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Article

A novel filtration model for microplastics using natural oils and its application to the environment

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SUMMARY

There is an urgent need to extract microplastics from the ocean. Current research aimed toward physical separation of microplastics from water by developing a filter that allows water to pass but captures microplastics. But the physical microplastic filters are too small that they can only filter small amount of water. Our research utilized chemical ideas to devise an effective filtering method that can potentially filter the ocean. We hypothesized that if microplastic contaminated water is mixed with a nonpolar solvent with a freezing point higher than that of water, then the microplastics will be separated from the water. In our experiments, we used two types of nonpolar solvents, palm oil and palm kernel oil, and we evaluated extraction of the three most abundant types of microplastics in the ocean (polystyrene, polyethylene, and polypropylene). The highest microplastic extraction percentage was 96.2% when filtering 500 µm polystyrene with palm oil, and the lowest was 94.2% when filtering 13 µm polypropylene with palm kernel oil. In addition to measuring extraction efficiency, we designed and conducted an experiment to find the amount of energy required to liquefy palm oil and palm kernel oil. Our calculations suggest that palm kernel oil is more energy-efficient and produces less environmental concerns. Furthermore, we proposed a real-world application of the system, which sheds light on the viability of attacking the microplastic problem in the ocean. Calculations using the model showed that it would take an estimated 48.7 years to filter microplastics from the Pacific Ocean. Overall, the results of this study yield an elegant solution to a global environmental problem that poses a grave threat not only to humanity but also to the whole ecosystem.

INTRODUCTION

Plastics are synthetic polymers that are designed to be highly durable. Owing to their cost-effectiveness, plastics are used in many areas such as packaging, building, and electronics (1). However, the great durability of plastics hinders them from biodegrading; a plastic piece may take approximately 465 years to degrade naturally (2). As a result, plastic garbage discarded in the ocean has formed plastic islands in the Pacific Ocean. The surface area of these islands is estimated to be 1.6 million square kilometers (3).

In addition to the problem of plastic islands, another crucial problem has risen from the plastics in the ocean: microplastics. Microplastics are small size plastics that move around the ocean by water current. There are two types of microplastics, primary and secondary. Primary microplastics are microplastics originally made to have small sizes such as plastic pellets and particles used in cosmetics. Secondary microplastics are microplastics produced from fragmenting larger plastics (3). Since most plastics are synthetic polymers, they can break down into smaller units. The size of microplastics can range from 5 mm down to 5 µm (3). Currently, there are microplastic filters for water used domestically. Carbon block filters, reverse osmosis filters, and distillation filters can remove nearly 100% of microplastics from water sources (4), but these filters are too small and cannot filter a large quantity of water. A system that can filter microplastics in the ocean is still needed.

The nonpolar nature of microplastics turned our attention to natural oils. Oil undergoes a favorable interaction with plastics since both compounds are nonpolar. There are contributing forces acting between oil and plastics such as the hydrophobic effect and London dispersion force. The hydrophobic effect is the tendency of water to aggregate nonpolar compounds together in aqueous solution (5). As oil and plastic are both nonpolar, water would separate them from aqueous components. London dispersion forces, which result from induced dipoles, exist between molecules that are in close contact (6). Therefore, oil and plastic exert London dispersion forces on each other which strengthens temporary attraction between each other. As a result of the forces, when microplastic contaminated water is mixed with oil, the microplastics stick to the oil. Both palm oil and palm kernel oil, two common natural oils, have freezing points higher than that of water (7). Therefore, in between the freezing points of these oils and water, the oils solidify while water remains liquid. This allows the purified water to exit the system without oil leakage.

