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Synthesis of an Eco-friendly and Reusable Magnetic Ferrofluid using Orange Peel Extract for Oil Spill Cleanup

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SUMMARY

Oil spills pose a huge threat to the marine ecosystem and have caused extensive damage to marine habitats, fishing and tourism industries, and even humans. Current oil spill cleanup methods include the use of booms, skimmers and chemical dispersants, which are inefficient and expensive. Recently, oil-based ferrofluids have gained traction in oil spill cleanup, but it is uneconomical to purify and obtain oleic acid (OA), one of the most frequently used surfactants in the synthesis of ferrofluids. An innovative, eco-friendly oil-based magnetite ferrofluid was synthesised via co-precipitation of iron salts. Its surfactant was derived from orange peels (OP), which is a widely available fruit waste with great potential to be used as capping agents due to its high fatty acid content. The hydrophobicity of magnetite particles with OA and OP surfactants was examined through water contact angle measurements. The simple and convenient application of OA- and OP-ferrofluids in the removal of spilled motor oil from seawater was demonstrated. The oil removal capacity and reusability of the ferrofluids were investigated. Results show that at 1 vol%, OP-ferrofluid's oil removal capacity of 59.7 g/g is comparable to that of OA-ferrofluid, outperforming several magnetic sorbents synthesised by other researchers and commercial polypropylene. The oil removal capacity of OP-ferrofluid was maintained above 50 g/g throughout 5 progressive cycles of oil removal, unlike OA-ferrofluid. Finally, a novel prototype was constructed to easily retrieve used OP-ferrofluid via a magnet for regeneration, facilitating the use of OP-ferrofluid to clean up oil spills in the ocean.

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List of Abbreviations

Abbreviation	Meaning
OA	Oleic Acid
OP	Orange Peel
TEM	Transmission Electron Microscope
EDS	Energy Dispersive Spectroscopy
SE	Standard Error

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1. Introduction

1.1 Literature review

Oil spills pose a serious threat to the ecosystem of the sea. They are mainly caused by occasional accidental episodes of super tankers, oil rig drilling and natural events (Bayat et al., 2005). A notable example is the Deepwater Horizon oil spill which occurred in 2010, spilling over 200 million tonnes of crude oil into the ocean (Kurtz, 2013) and causing massive damage to the marine ecosystem. Studies have shown that the cost of cleaning up the oil spill to the British Petroleum (BP) Company is 65 billion USD (Bousso, 2018), which is a substantial amount of money. Cleaning up oil spills is of paramount importance because oil spills have adverse effects on both marine plants and animals (Andersen, Melville, & Jolley, 2008). In the long run, bioaccumulation and biomagnification of polycyclic aromatic hydrocarbons up the food chain can poison humans who consume seafood (Laegdsgaard & Johnson, 2001).

Current methods of cleaning up oil spills include the use of booms and skimmers, in-situ burning, use of chemical dispersants and synthetic sorbents (Karakasi & Moutsatsou, 2010). However, booms and skimmers are expensive (Abdullah et al., 2019), in-situ burning releases large amounts of toxic gases (Allen & Ferek, 1993) and chemical dispersants are not only expensive but environmentally unfriendly (Page et al., 2002). Synthetic sorbents such as polypropylene are used commercially as they have high oil sorption capacities (Bayat et al., 2005), but their low biodegradability is a major environmental concern (Tokiwa et al., 2009). Hence, it is imperative to develop a novel, eco-friendly and cost-effective solution for oil spills.

An oil-based ferrofluid is a smart colloidal suspension of magnetite nanoparticles in an oil medium which possesses unique magnetic and fluid properties (Sangeetha et al., 2013). Being superhydrophobic and superoleophilic, they are able to attract contaminant oil while completely repelling water molecules (Rashin, Kutty, & Hemalatha, 2014). After use, oil-based ferrofluids can be easily and quickly retrieved from the ocean via the application of a magnetic field. Moreover, oil-based ferrofluids can maintain good dispersion stability even under the influence of external fields (Zhu et al., 2012). Magnetite nanoparticles in a colloidal suspension do not easily aggregate, dissociate or chemically react with the surroundings (Atta, Al-Lohedan, & Al-Hussain, 2015), hence the addition of the carrier oil is crucial. Ferrofluids are also easily recoverable and stable, thus showing great potential to be reused for multiple cycles.

One of the most common surfactants used to synthesise oil-based ferrofluids is oleic acid (OA) (Zhang et al., 2006). OA molecules have a hydrophilic head which is able to attach to the surface of magnetite nanoparticles (Tsai et al., 2010) and a long hydrophobic tail containing a cis-double bond, providing great steric hindrance to maximise the distance between magnetite nanoparticles (Harris, Shumbula, & Walt, 2015), preventing agglomeration. However, pure OA is commonly obtained via fractional distillation, rendering its synthesis process energy intensive (Elkacmi et al., 2016) and uneconomical.

