF@CTAB) by varying the stabilizer concentration in the range of 0.2, 0.4, 0.8, 1.0 wt%. Subsequently, the thermal efficiency of the nanofluids was investigated experimentally on a laboratory-scale cooling tower at 45°C, with a 0.06 m^3/h volume flow rate, and between 0.02 and 0.07 kg/s air mass flow rates. Finally, a comparative exploration of the gelatin and CTAB used in the studied nanofluids was done, examining their impact on both thermal efficiency and environmental sustainability.

METHODOLOGY

Experimental Setup

A laboratory-scale cooling tower experimental setup has been designed to facilitate the experiments. The schematic of the experimental setup is shown in Figure 1 [46]. All the apparatus and measurement devices are presented there.

Figure 2 presents a photograph of the experimental setup. The system has four different main parts: the measuring equipment, the heater, working fluid circulation system, and the cooling tower. The main body of the tower has a cylindrical cross-section with dimensions of 30cm and a height of 125cm. The nozzle diameter size for water spraying is 4 mm.

There are two cycles in the experimental system: the air cycle and the water cycle. The air cycle is a type of open

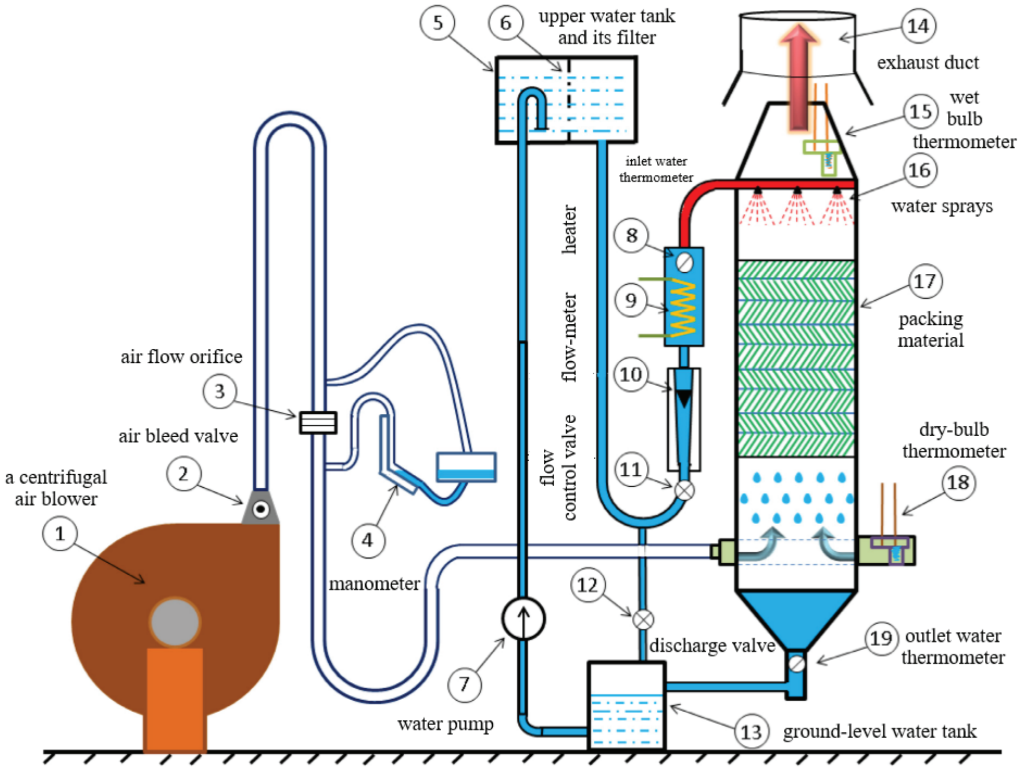


Figure 1. A Schematic diagram of the experimental setup.

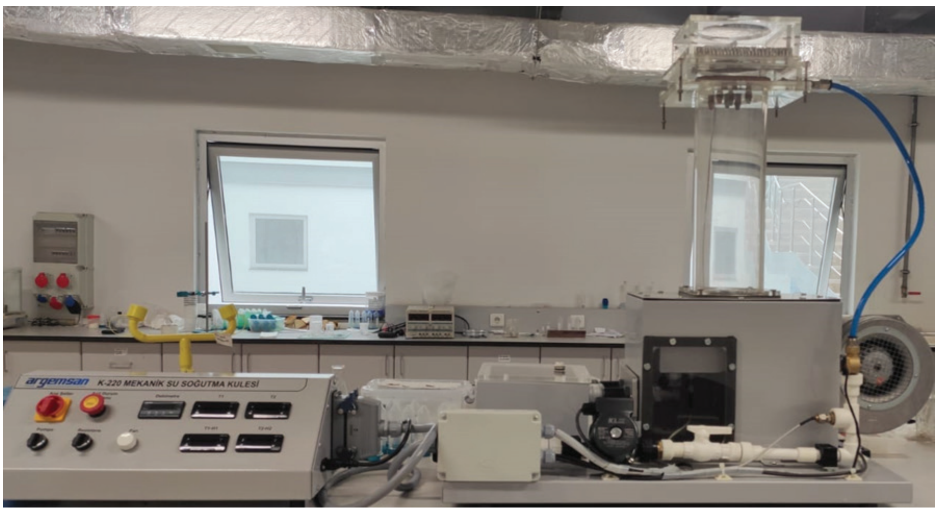


Figure 2. The laboratory scale mechanical draft cooling tower.