In this work, we hypothesized that when microplastic-polluted water is infused with a nonpolar solvent with a freezing point greater than that of water, the microplastics can be effectively separated from the water. We used a mathematical model to determine the energy requirement of this process and to estimate how long it would take to filter all microplastics out of the ocean. The experimental

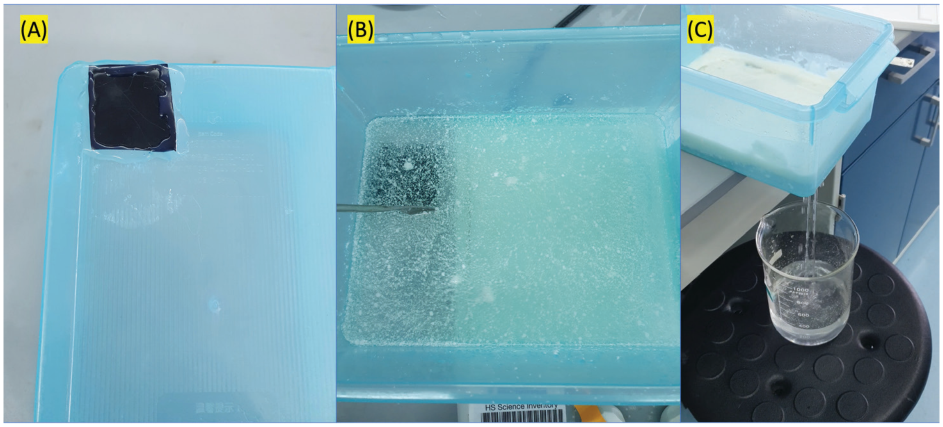

Figure 1: Major steps of microplastic filtration. (A) A piece of waterproof tape was glued onto the holes of the plastic box to prevent water leakage. (B) Natural oil was mixed with microplastic-infested water to separate the pollutants. (C) Tape was removed to discharge purified water after solidification of oil.

result showed microplastic filtration percentage of 94.2% or above for all trials. Calculations using the mathematical model showed that it would take an estimated 48.7 years to filter microplastics from the Pacific Ocean. The successful result of this research suggests a unique method of filtering microplastics from the ocean.

RESULTS

To test the effectiveness of using a nonpolar solvent with a freezing point greater than that of water to extract microplastics, we set up a lab-scale experiment using a plastic box to model the system **(Figure 1)**. Since polystyrene (PS), polyethylene (PE), and polypropylene (PP) are the most common types of plastics in the ocean, we performed experiments to test the effectiveness of the system for each type of plastic (8). To account for the variation of size among microplastics in the ocean, PE and PP were prepared in two sizes, 500 µm and 13 µm in diameter. Since uniformly sized PS was unavailable, Styrofoam balls were pulverized into microplastic powder. The original Styrofoam balls had a diameter of about 3 mm. The size of pulverized PS was assumed to be less than 3 mm **(Figure 2)**. When the microplastic-polluted water entered the box, it was mixed with liquid oil. The box was then placed inside a fridge to cool. It took about 15 minutes for 200 grams of palm kernel oil to freeze in the fridge. The temperature of the fridge was 12.1˚C. Since palm oil has a freezing point of 35˚C, it solidified at room temperature in 10 minutes. After the oil solidified, the purified water was discharged through holes at the bottom of the box.

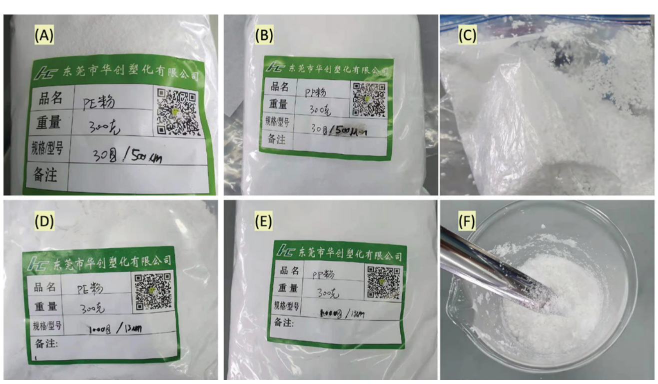

Figure 2: Purchase of plastic samples. (A) 500 µm PE; (B) 500 µm PP; (C) Styrofoam balls; (D) 13 µm PE; (E) 13 µm PP; (F) Blended PS. A blender was used to pulverize PS spheres.