Orange peels (OP) are an eco-friendly natural waste material commonly discarded after orange juice has been extracted (Olea-Mejía et al., 2017). The world's orange production is estimated to be about 60 million tonnes annually (Munagapati & Kim, 2016), demonstrating its wide availability. OP extract has great potential to be used as an alternative surfactant for magnetite nanoparticles to OA as it contains fatty acids with similar molecular structures as OA, such as palmitic acid, stearic acid and linoleic acid (Islam, Muslim, & Rahman, 2012). To date, there have been limited studies regarding the synthesis of oil-based ferrofluids using natural extracts for oil spill cleanup.

1.2 Scope and Objectives

The overarching aim of this study is to enhance the quality of seawater and protect the marine ecosystem by cleaning up oil spills. The scope of this study is not just limited to the local or regional context, as the use of a globally available food waste such as orange peels provides easy access to countries all over the globe. Oil spills have adverse impacts on marine animals and plants, as well as affect humans through the consumption of contaminated seafood, posing a serious threat to the environment and human health. This study involves the synthesis of an oil-based ferrofluid using orange peel extract (OP-ferrofluid), understanding its implications in the area of oil spill cleanup and the creation of a working prototype which demonstrates the application of OP-ferrofluid for oil spill cleanup in the sea.

The objectives of this study are:

1. To synthesise ferrofluid using orange peel extract as a surfactant (OP-ferrofluid) via the co-precipitation of magnetite particles
2. To evaluate the oil removal capacity of OP-ferrofluid on motor oil and compare it to that of conventional ferrofluid synthesised using oleic acid (OA-ferrofluid)
3. To investigate the reusability of OP-ferrofluid after 5 progressive cycles of oil removal and desorption
4. To construct a prototype for the application of OP-ferrofluid for oil spill cleanup.

2. Materials and Methods

2.1 Materials

Iron(III) chloride hexahydrate, iron(II) sulfate heptahydrate and 25% (w/w) aqueous ammonia were procured from GCE Chemicals; oleic acid from Sigma Aldrich; isopropanol and ethanol from Scharlau Chemicals and hexane from RCI Labscan. Corn oil was purchased from local supermarkets, motor oil (Ultra 5W-40) and diesel oil were purchased from the petrol kiosk and orange peels were collected from fruit stalls.

2.2 Synthesis of Ferrofluid using Orange Peel (OP) Extract and Oleic Acid (OA)

20g of dried orange peels (OP) were soaked in 100ml of hexane for 2 days. The mixture was filtered before a rotary evaporator was used to remove the hexane. OP extract was obtained. 1g of OP extract was dissolved in 25ml of isopropanol before 2.70g of iron(III) chloride hexahydrate and 1.39g of iron(II) sulfate heptahydrate were dissolved in 50ml of deionised water and mixed with OP extract in isopropanol. 25% (w/w) aqueous ammonia was added to induce the co-precipitation of magnetite coated with biomolecules present in orange peel extract (OP-magnetite). A magnet was used to retrieve the OP-magnetite which was washed until neutral pH and dried at 60°C until constant mass. The chemical reaction for the co-precipitation of magnetite is shown in equation (1).

$$2Fe^{3+}\,(aq) + Fe^{2+}\,(aq) + 8OH^{-}\,(aq) \rightarrow Fe_3O_4\,(s) + 4H_2O\,(l) \;\ldots(1)$$

Varying masses of OP-magnetite (0.259g, 0.517g, 0.776g) were added to 5ml of corn oil (carrier oil) to obtain 1 vol%, 2 vol% and 3 vol% ferrofluids respectively, where vol% represents (v/v). The ferrofluids synthesised using OP extract (OP-ferrofluid) were then sonicated for 1h.

The conventional synthesis of magnetite coated with oleic acid (OA-magnetite) using the phase-transfer method was adapted from Tsai et al., (2010). Oleic acid and aqueous ammonia were added to magnetite suspended in water. Ethanol was used to remove excess surfactant and as a medium to transfer the aqueous phase to the organic phase with corn oil as the carrier oil. 1 vol%, 2 vol% and 3 vol% oleic acid ferrofluids (OA-ferrofluid) were prepared respectively.

Water contact angle measurements and Fourier-transform Infrared Spectroscopy (FTIR) analysis were conducted on both magnetites while the ferrofluids were characterised by Transmission Electron Microscopy (TEM).

2.3 *Oil Removal Tests for OP- and OA-Ferrofluids*

Artificial seawater was prepared by dissolving 56g NaCl, 17g $MgCl_2$, 8.19g $MgSO_4$, 2.5g $CaSO_4$ and 2g KCl in 2 litres of deionised water (Thio et al., 2012). 0.500g of motor oil and 0.050g of 1 vol% OP-ferrofluid were added to 50ml of artificial seawater. As the use of crude oil is not permitted in school laboratory, motor oil was used instead. Motor oil contains long chain hydrocarbons and polyaromatic hydrocarbons, rendering it similar to typical crude oil (Lu & Kaplan, 2008). The chemical and physical properties of the motor oil used in the following tests are listed in Annex A, Page 12. The mixture was shaken on an orbital shaker at 100 rpm for 5 min before a magnet encased in a glass vial was used to retrieve the ferrofluid and motor oil mixture (Figure 1). The same procedure without the addition of a ferrofluid was used as the control experiment. Using a separating funnel and a rotary evaporator, the remaining motor oil was extracted using hexane and recovered. The mass of motor oil remaining was monitored until the mass remained constant. The procedure was repeated for 2 vol% and 3 vol% OP-ferrofluids, as well as OA-ferrofluids. The oil removal capacity was calculated using the following formula:

$$Q_o = \frac{m_i - m_f}{m_m}$$

where Q_O *is the oil removal capacity/g/g,* m_i *is the initial mass of motor oil/g,* m_f *is the final mass of motor oil/g and* m_m *is the mass of magnetite/g.*

