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Synthesis, characterisation and evaluation on the performance of ferrofluid for microplastic removal from synthetic and actual wastewater

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ABSTRACT

Synthesis of ferrofluid without the addition of stabilizing agents or surfactants is an innovation of new method for microplastic removal. This study focuses on the ability of several types of oils as carriers and how they may improve the removal efficiency of the microplastic. The method is relatively low cost, simple and sustainable. The formation of ferrofluid involved the mixing of oil and iron oxide powder. The experimental work was commenced by adding 2 mm polyethylene terephthalate (PET) microplastics into synthetic ferrofluid. Then, the removal efficiency of microplastics was examined by varying the elements of ferrofluid based on three specific parameters, namely type of oil, volume of oil and dosage of iron oxide to obtain a standard formulation of the optimum results. Overall findings of the study indicated that the optimum formulation for ferrofluid preparation was at a ratio of 1:2.5 (volume of oil: dosage of magnetite) using lubricating oil which has successfully removed 99% of microplastic from water media. Subsequently, the physical and chemical properties of the prepared ferrofluid were also analysed using scanning electron microscope (SEM) and Fourier transform infrared (FTIR) spectroscopy. Performance evaluation of the prepared ferrofluid on actual wastewater (laundry wastewater) revealed that 64% of microplastics were removed after treatment.

1. Introduction

The issue of microplastics (MPs) is currently emerging worldwide as widespread contaminants that attract significant attention from the scientific community and the public [1]. Microplastics are mainly originated from several sources including synthetic fibres, industrial processes, household dust and deterioration of plastic surfaces [2]. Fibres contributes to 52.7% of the total amount of microplastic in municipal wastewater treatment plants [3]. The use microbeads and resin pellets to produce various plastic commodities such as personal care products and cosmetics also increases the amount of microplastic emission to wastewater treatment plants through municipal effluent discharge system [4–6].

Microplastics are generated from the decomposition of larger plastic objects which end up in the marine environment. With respect to large amounts of microplastics released into water bodies, it is known that microplastics have negative impacts on aquatic organisms. The microplastics may be consumed by the aquatic and filter-feeding organisms due to the possibility of misinterpreting them as food as the colour and shape of microplastics are generally indistinguishable from the food they normally consume, which could not be broken down by the organisms' digestive systems [7]. In addition, the presence of microplastics in bottled and also tap water has been reported although not many studies have addressed this issue [8]. Potential threats which can be associated with microplastics include physical hazard posed by plastic particles, chemicals adsorbed from the environment, and

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bacteria or microbes that may bind to the microplastics forming biofilms [9]. Thus, microplastics may be able to extract toxic compounds even by leaching micro-molecules in the human body, thus creating oxidative stress in human [10].

In wastewater treatment plant (WWTP), large amounts of microplastics are detected daily [11] since the plant only impedes microplastics and tiny plastic particles in the aeration ponds but considerable amount of microplastics will escape through the filter and be released into the freshwater environment [12,13]. In some cases, treated effluents only contain a small amount of microplastics per litre but high volume of effluents discharged daily contributes to substantial aquatic ecosystem pollution [14]. In fact, there is still no specifically designed technology in wastewater treatment plant for the purpose of microplastic removal. Although there is an innovation for combination of wastewater treatment technology or filter system for higher extraction efficiency, the method is expensive and requires high maintenance cost. For example, the use of activated carbon as a common adsorbent is costly as it is generally produced from bitumen, coals and anthracite, all of which are likely to be depleted in the future. In tertiary water treatment, the effects on MP retention by gravity filters [15] or by membrane reactors [16] are low. Ultrafiltration and coagulation demonstrate high removal of organic matter in water; however, both technologies are not specifically designed for microplastic removal which still remains in the final effluents [17].

A study from Grbić et al. [18] reported on microplastic removal from water using magnetic extraction method. The method operated by magnetizing the plastics with Fe-coated nanoparticles which allowed the extraction of microplastics when an external magnetic field was exerted. The uniqueness of this method was that it demonstrated more effective performance when the particles were smaller in size. In other words, the extraction efficiency was greater when dealing with small-sized microplastics as more Fe nanoparticles could be bound per unit mass of plastic. An improvement from this technology is nano-ferrofluids which are colloidal compounds containing single-domain magnetic nanoparticles in a liquid carrier. Common nanoparticles used for this purpose is iron oxide or magnetite (Fe_3O_4) with a mean diameter of 10–20 nm as it is less toxic than its metal counterparts and it also has good super-paramagnetic properties [19] in various industrial and biomedical purposes [20]. Nevertheless, magnetite also has great biocompatibility, high control capability and flexible size and shape changes, proper chemical stability and high magnetic strength as well as low toxicity. Furthermore, iron oxide nanoparticles are very effective for hydrocarbon removal from water which means hydrocarbons are very attractive to iron oxide nanoparticles. In addition, small super-paramagnetic magnetite (Fe_3O_4) nanoparticles (NPs) are cheap in price, and have high sorption rate which cover a large surface-to-volume ratio. Moreover, magnetite is reusable for full-loop application, easily collected even dispersed in large areas of water and non-toxic [21]. Through different interactions, for example van der Waals forces, magnetostatic interactions or dipolar attractive interactions, it is possible for convenient application on the combination of fluid behaviour and magnetic properties as well as its stability [22].