We calculated filtration percentage by dividing the mass of microplastics filtered by the mass of original microplastics added in water. The greatest filtration percentage was 96.2% when using palm oil to filter 500 µm PS **(Table 1)**. When palm kernel oil was used to filter 13 µm PP, we achieved the lowest filtration percentage of 94.2% **(Table 2)**. Since the difference between the greatest and the least filtration percentage is only 2%, we concluded that this purification method works uniformly among different types of plastics. Control experiments without using oil showed 29.3% and 32.2% filtration **(Tables 1 and 2)**. The average filtration percentage of both palm oil and palm kernel oil were above 94% for all tested microplastics, suggesting that this purification method can effectively filter microplastics with sizes ranging from 13 µm to 500 µm in diameter. Furthermore, the qualitative analysis between palm kernel oil before filtering PP and after filtering PP shows clear evidence of purification **(Figure 3)**. We observed a drastic color change of palm kernel oil from gold and yellow to milky white after filtering, indicating that white PP powder is present in the oil after filtering.

Subsequently, we performed a calculation for the amount of energy needed to melt palm oil and palm kernel oil in order to discuss the energy efficiency of our filtration method. However, the heat of fusion values and specific heat values for these oils are not determined because they are heterogeneous in nature. Palm oil is comprised mostly of palmitic acid, stearic acid, oleic acid, and polyunsaturated linolenic acid (9). Palm kernel oil is mostly comprised of lauric acid, myristic acid, and oleic acid (10). Since the specific heat value for water is known, comparing it with each oil can estimate how much energy would be needed to melt each oil **(Figure 4)**. Since palm oil's melting point is 35˚C, its temperature must be

Type of oil	Remaining Polyethylene in grams	Remaining Polypropylene in grams	Remaining Polystyrene in grams	Percent filtered PE	Percent filtered PP	Percent filtered PS	Average percentage	Uncertainty*
Control (Without Oil)	3.459	3.928	3.211	30.8%	21.4%	35.8%	29.3%	±0.02%
Palm (Trial 1)	0.218	0.224	0.189	95.6%	95.5%	96.2%	95.8%	±0.02%
Palm (Trial 2)	0.209	0.239	0.191	95.8%	95.2%	96.2%	95.7%	±0.02%
Palm (Trial 3)	0.223	0.220	0.194	95.5%	95.6%	96.1%	95.7%	±0.02%
Kernel (Trial 1)	0.244	0.242	0.201	95.1%	95.2%	96.0%	95.4%	±0.02%
Kernel (Trial 2)	0.234	0.239	0.202	95.3%	95.2%	96.0%	95.5%	±0.02%
Kernel (Trial 3)	0.238	0.244	0.198	95.2%	95.1%	96.0%	95.4%	±0.02%

Table 1: Amount of 500 μm diameter plastics filtered. Table showing the percentage of 500 μm diameter microplastics of each type (PE, PP, PS) filtered by palm oil and palm kernel oil. Control experiment was performed without using a filter medium. *Uncertainty values obtained from Error Propagation rule.

Type of oil	Remaining Polyethylene in grams	Remaining Polypropylene in grams	Remaining Polystyrene in grams	Percent filtered PE	Percent filtered PP	Percent filtered PS	Average Percentage	Uncertainty*
Control (Without Oil)	3.184	4.034	2.948	36.3%	19.3%	41.1	32.2%	±0.02%
Palm (Trial 1)	0.282	0.274	0.271	94.4%	94.5%	94.6%	94.5%	±0.02%
Palm (Trial 2)	0.275	0.279	0.265	94.5%	94.4%	94.7%	94.5%	±0.02%
Palm (Trial 3)	0.283	0.264	0.259	94.3%	94.7%	94.8%	94.6%	±0.02%
Kernel (Trial 1)	0.270	0.287	0.264	94.6%	94.3%	94.7%	94.5%	±0.02%
Kernel (Trial 2)	0.279	0.271	0.244	94.4%	94.6%	95.1%	94.7%	±0.02%
Kernel (Trial 3)	0.280	0.292	0.278	94.4%	94.2%	94.4%	94.3%	±0.02%

Table 2: Amount of 13 μm diameter plastics filtered. Table showing the percentage of 13 μm diameter microplastics of each type (PE, PP, PS) filtered by palm oil and palm kernel oil. Control experiment was performed without using a filter medium. *Uncertainty values obtained from Error Propagation rule.