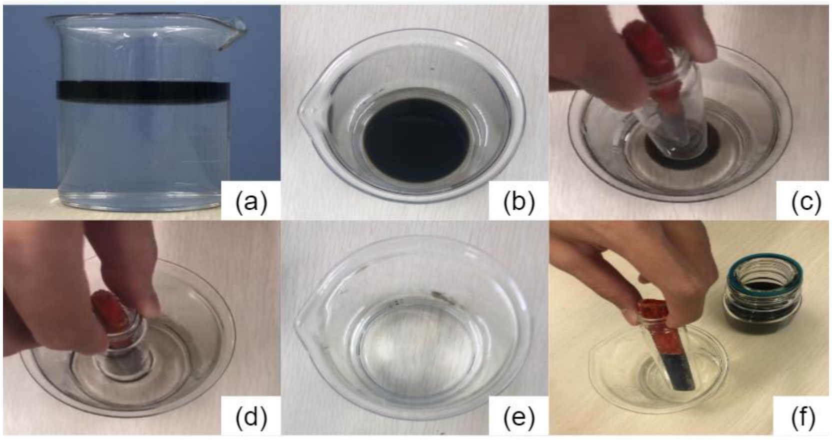

Figure 1: Optical images showing the process of oil removal: (a) Side view of motor oil with ferrofluid added, (b) Top view of motor oil with ferrofluid added, (c) Magnet dipped into mixture, (d) Magnetised oil attracted by magnet, (e) Cleaned seawater, (f) Cleaned seawater and retrieved oil

2.4 *Reusability of OP- and OA-Ferrofluids*

After each oil removal test, the glass vial with the magnet was soaked in 50ml of hexane to dissolve the motor oil. A magnet was used to recover the magnetite, which was dried and added to corn oil to obtain a new OP- or OA-ferrofluid. Motor oil was recovered easily using a rotary evaporator after the magnetite was separated. The regenerated ferrofluids were tested on their ability to remove motor oil for a total of 5 cycles.

3. Results and Discussion

3.1 Characterisation of OP- and OA-Ferrofluids

ImageJ, an image processing software, was used to determine the particle size of magnetite in the ferrofluids. Transmission Electron Microscopy (TEM) images show that OA-magnetite particles are monodispersed and spherical in shape, with an average size of 12.8 nm (Figure 2). On the other hand, OP-magnetite particles are slightly less well-dispersed and are cubic in shape, with an average size of 17.4 nm (Figure 3).

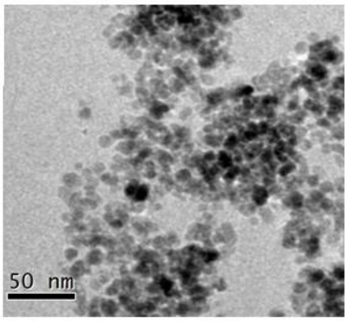

Figure 2: TEM image of OA-ferrofluid

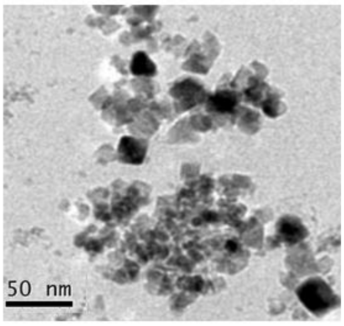

Figure 3: TEM image of OP-ferrofluid

Figures 4, 5 and 6 reveal that the water contact angles of both OA- and OP-magnetite are about 136°, exceeding 90°. When the contact angle is more than 90°, the material is hydrophobic (Förch, Schönher, & Jenkins, 2009). It can be concluded that both OA- and OP-magnetite are hydrophobic.