Table 1. Accuracy of components of the WCT [46]

Eq. No	Equipment Name and Specification	Unit	Quantity	Accuracy
1	Emko Esm3710-N Pt 100 Dashboard	PCS	2.00	± % 1
2	Emko Esm-3723.5.5.5.0.1/01.01/1.0.0.0 Temperature Humidity Dashboard	PCS	2.00	± % 1
3	Pmd-D-Dh0/T0.1.0.2 Temperature Humidity Sensor	PCS	2.00	Rel. Humidity: ±%2 Temp. Sensor: ±0,2 °C
4	Pt-100 Temperature Sensor	PCS	2.00	< +/- 1°C
5	Aircol Aks 160-60 200w 600 m^3/h Monophase Industrial Type Snail Radial Fan	PCS	1.00	None
6	220 V 1500 W Resistor	PCS	1.00	None
7	Klpro Klpsp256 100watt Circulation Pump	PCS	1.00	None
8	Emks Tcs37-100 Counter Turbine Type Flowmeter Dashboard	PCS	1.00	None
9	UT-363 Anemometer	PCS	1.00	± 0,5 m/s

cycle. Air from the laboratory environment under atmospheric conditions is introduced into the system with an air blower. The air volume flow rate is adjusted via the valve placed after the air blower. The magnitude of the air volume flow rate is also measured by the orifice meter. Air enters the cooling tower through the side surfaces. At the entry section, the dry bulb temperature of the air is measured. After that, it passes through the cooling tower and reaches the water spray section. Here, air comes into contact with high-temperature water spray, increasing its temperature and relative humidity. It enters the exhaust duct and discharges into the atmosphere. In the second cycle, the water is circulating in the system in a closed loop. The water is stored in a ground-level water tank. It is circulated by a pump into the system. The volume flow rate of water is controlled by the flow control valve and the flow meter located after it. After that, it enters the heater. In this section, the water is heated to the desired temperature. At the heater's exit section, the water temperature is measured with a thermometer. Afterward, it is pumped to the water spray section. The water is sprayed onto the airflow in this section. The heat is transferred from the hot water to the atmospheric air and the water temperature decreases gradually. It is collected at the bottom of the cooling tower. The outlet water temperature is also measured in this section. It is pumped to the ground level water tank and the closed cycling process continues in this way. All the measurement data during experimental procedures are monitored with the digital data logger unit. Furthermore, the accuracy and quantity of information for all measuring equipment are summarized in Table 1.

In the experimental analysis, the procedure starts with adjusting the temperature controller to the desired water temperature. Then, the pump is started, and the water flow circulation is initiated. Simultaneously, the air fan is turned on to blow air into the cooling tower. The warm water is in contact with the air flowing directly into the cooling tower. The airflow velocity is measured with an anemometer device with an accuracy of 0.1 m/s. During the interaction, the water temperature decreases as the temperature and relative humidity of the air increase. The water is cooled, and then collected in the ground-level water tank. This procedure is repeated for different air and water flow rates to evaluate experimental tower thermal performance. The water flow rate is set in the range of 0.06 L/s≤ $\dot{Q}$ ≤0.1 L/s, whereas the air mass flow rate is in the range of 0.02 kg/s≤ $\dot{m}$ ≤0.07 kg/s. A total of 26 experiments have been carried out. The error rate analysis has been conducted for the thermal efficiency of WCT and the formulation below has been created from the formula (Eq. (1)) given below [47].

$$\frac{\partial \eta_{\text{experimental}}}{\eta_{\text{experimental}}} = \left[\left(\frac{\partial \rho}{\rho}\right)^2 + \left(\frac{\partial \dot{V}}{\dot{V}}\right)^2 + \left(\frac{\partial c_p}{c_p}\right)^2 + \left(\frac{\partial \Delta T}{\Delta T}\right)^2 + \left(\frac{\partial A_c}{A_c}\right)^2\right]^{1/2} \quad (1)$$

The error rate analysis has been performed and the max error rate for the thermal efficiency of the WCT thermal efficiency was 0.35% using the relations of Holman [48]. The uncertainty analysis was done using Moffat's relations [49]. The average error rate of the experiments was found to be 3.423%.

Material Preparation

All chemicals were used as received. $FeCl_3$ was purchased from Sigma Aldrich (99% purity), EG (Ethylene Glycol) from ISOLAB (99.8% purity), CH_3COONa (Sodium Acetate) from Supelco (99% purity), $C_{18}H_{35}NaO_2$ (sodium stearate) from ISOLAB (98% purity) and gelatin from porcine skin was purchased from Fluka.

Synthesis of Fe_3O_4 nanoparticles

In the synthesis of Fe_3O_4 nanoparticles, anhydrous $FeCl_3$ (4 mmol) was first mixed with 40 mL of mono-ethylene glycol (EG) to form a clear solution [35]. Then, 1.6 mmol of Na_3Cit was added, and the mixture was heated at 80 °C and stirred until a clear solution was observed. After

12.0 mmol of anhydrous NaOAc was dissolved, the mixture was taken into a Teflon-lined stainless-steel autoclave of 100 mL capacity. Subsequently, the reaction was carried out at 220 °C for 10 h. After being cooled down to room temperature, the obtained black products were collected by applying centrifugation at a speed of 12000 rpm for 30 min. Then, the product was washed with ethanol three times. Finally, the resulting precipitate was dried at 60 °C and used in the experiments.

Stabilization of nanoparticles

Colloidal suspensions of nanofluids were prepared by dispersing fixed amounts of nanoparticles (0.1 wt%) in deionized water containing various amounts of CTAB or gelatin (0.2, 0.4, 0.8 and 1.0 wt %) and their stabilities were monitored by taking photographs at different time intervals before evaluating their performance on the WCT.