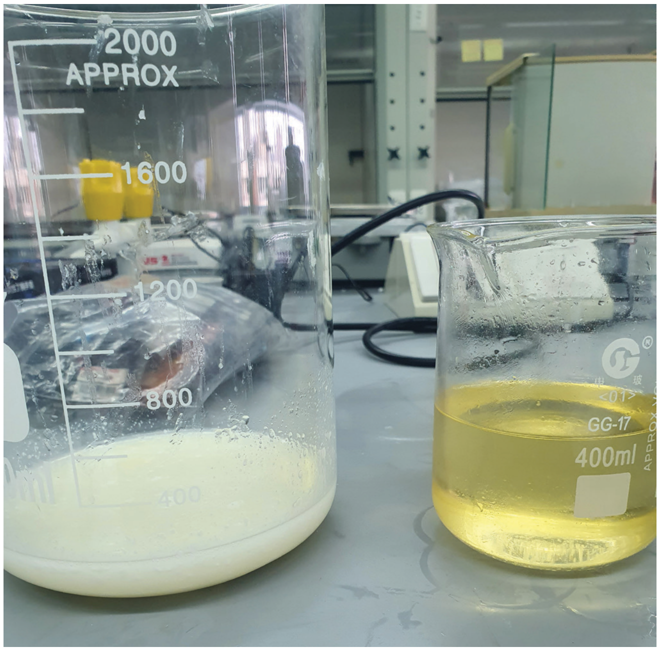

Figure 3: Qualitative analysis. Melted palm kernel oil after filtering PP (left). Palm kernel oil before filtering (right).

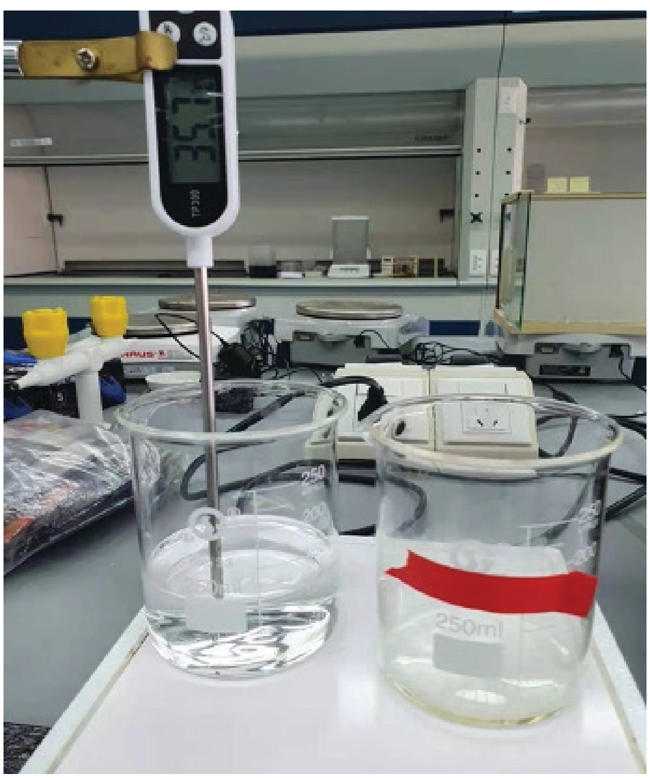

Figure 4: Setup to determine heat of fusion values. Two beakers with known mass were prepared on a hot plate. A thermometer was fixed using a metal clamp to prevent contact with the beaker. Solid oil was melted while water was heated to determine energy requirement for liquefying oil.

raised to its melting point before starting to melt. In contrast, palm kernel oil's melting point is around 25˚C (7). Palm kernel oil can melt at room temperature immediately without having to increase its temperature. Therefore 835.48 J is needed to melt 1 gram of palm oil at room temperature, while only 358.19 J is needed for palm kernel oil **(Table 3)**. The lower energy requirement for palm kernel oil indicates that it is more energy efficient and more scalable to the environment.