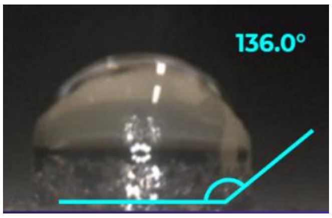

Figure 4: Water contact angle of OA-magnetite

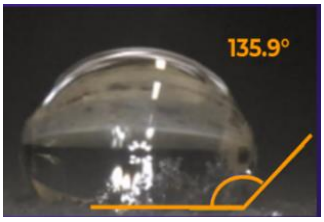

Figure 5: Water contact angle of OP-magnetite

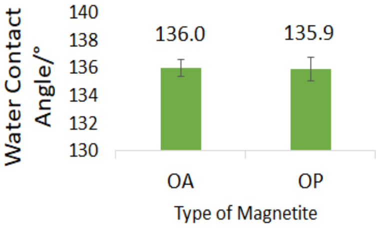

Figure 6: Comparing water contact angles of OA- and OP-magnetites. Data represents mean ± SE of 5 replicates

The FTIR spectrum of OA-magnetite (Figure 7) reveals two bands at 2929 cm^{-1} and 2852 cm^{-1} corresponding to the $-CH_2$ stretches respectively. The band at 1712 cm^{-1} can be attributed to the stretch of $-C{=}O$ group while the bands at 1575 cm^{-1} and 1521 cm^{-1} correspond to $-COO^-$ stretch. The presence of these two bands is due to the complexation between the iron(II)/iron(III) ions and carboxylate ions of oleic acid. This confirms the successful attachment of oleic acid to the magnetite surface. Similarly, Figure 8 reveals bands at 2925 cm^{-1} and 2851 cm^{-1} corresponding to the $-CH_2$ stretches and 1735 cm^{-1} corresponding to the $-C{=}O$ stretch. The bands at 1517 cm^{-1} and 1625 cm^{-1} can be attributed to the aromatic C-C stretches and the bands at 1268 cm^{-1}, 1107 cm^{-1} and 1077 cm^{-1} correspond to the $-C-O$ stretch. This suggests that there is a greater variety of molecules being coated onto OP-magnetite. Possible molecules present in the surfactant of OP-magnetite include linalool (Farhat et al., 2011) and 4-acetoxy-3-methoxystyrene (Erukainure et al., 2016), which are commonly found in orange peel.

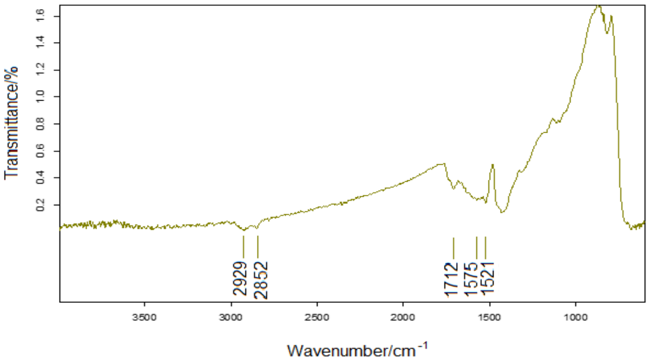

Figure 7: FTIR spectrum of OA-magnetite

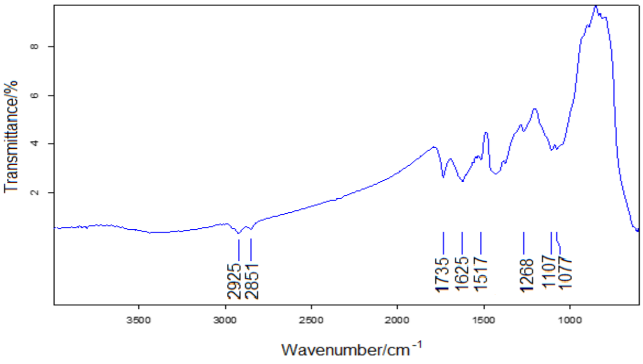

Figure 8: FTIR spectrum of OP-magnetite

3.2 *Oil Removal Tests for OP- and OA-Ferrofluids*

The mechanism of motor oil removal can be explained as follows. The hydrophobic motor oil molecules (in blue) are attracted to the hydrocarbon tails of the surfactant molecules and the carrier oil molecules (in yellow) via London dispersion forces (Figure 9). As oil molecules are attached to the magnetic ferrofluid, the whole mixture becomes magnetic. With the simple use of a magnet, the magnetic ferrofluid together with the motor oil can be easily separated from water.

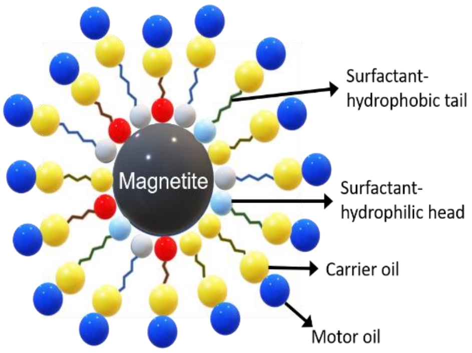

Figure 9: How ferrofluid removes oil

Figure 10 shows that at 1 vol%, the oil removal capacity of OP-ferrofluid is not significantly different from OA-ferrofluid.