Preparation of Fe_3O_4 nanofluids

Nanofluids of iron oxide were prepared using a two-step method. First, desired amounts of CTAB or gelatin that would produce nanofluids containing 0.2, 0.4, and 0.8 wt% CTAB or gelatin, were dissolved in deionized water. And secondly, the dissolution process was followed by the addition of fixed amounts of nanoparticles with an overall concentration of 0.1 wt%, and then placed in an ultrasonic bath for 1 hour to have well-dispersed, stable suspension nanoparticles. After that, all this composition was diluted to a final volume of 2.5 L with distilled water and stirred at 600 rpm for an additional hour.

Calculation of Experimental Data

In this section, important parameters for the thermal performance of WCT are presented. In this context, the water temperature difference, thermal efficiency, and tower characteristics are defined in detail.

The water temperature difference (ΔT) is calculated using Eq. (2) [46] as:

$$\Delta T = T_{w1} - T_{w2} \tag{2}$$

where T_{w1} [°C] and T_{w2} [°C] are the inlet and outlet water temperatures, respectively.

The thermal efficiency of the WCT is the ratio of the achieved temperature drop in the water to the maximum possible temperature drop [46]:

$$\varepsilon = \frac{T_{w1} - T_{w2}}{T_{w1} - T_{wb1}} \tag{3}$$

The T_{wb1} [°C] is the wet-bulb temperature of inlet air.

The parameter of tower characteristic (TC) can be defined as follows [50]:

$$TC = \int_{T_{w2}}^{T_{w1}} \frac{C_{p,w} dt}{h_{as} - h_{a1}} \tag{4}$$

Experimental data obtained from this study have been compared with the results of Rahmati et al. [46]. In this concept, all the experiments have been conducted under the same conditions as the reference work. The parameters used in the experimental analyzes and the ranges of these parameters are given in Table 2. The findings are also presented in Table 3. It is obtained that the deviation range between the present study and the experimental study of Rahmati et al. [46] is 7.74% on average (Table 3). Therefore, it can be stated that the experimental setup works correctly, and experimental measurements are accurate within acceptable limits.

After the verification of the setup, we performed confidence tests of the experimental data. An independent two-sample T-test with a 95% confidence level was performed using MiniTab software to statistically compare the present experimental data with that of Rahmati et al. [46], The results of the T-test showed no significant difference between the experimental data and that investigated by Rahmati et al.

Table 2. Selected ranges of water flow rate, air flow rate, and inlet water temperature for the cooling tower

Parameter	***Range***
Water flow rate (m^3/h)	0.06 – 0.1
Air flow rate (kg/s)	0.02 – 0.07
Inlet water temperature (°C)	45

Table 3. Comparison and validation of the present study with experimental results of Rahmati et al. [46] by deionized water as circulating fluid at T_w=45 °C q_w=0.08 $m^3 h^{-1}$

Mass Air Flow (kg/s)	**Error Rate**	**Cooling Tower Thermal Efficiency (%) [Rahmati et al.]**	**Cooling Tower Thermal Efficiency (%) [Present Study]**
0.02	0	17	17 ± 0.40
0.04	15.38	26	22 ± 0.76
0.06	23.53	34	26 ± 0.28
0.07	-7.95	35.2	38 ± 0.37

Table 4. Two-sample T-test.

	N	Mean	95% CI	StDev
Experimental	4	25.75	(11.495; 40.005)	8.9582
Literature	4	28.05	(14.65; 41.45)	8.4228
Difference = (Experimental) - (Literature)				
Estimate for difference: 2.3				
95% CI for difference: (-13.504; 18.104)				
T-Test of difference = 0 (vs ≠): T-Value = 0,25 P-Value = 0,724				

(P-value>0.05) as can be seen in Table 4. The table shows that the experimental data are consistent with the data reported in the literature. This in turn, states that the experimental setup works satisfactorily, precisely, and accurately.

RESULTS AND DISCUSSION

Characterization of MNPs

In this work, the structure, morphology, and particle size of Fe_3O_4 nanoparticles have been characterized using techniques such as SEM, FT-IR, UV-Vis, and XRD. Absorbance spectra of the nanoparticle dispersions were recorded on a UV-Vis spectrophotometer (Agilent Technologies Cary 60 UV-Vis spectrophotometer) between 300- 800 nm wavelength range. In addition, crystallography analysis was performed by the Rigaku Ultima IV X-ray diffraction (XRD) instrument. In these analyzes, Cu-based Ka radiation (λ = 0.1546 nm) was used with a fixed monochromator, using a value of 2θ in the range of 40 kV and 40 mA to 10-80°. Chemical bond analysis was done on a Bruker Alpha brand Fourier transform infrared spectrometer (FTIR) in transmission mode with a resolution of 2 cm^{-1} at a wavenumber of 400-4000 cm^{-1}. Moreover, the microstructure and morphological images of these components were examined using a scanning electron microscope (Carl Zeiss ULTRA PLUS Scanning Electron Microscope).

The FTIR spectra of Fe_3O_4 nanoparticles (Figure 3a) show absorption bands at 1652 and 1396 cm^{-1}, which could be ascribed to the stretching vibrations of the carboxyl group. Besides, the peaks at 2856 and 2921 cm^{-1} are due to the stretching vibrations of the methylene group. The peak at 1050 cm^{-1} could be associated with the Na_3Cit hydroxyl group. Additionally, the strong absorption band at 581 cm^{-1} is due to ν (Fe-O) in Fe_3O_4 nanoparticles, suggesting that the main phase of the nanoparticles is Fe_3O_4. The UV-vis spectrum of Fe_3O_4 MNPs shown in Figure 3b with a characteristic absorption band between 500 and 550 nm belongs to Fe_3O_4 nanoparticles as reported in other studies [51].

Figure 4a displays the SEM image of the MNPs, depicting the surface morphology. The SEM image indicates that the nanoparticles are in spherical morphology with a monodisperse size distribution. Line EDX analysis (Figure 4b) on the nanoparticles clearly indicates the presence of both iron and oxygen in the material and confirms the purity of the nanoparticles. Additionally, the average particle size (Figure 4c) was estimated to be around 200 (±8 nm).