Current research has started to focus on modifying and changing the presence of alternative solvents in various common carriers to innovate and create new types of ferrofluids with suitable properties in various applications [23]. Nano-ferrofluid is also attracted to be used in industrial applications, such as in removing oil spills from water due to its high surface area and its effectiveness in binding pollutants [24]. Chen and his co-workers studied the ability of ferrofluid as anionic dye removal, in which approximately 95% of the adsorption capacity could be achieved in 2 min and the adsorption equilibrium could be reached in 5 min [25]. Hatamie et al. [19] reported the use of ferrofluid as a novel coagulant in water treatment and found that this green and less expensive technology successfully removed high amounts of hazardous ions, turbidity, bacteria and chemical oxygen demand. In fact, this ferrofluid also reduced the separation process unlike the available commercial coagulants. In addition, this magnetic coagulant be recovered by an external magnetic field, which gives high interest in the application of magnetic nanomaterials for water treatment. Pramanik et al. [6] reported the removal of nano/microplastic from wastewater using membrane, air flotation and nano-ferrofluid. This study found less significant removal efficiency of nano/microplastic by the two types of ferrofluids used in this study with average removals of 43% for magnetite and 55% for cobalt ferrite. Thus, the formulation of high-performance ferrofluid should be continuously explored.

This study presents the synthesis of ferrofluids using different formulations for the application of microplastic removal in synthetic and selected wastewater. The synthesis of ferrofluid without the addition of stabilizing agents or surfactants is an innovation a novel method for microplastic removal. Basically, the formulation of ferrofluid involved mixing an oil with magnetic powder (Fe_3O_4). This study focuses on the ability of cooking oil, used cooking oil, lubricating microplastic. The formulations varied in terms of different volumes of oil and dosages of iron oxide. Polyethylene terephthalate (PET) was used as a microplastic model in synthetic wastewater. Scanning electron microscope (SEM) and Fourier transform infrared (FTIR) spectroscopy were used to analyse the surface morphology and functional groups of ferrofluid. Dissecting microscope was used by applying visual counting method to determine the concentration of microplastics in water samples before and after the application of ferrofluid. Finally, this study also focuses on the application of optimum ferrofluid for microplastic removal in laundry wastewater.

2. Methodology

2.1. Materials

Materials used in this study were distilled water, polyethylene terephthalate (PET) as microplastic, iron (III) oxide (Fe_3O_4) as magnetic powder supplied by Sigma Aldrich. Four types of oil, namely lubricating oil, used lubricating oil, cooking oil and used cooking oil, were used as liquid carriers.

2.2. Microplastic suspension preparation

In this study, PET was employed to prepare synthetic wastewater. The PET was cut and ground into small pieces using a grinding machine. The grinded PET was sieved using 2 mm mesh size. Large particles remained on the mesh, while smaller microplastic particles were collected. The synthetic waste water was prepared by adding PET in distilled water and then stirred before use.

2.3. Ferrofluid synthesis and its application for microplastic extraction

Four types of oil, namely cooking oil, used cooking oil, lubricating oil and used lubricating oil were used as liquids carriers to synthesize ferrofluid. About 2.5 ml/L of oil was added into the microplastic suspension and then 0.50 g/L magnetite powder was added into the mixture to form ferrofluid. After rapid stirring of the solution, a magnet was immersed into the solution to trap the microplastic-containing ferrofluid which was then removed from the solution. The remaining water sample was then analysed for the amount of microplastic retained in the water after adsorption by ferrofluid and its removal efficiency was determined.

The test was repeated using other types of oil to determine their respective removal efficiency. Subsequently, experimental work was conducted using different volumes of oil (0.5, 1.0, 1.5, 2.0 and 2.5 ml/L) and different dosages of Fe_3O_4 powder (0.25, 0.50, 0.75, 1.0 and 1.25 g/L). Statistical analysis of *t*-test was used to determine the correlation between the two variables. Optimum ferrofluid formulation based on the three parameters studied was used for microplastic removal application in actual wastewater.