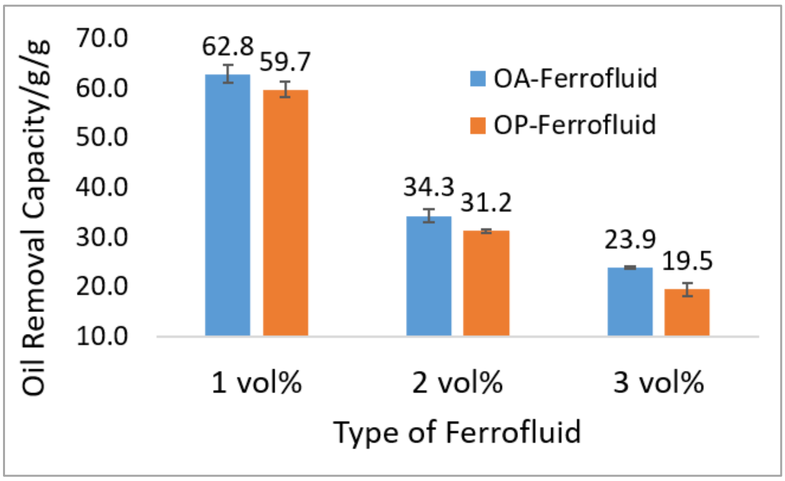

Figure 10: Oil removal capacities of OA- and OP-ferrofluids. Data represents mean ± SE of 5 replicates

Even though OP-ferrofluid has surfactant molecules with various polar heteroatom functional groups (Figure 8), Energy Dispersive Spectroscopy (EDS) shows that OP-magnetite has a higher carbon content than OA-magnetite (Figures 11 and 12). This suggests that the surfactant molecules on OP-ferrofluid are also relatively large molecules with large electron clouds that can be easily polarised to generate strong dispersion forces. In addition, the polar components of these surfactant molecules may form permanent dipole-permanent dipole interactions with substances in motor oil such as phenols and aldehydes in additives (Lu & Kaplan, 2008), increasing OP-ferrofluid's affinity with motor oil.

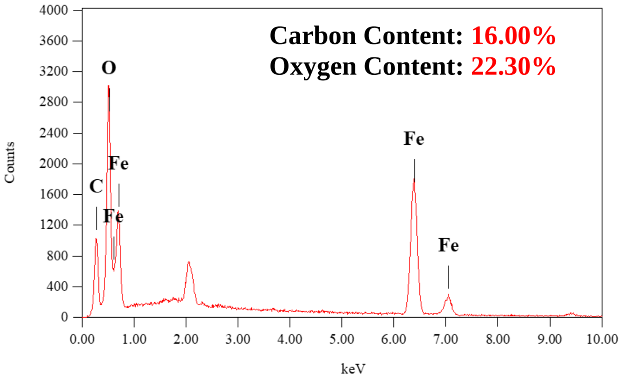

Figure 11: EDS of OP-magnetite

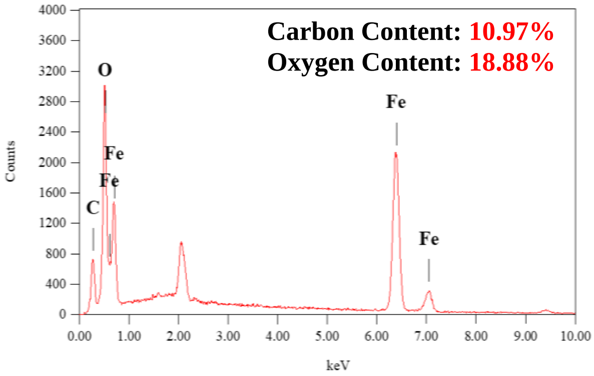

Figure 12: EDS of OA-magnetite

It was also observed that 2 vol% and 3 vol% ferrofluids have lower oil removal capacities than 1 vol% ferrofluids (Figure 10). The reason could be attributed to the larger number of magnetite particles per unit volume of ferrofluid. This results in a higher chance of agglomeration, decreasing the surface area to volume

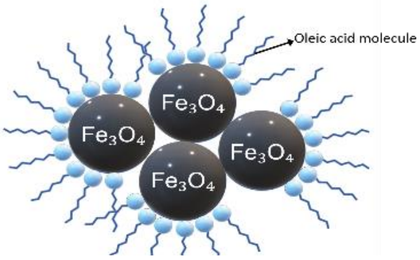

Figure 13: Agglomeration of magnetite in ferrofluid

ratio for the attraction of motor oil, as shown in Figure 13. Thus, 1 vol% OA- and OP-ferrofluids were selected for future tests. Table 1 shows that both ferrofluids have higher oil removal capacities than several magnetic absorbents reported in literature and commercial polypropylene, suggesting that OP-ferrofluid has huge potential to be used as an effective material to clean up oil spills.

Table 1: Comparison of motor oil removal capacities of different sorbents

Type of Sorbent	**Oil Removal Capacity/g/g**	**Reference**
1 vol% OA-ferrofluid	63	This study
1 vol% OP-ferrofluid	60	This study
Magnetic hexagonal boron nitride	53	Leyva et al., 2018
Magnetic exfoliated graphite	45-52	Pavlova et al., 2018
Magnetic polystyrene/magnetite/graphite aerogel	40	Zhou et al., 2015
Magnetic polyurethane sponge	32-40	Jiang et al., 2020
Commercial polypropylene	10-20	Senanurakwarkul et al., 2013