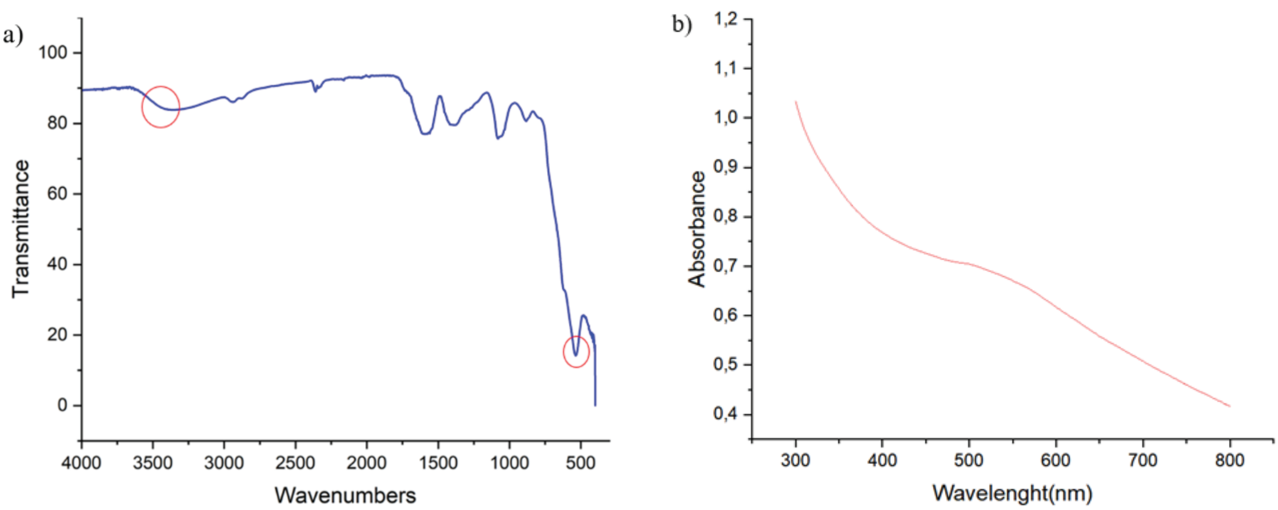


Figure 3. FTIR spectrum of synthesized nanoparticles (a), and their corresponding UV- Vis spectrum (b).

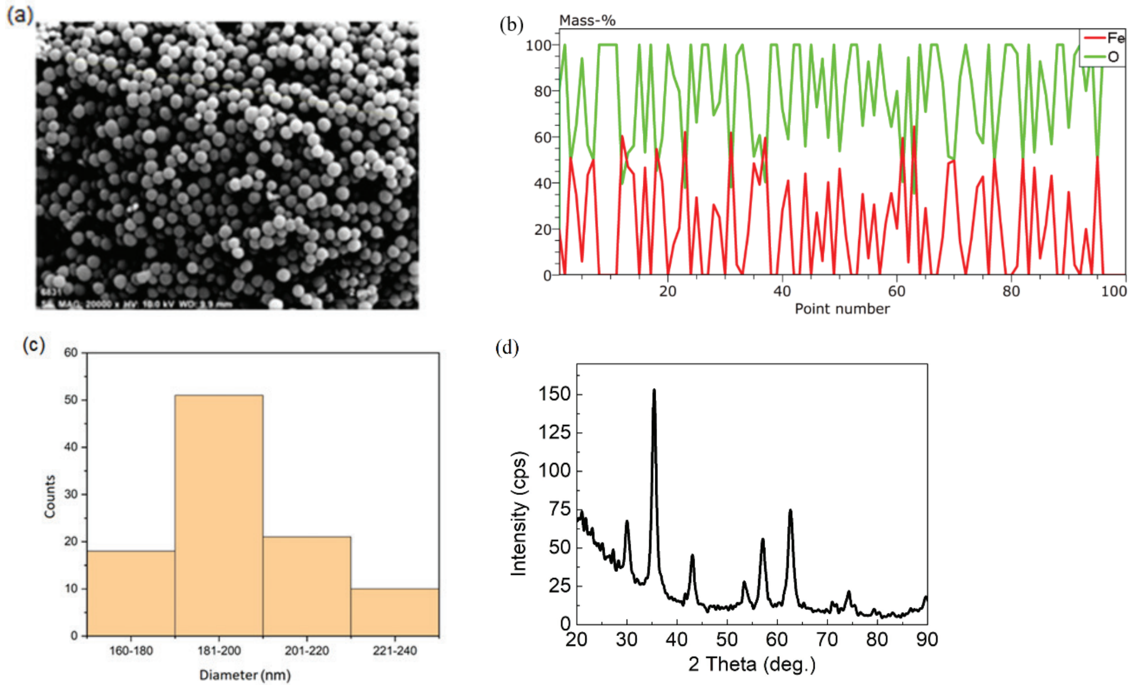


Figure 4. SEM image of the synthesized nanoparticles (a), EDX spectra (b), MNP size distribution (c), and XRD pattern of the synthesized nanoparticles (d).

XRD characterization was employed to confirm the crystal structure of nanoparticles. The phase composition and crystal structures of the Fe_3O_4-based nanoparticles were determined through the XRD. Figure 4d shows that the peaks in the data are based on the spinel structure of the crystal, confirming that the products are truly pure phase Fe_3O_4 [52]. The XRD pattern of the sample, which is quite identical to pure magnetite (JCPDS Card No. 019-0629) and matched well with it, indicates that the sample has a cubic crystal system [53]. The discernible peaks are indexed to (220), (311), (400), (422), (511) and (440) [54]. Also, we can observe that there are not any characteristic peaks of impurities observed.