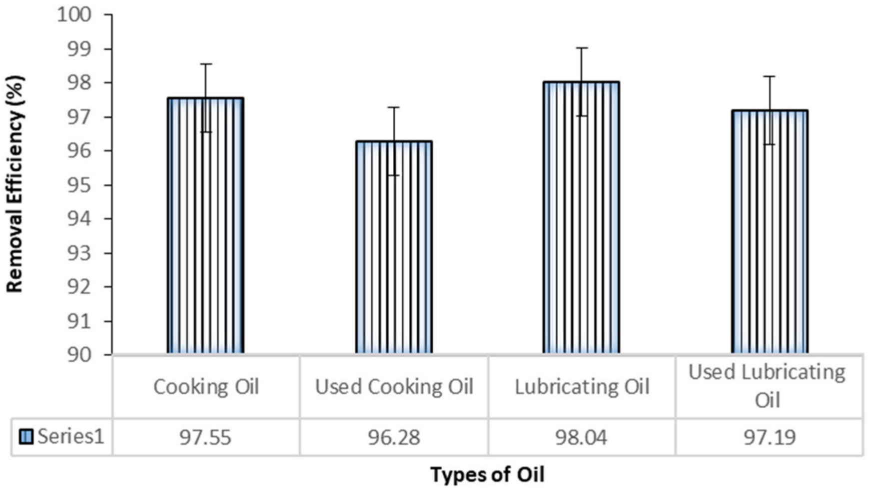

Fig. 1. Removal efficiency of microplastic using ferrofluid based on different types of oil (Oil volume: 2.5 ml, magnetite: 0.5 g/L sample).

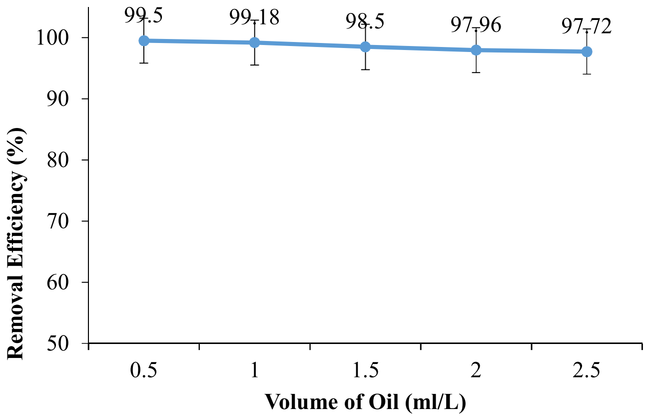

Fig. 2. Removal efficiency based on different volumes of oil.

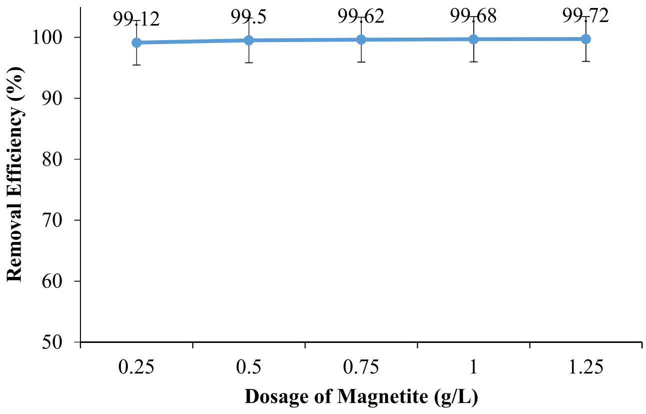

Fig. 3. Removal efficiency based on different dosages of magnetite.

Table 1

Results of *t*-test for effect of removal efficiency against different volumes of oil.

	Volume of oil (ml/L)	Removal efficiency (%)
Mean	1.5	98.572
Variance	0.625	0.58412
Observations	5	5
Pearson Correlation	-0.988887444	
Hypothesized Mean Difference	0	
Df	4	
t Stat	-139.9912557	
P(T < =t) one-tail	7.80854E-09	
t Critical one-tail	2.131846786	
P(T < =t) two-tail	1.56171E-08	
t Critical two-tail	2.776445105	

* ** *t*-test: Paired two sample for means

Table 2

Results of *t*-test for the effect of removal efficiency against mass of FeO.