3.3 *Reusability of OP- and OA-Ferrofluids*

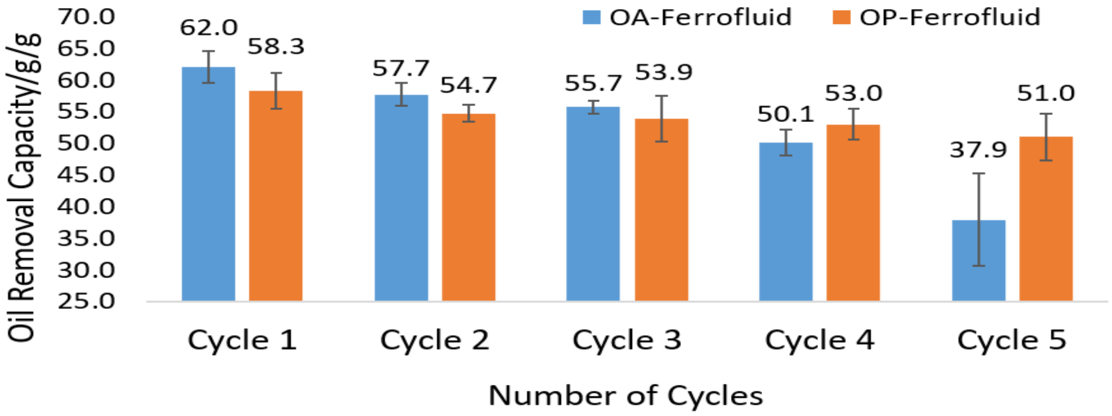

Figure 14: Regeneration of OA- and OP-ferrofluids for progressive cycles of oil removal. Data represents mean ± SE of 5 replicates

After 5 cycles of oil removal, it is observed that OP-ferrofluid experiences a less substantial drop in effectiveness than OA-ferrofluid (Figure 14). At Cycle 4, the oil removal capacity of OP-ferrofluid exceeded that of OA-ferrofluid. While the oil removal capacity of OA-ferrofluid plummeted to 37.9 g/g (24% decrease from Cycle 4) in Cycle 5, that of OP-ferrofluid remains above 50 g/g (4% decrease from Cycle 4). FTIR spectroscopy was conducted to find out why.

The FTIR spectrum of OA-magnetite at the end of Cycle 4 (Figure 15) shows an absence of a distinctive peak at about 2900 cm^{-1}, which corresponds to the C-H stretch. This suggests that after a few cycles, most of the oleic acid surfactant had been washed off during the desorption process using hexane. A lower amount of surfactant increases the chances of agglomeration of magnetite particles, so they cannot be evenly dispersed, leading to a decrease in surface area to volume ratio to attract motor oil. This explains the lowered oil removal capacity of OA-ferrofluid over 5 cycles.

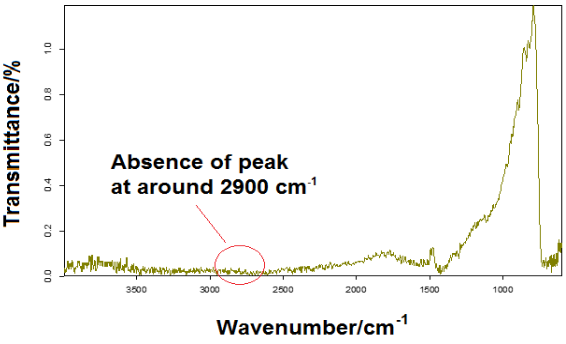

Figure 15: FTIR spectrum of OA-magnetite at the end of Cycle 4

On the other hand, the FTIR spectrum of OP-magnetite (Figure 16) at the end of Cycle 4 reveals a distinctive peak at 2925 cm^{-1} corresponding to the C-H stretch, hence suggesting that the -C-H group is still present within the surfactant, together with other heteroatom functional groups such as the -C=O group (1735 cm^{-1}) and the -C-O group (1268 cm^{-1}). This is because the surfactant molecules of OP-ferrofluid, some of which have slight polar properties, form relatively weaker attractive forces with hexane, hence it is easier to desorb the contaminant oil from OP-ferrofluid without fully washing off the surfactant. The presence of surfactant molecules prevented the magnetite from agglomerating, maintaining a high surface area to volume ratio to attract motor oil.

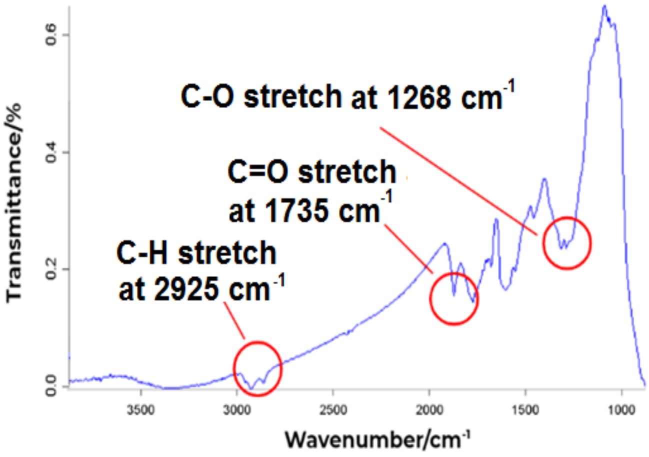

Figure 16: FTIR spectrum of OP-magnetite at the end of Cycle 4

Due to its excellent magnetic property (Figure 17), 99.1% of OP-ferrofluid introduced into seawater can be rapidly retrieved using a magnet, making it much more feasible to be reused for multiple cycles. Hence, the use of OP-ferrofluid is a potentially more sustainable method as compared to the use of booms and synthetic sorbents, which are often not recycled.