Effect of Stabilizer on The Nanofluid Stability

The effect of stabilizer type and concentrations (0.2, 0.4, 0.8, and 1.0 wt%) on the stability of the nanofluids was qualitatively assessed and compared to the stability of nanofluids without a stabilizer. Figure 5 shows a series of optical images that were taken at different time intervals to monitor the bench stabilities of the prepared nanofluids. As can be seen from the images, MNFs completely lose their stability after one day in the absence of any stabilizer.

In the case of CTAB containing NFs, stability is improved by adding CTAB, which restricts particle agglomeration and sedimentation. Thus, nanoparticles surrounded by stabilizers exhibit greater Brownian diffusion and thermo-migration effects, ultimately improving the nanofluids' heat transfer efficiency. However, adding different amounts of CTAB did not produce the same nanofluid stability over the three-week period. Apparently, CTAB provided the nanofluid with improved stability for up to one week at a concentration of 0.4 wt%, but a further increase in CTAB concentration did not display any improvement in stability. This might be due to the existence of an optimum nanoparticle/stabilizer ratio, which might be considered as an intrinsic property.

CTAB is a cationic surfactant, and an electrical double layer is created at the nanoparticle surface by the adsorption of CTAB ions. This kind of stabilization is known as electrostatic stabilization. The resulting electrostatic repulsive forces between the nanoparticles are responsible for long-term stability [55] [56]. It is worth emphasizing that many parameters such as nanoparticle type, size and shape, as well as nanofluid preparation conditions, including the base fluid, temperature, pH, nanoparticle/stabilizer ratio, mixing, and sonication, can significantly affect long-term stability [57].

Since each research study has its own unique parameters, it is difficult to compare the results with the existing literature. For instance, a recent study by Mostafizur *et al.* reported that CTAB ensured long-term stability for more than six months for 0.10 wt% Al_2O_3-methanol nanofluid, which contains nanoparticles of about 115 nm [57]. The nanoparticle size might be considered as a predominant parameter above a certain value, and this may influence the particle stability in the nanofluid. Smaller particles are expected to disperse easily to form more stable nanofluids in the presence of the stabilizer.

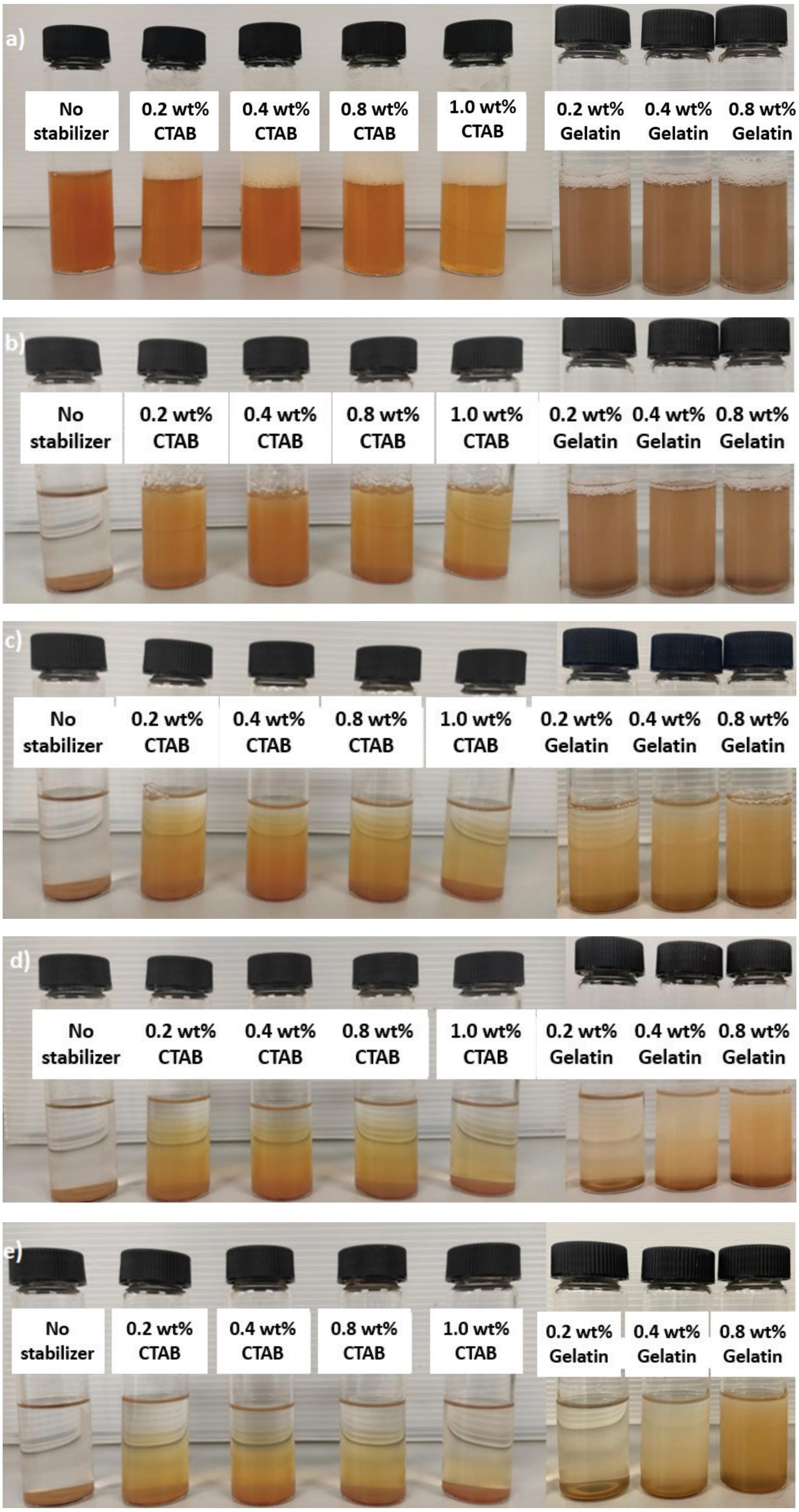


Figure 5. Variation of stabilities of the prepared nanofluids in time: (a) at the beginning, (b) after one day, (c) after a week, (d) after two weeks, (e) after three weeks.