	Mass of FeO (g/L)	Removal efficiency (%)
Mean	0.75	99.528
Variance	0.15625	0.05892
Observations	5	5
Pearson Correlation	0.898913125	
Hypothesized Mean Difference	0	
df	4	
t Stat	-1069.261449	
P(T < =t) one-tail	2.295E-12	
t Critical one-tail	2.131846786	
P(T < =t) two-tail	4.59E-12	
t Critical two-tail	2.776445105	

* ** *t*-test: Paired two sample for means

2.4. Analysis of microplastics in water media

Analysis of microplastics in water was determined according to Sturm et al. [26] with some modifications. The ferrofluid suspension was filtered to determine the amount of microplastics removed from the water medium. It was conducted by weighing the mass of filter paper containing microplastic substrate after drying. First, the oven was preheated to 90°C. Then, the filter paper was oven-dried for a few minutes to obtain its dry weight. Next, filtration phase was conducted by placing the filter paper on the filtration set and turning on the vacuum pump as the filter paper was moistened with a small amount of distilled water. The water sample was vigorously shacked and filled in 100 ml volumetric cylinder. The sample was then filtered through the filter paper and distilled water was used to wash off any microplastic substrate visible on the beaker wall into the filtration set. The vacuum pump was then turned off. The filter papers were carefully removed using a forcep from the filtration set and placed on the glass petri dishes. Upon completion of the filtration process, tpetri dishes containing filter papers were then oven-dried at 90 °C for 1 h until it appeared dry and allowed to cool at room temperature. After the petri dishes were cooled, the filter paper together with the petri dish were weighed on analytical balance and the readings were recorded as C and the values of total suspended

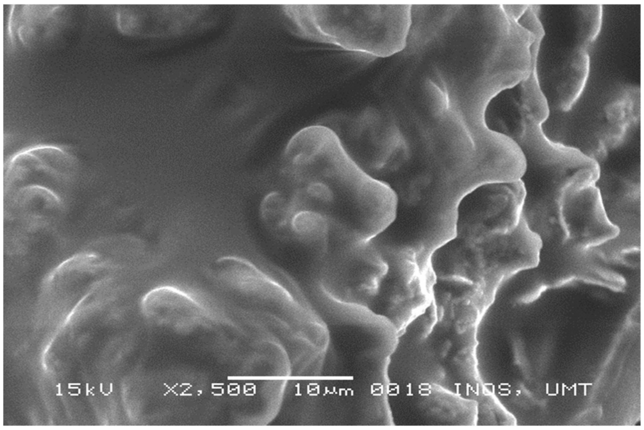

Fig. 4. SEM image of oil-based ferrofluid particles at magnification of 2,500x.

microplastic substrates were calculated using Eq. (1) and Eq. (2);

$$\text{Total suspended microplastics, mg}\Big/\text{L}\,\frac{\text{C}-\text{B}}{\text{SampleVolume, mL}}1000 \qquad (1)$$

where, C is the final mass of petri dish with dry filter paper (g), and B is the initial mass of petri dish with filter paper (g);

$$\%\text{Removalefficiency} = \frac{CI - CF}{CI} \times 100\% \qquad (2)$$

where, CI is the initial mass concentration of the added microplastic particles (g/L), and CF is the final mass concentration of total suspended microplastic substrates (g/L).

2.5. *Ferrofluid characterisation*

Scanning electron microscopy (JEOL JSM-6360 LA model) was used to examine the surface morphology of the ferrofluid. For this purpose, the sample was sputtered with gold, transferred to the microscope, and viewed at 2500 × magnification. The functional groups present in ferrofluid were determined using FTIR (Shimadzu/IRTracer-100 model). FTIR scan was conducted at frequencies of 4000–500 cm^{-1} and 4 cm^{-1} spectral resolutions in a sample holder.

This spectroscopic technique has high sensibility which enables the detection of various components, even at very low amounts. The FTIR analysis method produces an infrared absorption spectrum to enable the identification of chemical bonds in a molecule. The absorption is precisely correlated with the bonds present in the molecule.

2.6. *Application of ferrofluid for microplastic extraction from actual wastewater*

Optimum ferrofluid formulation was used to remove the microplastics laundry wastewater. The wastewater was collected from a top-load washing machine with a standard washing load of about 15 pieces of clothing, with one cup of liquid detergent. One litre of wastewater sample was collected after the first washing cycle. Next, 500 ml of the wastewater sample was filtered using a vacuum pump through 0.45 µm pore size of G/F filter papers to collect microplastics in the wastewater sample. The filter apparatus was set up by placing the filter funnel on the filtering flask and attaching the vacuum pump to the flask. The filter funnel was rinsed thoroughly a few times before the filtration started to remove contaminants. During wastewater filtration, an aluminium foil was used to act as a lid to cover the filter funnel immediately after the filtering process began to avoid contamination of filter paper with surrounding pollutants. Wastewater sample was added continuously into the funnel until the entire 500 ml sample was run through the filter. After filtration, the filter paper was placed in a glass petri dish and carefully covered. Then, the glass petri dish was kept inside the desiccator for 24 h to let it dry before being subjected to microplastic sorting.