Real life application

The result of this study has major implications for large-scale applications outside a laboratory setting, and we designed a model to purify microplastics **(Figure 5)**. This system was designed to travel across areas of the ocean and filter microplastics. It would work in areas with a high concentration of microplastics, such as the Great Pacific Garbage Patch. In addition, the system could be integrated to existing ships to filter microplastics as they travel in the ocean. The sysem would be a long rectangular prism containing solid oil **(Figure 6)**.

An equation to represent the relationship between the amount of energy needed to purify a certain amount of water was devised in order to visualize the practicality of this research.

$$W = k \bullet O \quad (1)$$

$$E = Q \bullet D \bullet O \quad (2)$$

$$E = Q \bullet D \bullet \frac{W}{k} \quad (3)$$

Where W=Volume of water purified (L), k= Optimal Efficiency Constant, O=Volume of oil used (L), E1=Energy needed (kJ), Q=Amount of energy needed to melt 1 kg oil (kJ/kg), D=Density of oil (kg/L).

To determine how much energy is needed to purify a certain amount of water, the equation considers the amount of energy used to liquefy oil that purifies water. Equation 1 shows the ratio of how much oil is used to purify water. Equation 2 shows the amount of energy needed to liquefy a certain amount of oil. Combining Equation 1 and 2 produced Equation 3, which represent the amount of energy needed to purify a certain amount of water. If 1 L of palm kernel oil is used to purify 20 L of water, the constant k has a value of 20. Since 358.19 kJ of energy is needed to liquefy 1 kg of palm kernel oil, Q is 358.19 kJ/kg. The density of palm kernel oil is 0.8965 kg/L (11), so D=0.8965 kg/L. Plugging these values in Equation 3 gives E=321.117 kJ. This means that 321.117 kJ of energy is needed to purify 20 L of water when the oil-to-water ratio is set to be 1:20. We did not optimize the oil-to-water ratio in this research. Using less oil to purify water would increase the k constant and decrease the energy requirement according to Equation 3. However, using less oil could decrease the water purification percentage if the oil becomes saturated with pollutants more easily. Therefore,

Type of oil	Mass of Beaker 1	Initial temperature of water	Mass of Beaker 1 (with oil)	Final temperature of water	Mass of Oil	Amount of energy absorbed by water	Amount of energy needed to liquefy oil (joules/gram)	Uncertainty
Palm	99.461g	26.6˚C	104.016g	35.7˚C	4.555g	3805.62 Joules	835.48 J/g	±0.011 J/g
Palm kernel	99.555g	26.5˚C	104.552g	30.8˚C	4.997g	1789.89 Joules	358.19 J/g	±0.023 J/g

Table 3: Amount of energy required to liquefy oil. Table showing the steps of how heat of fusion values were calculated for palm oil and palm kernel oil. The known heat of fusion value of water was utilized in the experiment. *Uncertainty values obtained from Error Propagation rule.

the best ratio to purify water and minimize energy cost must be researched in the future.