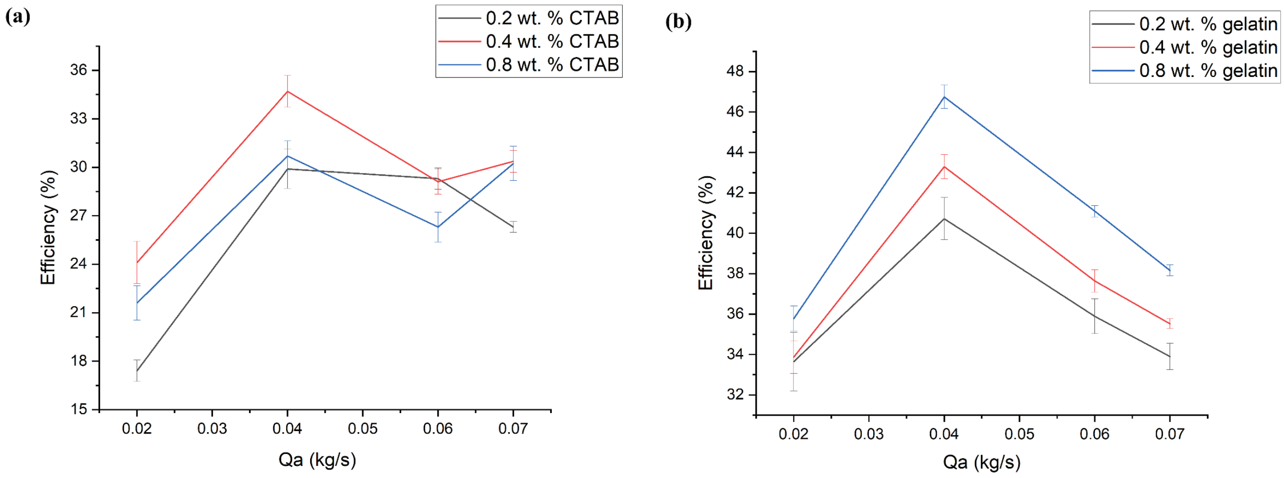


Figure 6. Thermal efficiency of WCT versus air mass flow rate for MNFs with various concentrations of (a) CTAB (b) gelatin stabilizers at a fluid volume flow rate of 0.06 m^3/h.

In the case of MNF@gelatin, clear sedimentation was observed after two weeks, especially for the ones containing 0.2 and 0.4 wt% gelatin. The results indicate that MNF@gelatin with 0.8 wt% gelatin achieves maximum stability for up to three weeks, significantly outperforming MNF@CTAB, which stabilizes only up to one week. This superior stability correlates with enhanced thermal efficiency, where MNF@gelatin consistently outperforms its CTAB counterpart. The main reason for better colloidal stability of MNFs due to gelatin rather than CTAB could be ascribed to steric polymer stabilization. This is based on steric hindrance caused by organic functionalities such as amine and carboxyl groups, which may act as coordinating sites for the nanoparticle surface and form a protective layer that prevents the sedimentation.

Furthermore, when comparing the zeta potential, a measure of the stability of particles in suspension, gelatin exhibits higher zeta potential, reaching up to 40 mV at around 0.1 wt% concentrations, as reported by Musa et al. [58]. Besides, Anandan et al. [59] reported lower mV of zeta potential, such as 25.23 mV after 24 hour duration of CTAB stabilized NPs. This, in turn, enhances the stabilization of particles of the constituent nanofluid, thereby resulting in an improvement in thermal performance [60].

An additional increase in the gelatin concentration (1.0 wt%) did not produce more stable dispersions. Rather, it led to the gelatinization of the mixture. Therefore, nanofluids with varied concentrations of CTAB and gelatin, including 0.2, 0.4, and 0.8 wt%, were selected for their performance on the WCT.

Effect of Air Flow Rate, Volume Flow rate of fluid and Stabilizers on WCT Performance

In this section, the impacts of CTAB and gelatin stabilizers on the formulated MNFs as well as their concentrations on the thermal efficiency of the WCT through various air and nanofluid volume flow rates have been discussed. Three nanofluid volume flow rates of 0.06, 0.08, and 0.1 ($m^3 \cdot h^{-1}$) and a single hot water temperature (45 °C) were selected [61]. The experiments were repeated three times and average values were calculated. The inlet water temperature was selected as 45 °C as it is the optimum value in terms of viscosity and Brownian motion, and it enhances the thermal conductivity of nanofluids [23,62].

Figure 6 clearly illustrates the variation in thermal efficiency among nanofluids with different stabilizers, providing a visual comparison that highlights the superior performance of MNF@gelatin. As shown in the figure, thermal efficiency increases for all MNFs with the increment of the air mass flow rate up to a value of 0.04 kg/s, then tends to decrease with further increase in air mass flow rate. In the case of base fluid as presented in Table 3, the thermal efficiency increases as the air mass flow rate increases in a range of 0.02 to 0.07 kg/s which is consistent with the literature [46].

The thermal efficiency values were calculated using the equations provided in the “Calculation of Experimental Data” section, Eq. 2.