The microplastic removal efficiency was then analysed using a dissecting microscope by applying microplastic counting and a table was compiled to indicate the amount of microplastic before and after the ferrofluid application. The microplastics retained on the filters were analysed optically using a Stereo Microscope/ Dissecting Microscope (Olympus SZ51) which offers a zoom range of 0.8x – 4x which was also connected to the Dino-Capture 2.0 software program. Dissecting

Table 3
Comparison of the amount of microplastics extracted before and after the application of ferrofluid, and the removal efficiency (%).

Before treatment (No. of Microplastics)	After treatment (No. of microplastics)	Removal efficiency (%)
455	164	64

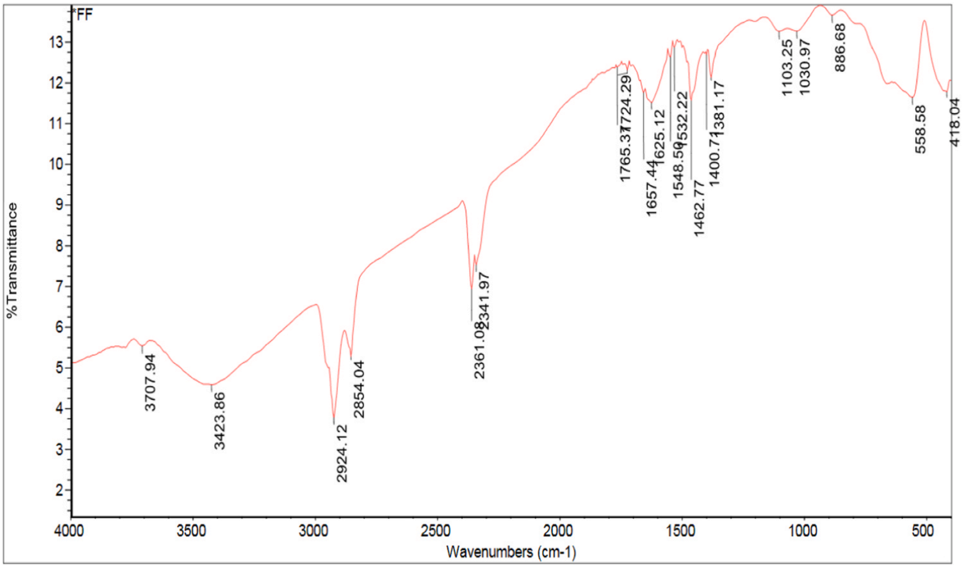

Fig. 5. FTIR spectrum of the prepared ferrofluid samples.