Figure 17: Magnetic property of OP-ferrofluid

3.4 *Cost Consideration*

One of the greatest advantages that OP-ferrofluid has over OA-ferrofluid is its cost. Table 2 and Table 3 detail the costs of various materials needed for the synthesis of the volume of OP-ferrofluid and OA-ferrofluid required to remove 1 litre of motor oil from seawater respectively. The materials were of analytical grade and were of at least 99% purity. The transportation, rental and labour costs of producing both OA- and OP-ferrofluids were estimated to be about 40% of their average cost of production.

Table 2: Estimated cost of OP-ferrofluid needed to remove 1 litre of motor oil

Synthesis of OP-Ferrofluid	Cost/USD
Iron(III) chloride	1.31
Iron(II) sulfate	0.63
Isopropanol	3.54
Aqueous ammonia	9.82
Hexane	3.97
Corn oil	0.77
Orange peels	0.12
Miscellaneous (Eg. Transportation, labour)	10.00
Total	**30.16**

Table 3: Estimated cost of OA-ferrofluid needed to remove 1 litre of motor oil

Synthesis of OA-Ferrofluid	Cost/USD
Iron(III) chloride	1.26
Iron(II) sulfate	0.60
Ethanol	9.95
Aqueous ammonia	9.17
Oleic acid	8.28
Corn oil	0.74
Miscellaneous (Eg. Transportation, labour)	10.00
Total	**40.00**

To clean up one litre of motor oil, the cost of OP-ferrofluid is about 25% less than that of OA-ferrofluid. Furthermore, it is reported that BP had to pay the equivalent of about 65 billion USD to clean up the 800 million litres of oil spilled during the Deepwater Horizon oil spill, which averages about 81.25 USD per litre of oil (Bousso, 2018). Hence, the use of OP-ferrofluid is potentially more affordable than that of OA-ferrofluid and the conventional method. Coupled with the fact that OP-ferrofluid is reusable, it would be an attractive product for companies in the petroleum and oil sectors looking to simultaneously cut their losses in the case of an accident, as well as protect the environment and human health.

4. Conclusions and Future Work

OP-ferrofluid was successfully synthesised using orange peel (OP) extract as the surfactant. 1 vol% OP-ferrofluid was most effective in removing motor oil from seawater, with its oil removal capacity of 59.7 g/g being comparable to that of 1 vol% conventional OA-ferrofluid and higher than several magnetic sorbents reported by other researchers, as well as commercial polypropylene. The magnetic property of OP-ferrofluid allows for a rapid and simple method of recovery by the use of a magnet, enabling it to be recycled effectively. OP-ferrofluid can be reused for at least 5 progressive cycles of oil removal without a significant drop in effectiveness, potentially saving cost and making the use of it in cleaning oil spills even more eco-friendly. Thus, OP-ferrofluid shows great promise to be an environmentally friendly alternative to current methods of oil spill cleanup.

Utilising programming, robotics technology and LEGO Mindstorms, a fully automated prototype was constructed to showcase how OP-ferrofluid could be used to clean up oil spills in real life (Figure 18). A magnet, located inside the conveyor belt, attracts the ferrofluid-motor oil mixture towards it. The mixture is then elevated to a collection well via the rotating conveyor belt, where the ferrofluid can be retrieved and reused. As a boat with such a mechanism moves through the ocean, large areas of oil spills can be cleaned at a fast rate. This system could potentially facilitate the rapid and efficient use of OP-ferrofluid when cleaning up oil spills. A video of how the prototype works can be viewed at https://www.youtube.com/watch?v=8uUXL2udEsg

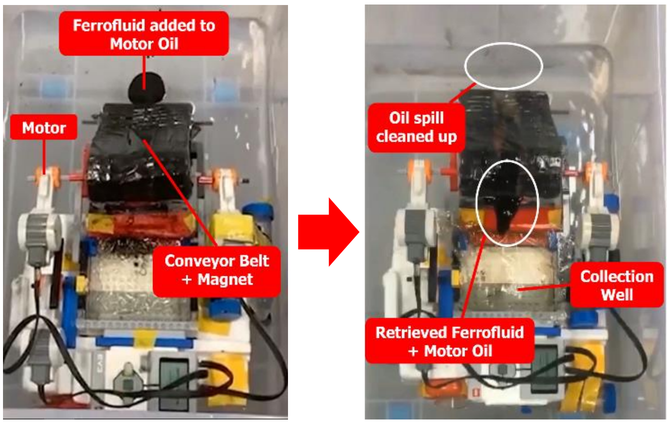

Figure 18: Self-constructed prototype using robotics technology for the real-life application of OP-ferrofluid in oil spill cleanup