All the studied MNFs showed improved thermal efficiency values compared to the base fluid for the air mass flow rates ranging between 0.02 and 0.04 kg/s. Above 0.04 kg/s, MNFs exhibited a decreasing thermal efficiency regardless of stabilizer type and concentration. Here, it is worth noting that the maximum heat transfer efficiency was calculated at the air mass flow rate of 0.04 kg/s where MNF@CTAB (with 0.4 wt% CTAB) showed 35 ± 0.98 % (Table 5).

Figure 6b refers to the thermal efficiency of MNF@gelatin as a function of air mass flow rate. The most significant enhancement of the heat transfer efficiency (47%) of MNF@gelatin (with 0.8 wt% gelatin) was obtained at 0.04 kg/s air mass flow rate. MNF@gelatin with 0.8 wt% gelatin

Table 5. Cooling efficiencies of MNF@gelatin (0.8 wt%) and MNF@CTAB (0.4 wt% CTAB), and water as the base fluid at different air mass flow rates, at a circulating volume flow rate of 0.06 m^3/h and a temperature of 45°C.

Air Mass Flow Rates (Qa) kg/s	Thermal efficiency (%) of the base fluid (water)	Thermal efficiency (%) of MNF@ gelatin (0.8 wt% gelatin)	Thermal efficiency (%) of MNF@ CTAB (0.4 wt% CTAB)
0.02	17 ± 0.40	36 ± 0.62	24 ± 1.31
0.04	22 ± 0.76	47 ± 0.58	35 ± 0.98
0.06	26 ± 0.28	41 ± 0.28	29 ± 0.77
0.07	38 ± 0.37	38 ± 0.27	30 ± 0.68

achieves a relative increase in thermal efficiency of 114 % over the base fluid. This result reveals that gelatin, a natural polypeptide, is more suitable than CTAB for nanofluid formulations, offering both thermal efficiency enhancement and environmental benefits due to its non-toxic and low-cost nature.

It is worth noting that thermal efficiency values from the present WCT experiments are closely correlated with the colloidal stabilities from optical images of MNFs over time. From the optical images, MNF@gelatin (0.8 wt% gelatin) had the highest colloidal stability, followed by MNF@CTAB (0.4 wt% CTAB). Our findings also revealed that improving thermal efficiency can be achieved by selecting the appropriate stabilizers and adjusting their content, while keeping a constant nanoparticle concentration. Present experimental results suggest that the optimal stabilizer/nanoparticle mass percentage ratio for CTAB- and gelatin-contained MNFs, which were 4 (0.4 wt% / 0.1 wt%), and 8 (0.8 wt% / 0.1wt%), respectively.

The types of stabilizing agents, as well as their relative mass fractions relating to that of the nanoparticles, play a vital role in enhancing the thermal efficiency of WCT. The use of non-toxic, low-cost natural materials such as gelatin has much less environmental impact, there is no need to employ synthetic production. Therefore, gelatin is more suitable than CTAB for optimal nanofluid formulations, both in terms of thermal efficiency and environmental impact. Besides, the right balance between the mass fractions of nanoparticles and stabilizing agents is important to achieve enhanced thermal efficiency. Increasing the stabilizer concentration does not necessarily guarantee an enhancement in thermal efficiency.

Table 6 shows the thermal efficiencies of some of the nanofluids studied previously and reported in the literature. Concerning previous studies, the thermal efficiency of the MNF@CTAB (with 0.4 wt% CTAB) is just below the highest efficiency reported for Al_2O_3/water nanofluid stabilized by SDBS, which is 39.57% [63]. However, it should be noted that the highest efficiency enhancement relative to water is only 7.2 %. Our experimental results indicate that the relative increment in the efficiency compared to water is almost 59 %, which suggests that MNF@CTAB surpasses the Al_2O_3/water nanofluid, considering the relative increase in the thermal efficiency. In another report, the effect of Al_2O_3/water and black carbon/water nanofluids on velocity and temperature distributions along reverse spray cooling towers at various concentrations were investigated [64]. Gum Arabic (GA), which is a natural gum used as a

Table 6. Thermal efficiency comparison of the present work with some previously published reports.

Nanofluid type	Stabilizer type	Nanofluid concentration	Stabilizer concentration	Mass flow rate (air)	Mass flow rate (fluid)	Efficiency (%)	Reference
Al_2O_3/water	SDBS*	0.15 wt%	Not described	0.24 $m^3.h^{-1}$	0.12–0.72 $m^3.h^{-1}$	39.57%	[63]
Al_2O_3 or black carbon/Water	Not used	0.1 wt%	-	L/G**=1	L/G=1	44.3% - 63.2%	[64]
Fe_3O_4/CQD	Not used	0.5 wt%	-	0.85 $m^3.h^{-1}$	1.37 $m^3.h^{-1}$	44%	[23]
Base fluid (water)	Not used	-	-	0.04 $kg.\ s^{-1}$	0.06 $m^3.h^{-1}$	22%	Present study
Fe_3O_4/water	CTAB	0.1 wt%	0.4 wt%	0.04 $kg.\ s^{-1}$	0.06 $m^3.h^{-1}$	35%	Present study
Fe_3O_4/water	Gelatin	0.1 wt%	0.8 wt%	0.04 $kg.\ s^{-1}$	0.06 $m^3.h^{-1}$	46.8%	Present study

*SDBS: Sodium dodecyl benzenesulfonate, **L/G refers to water to air flow ratio.

food additive, was added to improve the stability of the particles of the prepared nanofluids. The results indicate that the highest achieved efficiency varies between 44.3% to 63.2%. However, although a natural origin stabilizer (GA) is employed in the nanofluid stabilization, it is worth noting that nanofluids such as alumina (Al_2O_3) and titania (TiO_2), possess some inherited toxicity, whereas the toxicity potential of magnetite nanofluids is consistently low or no toxicity, concerning the environmental impact. Furthermore, black carbon is a global environmental problem [65].