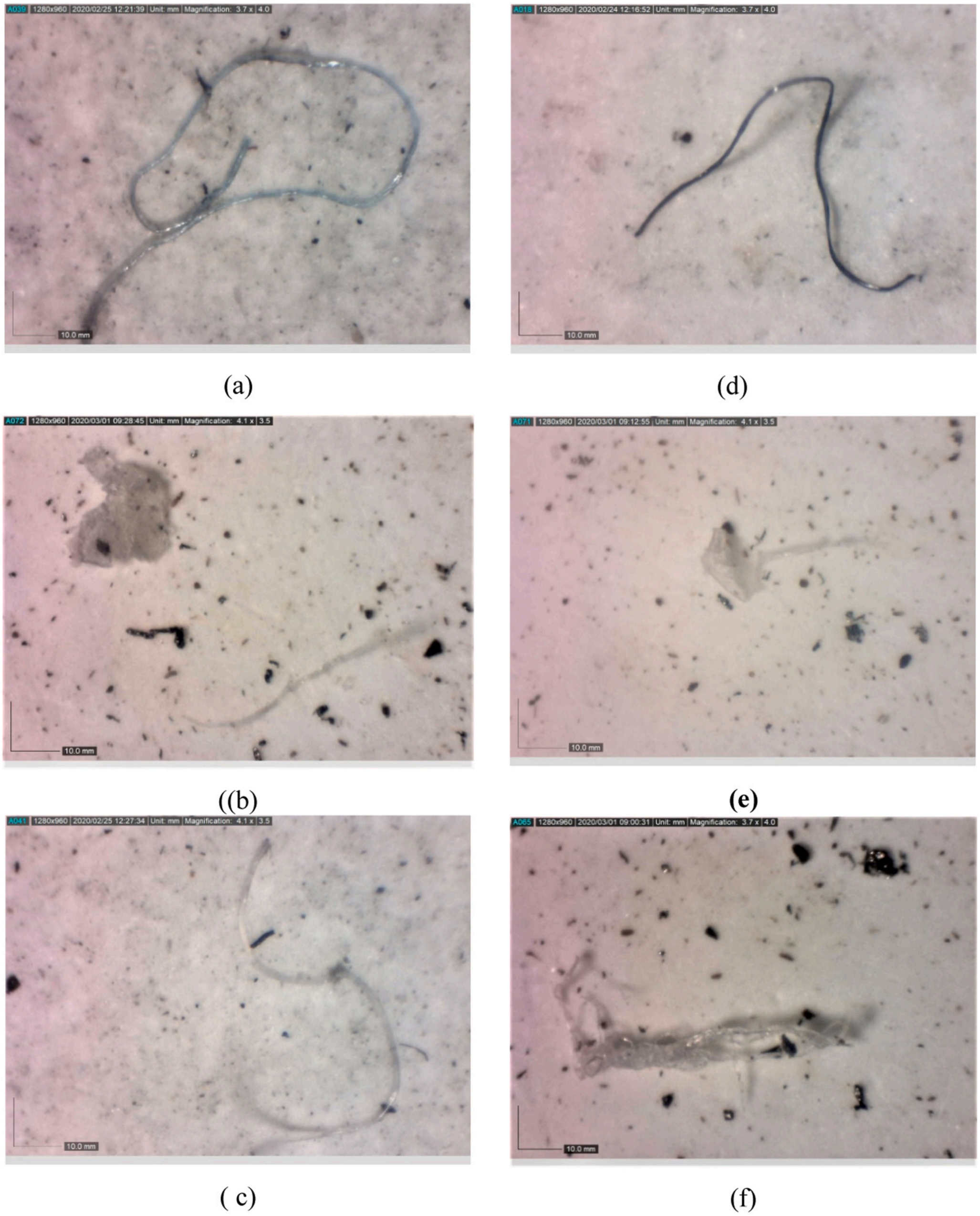

Fig. 6. Images of microfibers and fragments extracted from laundry wastewater.

microscopy is a valuable tool for the measurement of physical characteristics of microplastics (Manuscript, 2016). The images of microplastics were directly captured on the filters. The microplastics were extracted using a tweezer with the naked eye under dissecting microscope and stored in a clean vial containing distilled water for further analysis. For better identification, specific characteristics were clarified, such as colours, thickness and size of the fragments. Afterwards, the vial containing microplastics was subjected to treatment using ferrofluid and the remaining water sample was filtered similar to on the previous steps. The microplastics retained on the filter paper were sorted again using tweezer under the dissecting microscope and the amount of microplastics extracted was tabulated to compare the amount of microplastics before and after ferrofluid treatment.

3. Result and discussion

3.1. *Effect of different types of oil*

Four types of oil (cooking oil, used cooking oil, lubricating oil and used lubricating oil) were used for the preparation of ferrofluid and their efficiencies in removing microplastics from water media are shown in Fig. 1. The results exhibited that all types of oil used in ferrofluid synthesis demonstrated excellent performance since all oil types achieved $> 95\%$ microplastic removal efficiency.

However, the lubricating oil achieved the highest removal efficiency of 98.04%. This could be due to high stability of this oil which consists of complete mixture of hydrocarbons (molecules composed of only hydrogen and carbon atoms). In contrast, cooking oil is not a complete hydrocarbon as it contains fat molecules, which are composed of tri-esters. Tri-esters are organic compounds comprising three hydroxyl groups (-OH) known as glycerol, three fatty acid molecules (each consisting of long hydrocarbon chains (R)) and a carboxylic acid group (-COOH). The finding of this study is in agreement that of Khan et al. [27] who reported that ferrofluids synthesized using lubricating oil as carrier fluid demonstrated higher stable properties compared to paraffin oil and sunflower oil as carrier fluid. High stability properties of ferrofluid in lubricating oil may be due to the refractive index or dielectric constant of the solvent.