Preliminary tests were conducted to determine the oil removal capacity of OP-ferrofluid on other types of contaminant oil such as diesel oil (Annex B, Page 13). In the future, the use of other plant extracts in the synthesis of ferrofluid could be investigated and compared with orange peel. It would also be interesting to determine the exact identities of the biomolecules from OP extract which have coated onto the magnetite using Liquid Chromatography-Mass Spectrometry (LC-MS). The effectiveness of OP-ferrofluid in removing motor oil from freshwater instead of seawater can be further explored, due to the increasing frequency of freshwater oil spills such as the 2010 Kalamazoo River oil spill in Michigan, USA (Zhu, Waterman, & Garcia, 2018). Finally, the model could be extensively tested to assess its feasibility in the real-life context.

Annexes

Annex A: Chemical and Physical Properties of Motor Oil

The motor oil used in this study contains molecules ranging from C_{20} to C_{35} (where C represents the number of carbon atoms in an oil molecule) (Farhat et al., 2011) and has a grade of 5W-40. The grading system is designated by the Society of Automotive Engineers: “5” describes the viscosity of the oil at cold temperatures, usually measured at 0°F, “W” stands for “Winter” and “40” describes the viscosity of the oil at 100°F, the usual operating temperature. The smaller the number, the better the flow rate of the oil at a specific temperature. Table 4 shows the chemical and physical properties of the motor oil used, according to its Material Safety Data Sheet.

Table 4: Chemical and physical properties of motor oil

Carbon Number	C_{20} to C_{35}
Density	851 kg m^{-3} at 15°C
Kinematic Viscosity	75 mm^2 s^{-1} at 40°C
Flash Point	217°C

Annex B: Oil Removal Tests on Diesel Oil

The efficiency of oil removal depends on the quality of the oil used, as shown in the study by Ko et al., 2016, where the same material removed different percentages of oil depending on the type of oil used in the study. Therefore, in addition to motor oil, experiments to determine the oil removal capacity of OA- and OP-ferrofluids on diesel oil were also conducted. The chemical and physical properties of the diesel oil used are shown in Table 5, according to its Material Safety Data Sheet.

Table 5: Chemical and physical properties of diesel oil

Carbon Number	C_9 to C_{25}
Density	831 kg m^{-3} at 15°C
Kinematic Viscosity	2 – 4.5 mm^2 s^{-1} at 40°C
Flash Point	>60°C

Figure 19 shows that the oil removal capacity of both OA- and OP-ferrofluids on diesel oil is lower than that on motor oil. This is possibly because the carbon number of diesel oil molecules are lower than that of motor oil (Tables 4 and 5), thus the electron clouds of diesel oil molecules are smaller and less easily polarised, leading to weaker dispersion forces between the ferrofluids and the diesel oil and weaker attraction, lowering the oil removal capacity.

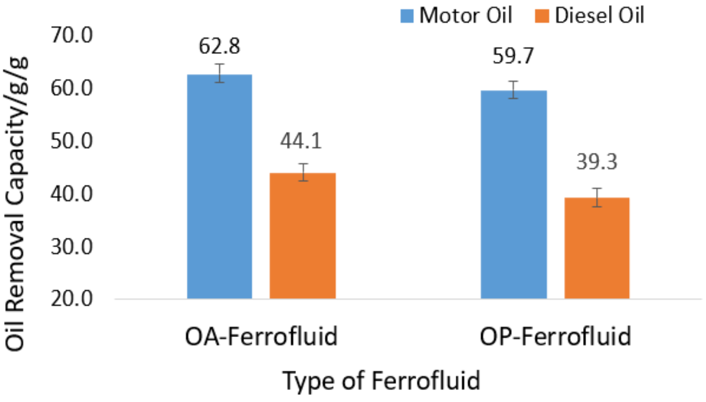

Figure 19: Diesel oil removal capacities of 1 vol% OA- and OP-ferrofluids. Data represents mean ± SE of 5 replicates

1 vol% OP-ferrofluid is not significantly different from 1 vol% OA-ferrofluid in terms of diesel oil removal capacity. Table 6 shows that both ferrofluids have relatively higher diesel removal capacities than several sorbents reported in literature and commercial polypropylene, losing out only to magnetic polyaniline nanocomposites, suggesting that OP-ferrofluid is versatile and can remove oils of different characteristics.

Table 6: Comparison of diesel oil removal capacities of different absorbents

Type of Adsorbent	**Diesel Oil Removal Capacity/g/g**	**Reference**
Magnetic polyaniline nanocomposite	60	Abdelwahab, & Abd El-Ghaffar, 2016
1 vol% OA-ferrofluid	44	This study
1 vol% OP-ferrofluid	39	This study
Magnetic Au/Fe_2O_3 nanocomposite	21	Sharma, Sharma, & Kim, 2018
Three-dimensional graphene sponge	11	Bagoole et al., 2018
Commercial polypropylene	5-10	Jiang et al., 2020

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