Another study, which was reported recently, focuses on the hybrid types Fe_3O_4/carbon quantum dots and CuO/carbon quantum dots nanofluids and their tower effectiveness against water-base fluid [23]. The highest tower effectiveness was found to be 44% and 49% for Fe_3O_4/CQD and CuO/CQD nanofluids, respectively. Relative to water, the efficiency of the wet cooling tower is improved by 25% and 12% for Cu/CQD and Fe_3O_4/CQD, respectively. Since there is a growing concern for carbonaceous nanoparticles because they are emerging environmental contaminants, seeking more environmentally friendly alternatives is expected to be of primary concern in sustainable thermal energy management [66]. In comparison to previous studies, which reported a maximum thermal efficiency range between 40% and 65% for different nanofluids, this study's MNF@gelatin achieved as high as the reported records, making them a potential alternative owing to their non-toxicity, low cost and less environmental impact.

Determining the optimum experimental parameters, such as mass and volumetric flow rates, is essential in studies seeking to enhance heat transfer. However, it is also understood that the type and optimum concentration of the stabilizer are significant in improving the WCT efficiency. Further investigation and experimentation could shed more light on the intricate relationship between these parameters and provide insights into improving the cooling tower's overall performance. It is found that nanofluid characteristics such as particle size and shape, particle and stabilizer type and their ratio, and sort of working fluid significantly influence the nanofluid stability and thermal application performance. Therefore, each report in the literature should be considered on a case-by-case basis to avoid any confusion caused by discordant findings.

CONCLUSION

This study provides an in-depth exploration of gelatin and CTAB as stabilizers in Fe_3O_4-water nanofluids, examining their impact on both thermal efficiency and environmental sustainability.

Fe_3O_4 nanoparticles were successfully synthesized with an average size of about 200 nm through a hydrothermal method and characterized by XRD, SEM, UV-Vis, and FT-IR spectroscopy. A two-step method was employed to prepare nanofluids of a fixed mass fraction of 0.1 wt% Fe_3O_4 with mass concentrations of the stabilizers in the range of 0.2 to 1.0 wt%. The nanofluids prepared in the presence of gelatin achieved maximum stability, significantly outperforming the nanofluid prepared with the CTAB. The cooling tower experiments were meticulously conducted at a controlled fluid volume flow rate of 0.06 m^3/h and a consistent temperature of 45 °C, ensuring enhanced thermal efficiency for the prepared nanofluids, where gelatin stabilized nanofluids (with 0.8 wt% gelatin) consistently outperforms its CTAB counterpart.

Some key findings of this study are summarized below:

- Magnetite-water nanofluids were prepared at a nanoparticle weight fraction of 0.1 wt%. Although nanofluids without any stabilizer showed poor colloidal stability, both CTAB and gelatin, when added as the stabilizer, enhance the colloidal stability. The utilized stabilizers improved the stability of the prepared nanofluids and slowed down the sedimentation rate, and enhanced the thermo-migration and Brownian diffusion effect, ultimately improving the heat transfer performance. It was found that the stabilizer/nanoparticle concentration ratio plays a significant role in achieving optimum stability. While visual inspection over three weeks showed that gelatin-stabilized nanofluids exhibited better colloidal stability than the CTAB-stabilized ones,
- The nanofluids containing 0.4 wt% CTAB increased thermal efficiency by 59 % relative to the base fluid (water), whereas the nanofluids containing 0.8 wt% gelatin yielded an increment of almost 114 %. This remarkable increase with gelatin points out the highest thermal efficiency rate, outperforming CTAB.
- As a future recommendation, an optimization study is needed to optimize the nanoparticle concentration by varying both the nanoparticle and stabilizer concentrations. Additionally, it would be valuable to investigate the effects of varying temperature and pH levels on gelatin-stabilized nanofluids, as these factors play a critical role in the performance and durability of the fluid. Understanding how these variables influence nanoparticle dispersion and thermal efficiency could provide deeper insights for improving nanofluid formulations. Also, further work in the field of nanofluid preparation through natural, non-toxic, environmentally benign stabilizers other than gelatin could certainly contribute to energy efficiency improvements considering the environmental impact of the nanofluids as well. Synthesis of magnetic nanofluids with controlled size and stability with efficient surface coating moieties requires further attention to studying magnetic nanofluids under an external magnetic field. Therefore, gelatin-stabilized magnetite-water nanofluids can also be considered in thermal transport through the application of an external magnetic field.

In conclusion, our findings assess both the stability and heat transfer efficiency of magnetite nanofluids concerning the nature of surfactants. Our study revealed that gelatin can be a viable and effective option. Given its non-toxic nature and lower environmental impact, gelatin emerges as a preferable alternative to CTAB, aligning with the growing emphasis on sustainable and eco-friendly thermal engineering solutions.

NOMENCLATURE

MNFs	Magnetite Nanofluids
MNP	Magnetite Nanoparticles
WCT	Wet Cooling Tower
Ac	Cross-sectional area of the WCT (m^2)
h_{as}	Air-saturated enthalpy at water temperature ($J \cdot kg^{-1}$)
h_{a1}	Air enthalpy at the inlet conditions ($J \cdot kg^{-1}$)
wt %	Weight percent
ΔP	Pressure difference (Pa)
ε	Thermal efficiency
Cp	Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
$C_{p,w}$	Specific heat capacity of water ($J \cdot kg^{-1} \cdot °C^{-1}$)
T	Temperature (K)
L/s	Liters per second
kg/s	Kilograms per second
m/s	Meters per second
Tw_1	Inlet water temperature
Tw_2	Outlet water temperature
TC	Tower characteristic

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

he authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article..

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