It was also observed that the ferrofluids synthesized using cooking oil produced small and low spikes when reacting with neodymium magnet. However, the lubricating oil-based ferrofluid produced strong and visible spikes in the presence of magnetic field, thus coagulating more microplastics together. On the other hand, used oil has higher viscosity due to external factors such as contaminants or temperature, while fresh unused oil base is a clear and free-flowing liquid. High viscosity of heavy oil greatly affects the capillary penetration of the oil into the small polymer pores which act as sorbent material of oil. This is also supported by the Darcy's law which states that pores can become obstructed when the oil is in high viscosity and thus inhibit the sorption ability of the polymers. Liquids with higher viscosity require more time to pass through the pores compared to liquids of less viscosity. Absorption rate varies with different oil viscosities. In brief, heavy oils are soaked up slower than light oils. As the viscosity of oil increases, the sorption capacity decreases [28]. Consequently, unused oil exhibited higher microplastic removal efficiency compared to used oil as less viscous oil attracted more microplastics, and thus enabled the efficient extraction of large amounts of microplastics together with oil by magnetite powder.

3.2. *Effect of different volume of oil*

For the second parameter studied, different volumes of lubricating oil were used to determine their efficiency for microplastic removal and the results are shown in Fig. 2. According to the results obtained, ferrofluid using 0.5 ml/L of oil indicated the highest removal efficiency of 99.5%. Apparently, the increase in the volume of oil has reduced the removal efficiency.

These results are consistent with the findings of Aboul-Gheit et al. [29] who revealed that the sorption efficiency of plastic particles towards oil was optimum when the plastic to oil ratio is in the range of 0.5–2. The higher the volume of oil added, the sorption of plastics on the oil becomes less effective, hence indirectly affecting the extraction efficiency of microplastics using oil-based ferrofluid. If oil is able to capture all microplastics, then magnetite can remove high proportion of microplastics suspended in water. This result can also be explained based on the hydrophobicity and oleophilic of a solid material. Hydrophobic materials inhibit sorption of water and thus increase the oil sorption capacity due to the lack of interaction between water and oil molecules. Strong hydrophilic particles will remain dispersed in the aqueous solution phase, while strong hydrophobic particles remain in the oil as they are only wetted by the oil phase [30]. The strong cohesion between the oil matrix and the polymer matrix ensures the integrity of structure and consistency of oil absorption. In practice, it will also be stable under ocean environment including waves, wind, sunlight, and can be easily extracted from the surface of water by applying magnetic field.

Table 1 shows the *t*-test results of removal efficiency against different volumes of oil used for ferrofluid synthesis. The Pearson's correlation of both variables was − 0.988. Since the Pearson's correlation is close to 1, this indicates that there is a strong relationship between these two variables. In other words, changes in one variable are strongly correlated with changes in the second variable. Thus, it can be concluded that there was a strong relationship between volume of oil and removal efficiency. Moreover, the Pearson correlation recorded a negative value, signifying that when one variable has a decreasing value, the second variable value will increase. For this study, it can be inferred that as the volume of oil decreased, the removal efficiency increased. Moreover, the absolute value of the results for the two variables was 139.991, which was greater than the critical t-value (2.776), while the two-tailed P-value was 1.56171E-08 or 0.0000000156171 which was extremely lesser than the alpha value (0.05). Thus, we can conclude that there was high significant difference between the two variables as the P-value was less than the alpha ($p < 0.05$) and the t-value was greater than the critical t-value.

3.3. *Effect on different dosages of iron oxide*

With the use of lubricating oil at a constant volume of 0.5 ml/L, the dosage of magnetite was varied to determine the optimum amount of iron oxide on ferrofluid efficiency. Based on the results obtained, 0.25 g/L of iron oxide indicated the lowest removal efficiency of 99.11% and increasing the dosage of iron oxide improved the removal efficiency up to 99.72%. In addition, there was no significant difference in removal efficiency of microplastic when the magnetite was used between 0.25 and 1.25 g/L. Only a small amount of magnetite is required to produce strong electro-positivity of ferrofluid [25] which can induce fast aggregation with oil and microplastic suspension in water media. With the addition of external magnetic field, the interparticle interaction has significant impact on the properties of the fluid as the magnetic dipole interaction forces activate the agglomeration behaviour of the particles. This phenomenon can be seen when the viscosity of the fluid changes. Fig. 3.

This finding is in line with Osch [3] who stated that thermal conductivity increases continuously with increasing magnetic field strength to a certain extent. In this study, the efficiency of ferrofluid on thermal conductivity was able to reveal the magnetic field strength of the ferrofluid. The thermal conductivity increased with increasing dosage of magnetic particles. Based on the results obtained, at 1.25 g/L magnetite dosage, the removal efficiency of ferrofluid became high but it was expected that increasing the magnetite concentration may reduce the removal efficiency.

Table 2 shows the *t*-test results for removal efficiency against mass of FeO. The Pearson's correlation value obtained was 0.8989, which was close to 1 indicating that there was a strong relationship between the two variables. It seemed that the removal efficiency was rather closely correlated with any changes in the mass of FeO added. In addition, the Pearson's correlation value was positive, signifying as one variable increases, the second variable also increases and vice. In this study, it can be inferred that as mass of FeO increased, the removal efficiency also increased. Moreover, the results showed that the absolute value was 1069.261, larger than the critical t-value of 2.776. Therefore, the null hypothesis was rejected as there was no significant difference for the two variables. Referring to the two tailed p-value of 4.59×10^{-12}, the p-value was smaller than alpha ($p < 0.05$), indicating a significant difference between the two variables.

3.4. *Physical and chemical analysis of ferrofluid*

The surface morphology of the oil-based ferrofluid particles was examined using SEM as depicted in Fig. 4. It revealed that most of the Fe_3O_4 particles were spherical-shaped and the particle surface was rough. There were agglomerations between the particles, which made it difficult to define the shape of other particles. Aggregation behaviour for high concentration of the fine particles was observed at various extent. This may be due to the enhanced magnetic dipole moment with interparticle interactions between the particles. In fact, it was not easy to verify the size of the nanoparticles accurately based on the SEM images.

The ferrofluid sample for FT-IR characterization was prepared as a pellet by mixing ferrofluid nanoparticles with KBr powder using hydraulic press. The characteristic bonds at 558.58 cm^{-1} was associated with the Fe-O bonding which confirmed the presence of magnetic core and it was more pronounced in the magnetite nanoparticles. The hydroxyl (-OH) group of water used in the synthesis of Fe_3O_4 nanoparticles was observed at the characteristic peak of 3423.86 cm^{-1}. Furthermore, the position band at 2924.12 cm−1 was attributed to C–H stretching vibrations, indicating the occurrence of hydrocarbons as hydrocarbons exhibited IR adsorption peaks between 2800 cm^{-1} and 3300 cm^{-1}. This also indicated hybridization of sp3C-H stretching with stiffer bonds vibrating at high frequencies. The FTIR spectrum image is depicted in Fig. 5.

3.5. Microplastic extraction, identification and quantification from laundry wastewater

During the extraction of microplastics from wastewater samples, all equipment was ensured to be cleaned and covered with clean aluminium foil to minimise contamination. The wastewater selected in this study was domestic washing wastewater from top-load washing machine. Emission of textiles as a microplastic source into the environment reaches 0.5 million tonnes yearly [31]. Abrasion on synthetic textiles induces shedding upon mechanical stress of the textile fibres during washing or drying procedures [32].

Based on the results obtained, the amount of microplastics extacted from the wastewater before ferrofluid application was 455 but after ferrofluid application, the microplastics removed reduced to 164 which was equivalent to 64% removal efficiency as shown in Table 3. It has been reported from a previous study that the treated effluents discharged to the North Sea, Oude Maas River or North Sea Canal from to contained average of 52 pieces of microplastics per litre [16].

Thus, this suggested that the application of ferrofluid in laundry wastewater treatement was considered successful as the amount of microplastics was favorably removed. The collected microplastics were sorted directly from the filter paper were directly categorised based on the type and appearance of microplastics. Based on the results obtained, it was found that the majority of microplastics sorted from the laundry wastewater were fibres or microfibres, and followed by fragments. Several images of microplastics were captured using the Dino-Capture software program and displayed in Fig. 6(a)-(f).

4. Conclusion

Based on the results obtained, the synthesis of ferrofluid using lubricating oil induced the highest removal efficiency of microplastics due to its stable properties of complete mixture of hydrocarbons. Nevertheless, high volume of oil in based on the ratio of plastic to oil exhibited less effective oil sorption, thus affecting the overall performance of microplastic extraction efficiency by ferrofluid. Moreover, the result obtained showed that the higher the dosage of magnetite powder added into the ferrofluid, the stronger the magnetic field strength, and the higher the extraction efficiency of microplastic using neodymium magnet. In summary, this study inferred that the ferrofluid prepared with standard optimum formulation was effective in removing microplastics from laundry wastewater.

CRediT authorship contribution statement

Sofiah Hamzah: Conceptualization, Validation, Writing - original draft, Supervision, Writing - review & editing, Project administration, **Lau Yuke Ying:** Investigation, Writing - original draft, **Alyza Azzura Abd. Rahman Azmi:** Methodology, supervision, **Nurul Ashraf Razali:** Writing - review & editing, **Nur Hanis Hayati Hairom:** Writing - review & editing, **Nurul Aqilah Mohamad:** Investigation, Writing - original draft, **Mohammad Hakim Che Harun:** Visualization, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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