To integrate our derived energy equations into a larger scale, we devised a series of equations to calculate the filtration capacity if the purification system were to be integrated on ships.

$$P_1 = (w \bullet l \bullet h - O) \bullet P_p \bullet \rho \qquad (4)$$

$$P_2 = \frac{\left((w \bullet l \bullet h - O) \bullet P_p \bullet \rho\right) \bullet d}{vt} \qquad (5)$$

$$P_f = P_i - N \bullet \frac{\left((w \bullet l \bullet h - O) \bullet P_p \bullet \rho\right) \bullet d}{vt} \qquad (6)$$

Where w=width of the system (m), l=length of the system (m), h=height of the system (m), O=Volume of oil in the system (m^3), P_p=Purification percentage in the experiment, ρ=concentration of microplastics in water (kg/m^3), P_1=Amount of microplastics filtered once by the system (kg), P_2=Amount of microplastics a ship can filter during its sail (kg), d=Distance travelled by the ship (km), v=Velocity of the ship (km/hour), t=Time it takes to run the system once (hour), P_i=Amount of microplastics initially present (kg), P_f=Amount of microplastics left after purification (kg), N=Number of ships on voyage.

Equation 4 solves for the amount of microplastics filtered once by the system integrated on a ship in kg. Equation 5 solves for the amount of microplastics filtered by a ship during its entire sail in kg. Equation 6 solves for the amount of microplastics left in the ocean after certain number of ships finished sailing.

MSC Gulsun is a container ship that has one of the greatest capacities. It is 400 meters in length, 61.5 meters in width, and 16.5 meters draught (11). If the system was designed to be attached at the hull of MSC Gulsun, it could have slightly smaller dimensions such as 350 meters in length, 50 meters in width, and 12 meters draught. Then, the capacity of the system would be w • l • h = 210,000 m^3. The Great Pacific Garbage Patch has an area of 1.6 million square kilometers and contains 80,000 tons of microplastics (3). Since the average depth of the ocean is 3.7 km, the volume

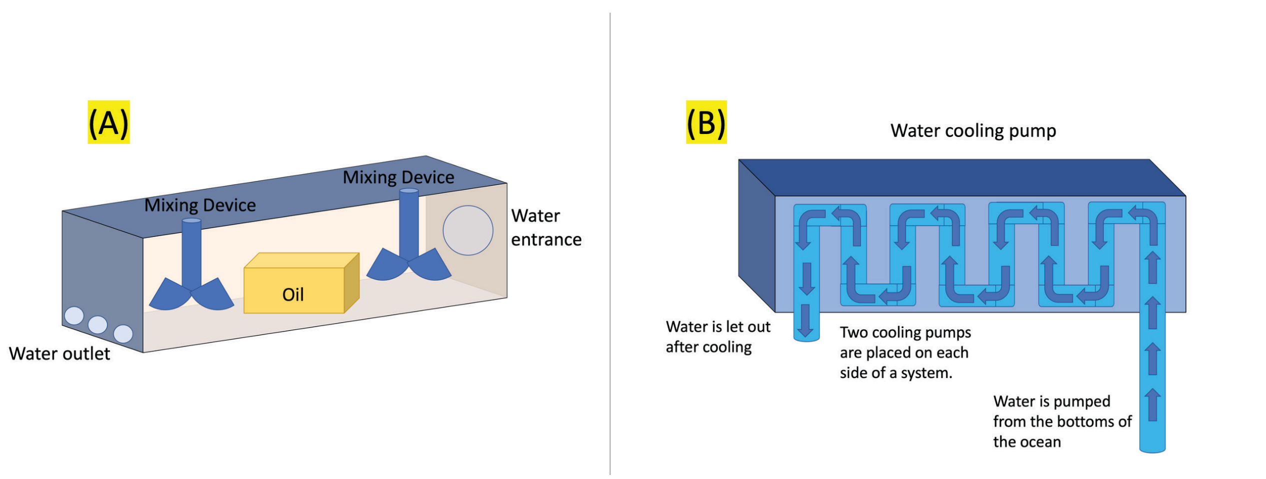

Figure 5: Design of an applicable system. (A) Inside of the system and (B) outside of the system. The system has a water entrance hole where sea water enters and a water outlet where filtered water exits. On the inside, it contains oil and mixing devices that help mix the oil with polluted water. On the outside, the system has a water pump that raises water from seabed to cool the system.

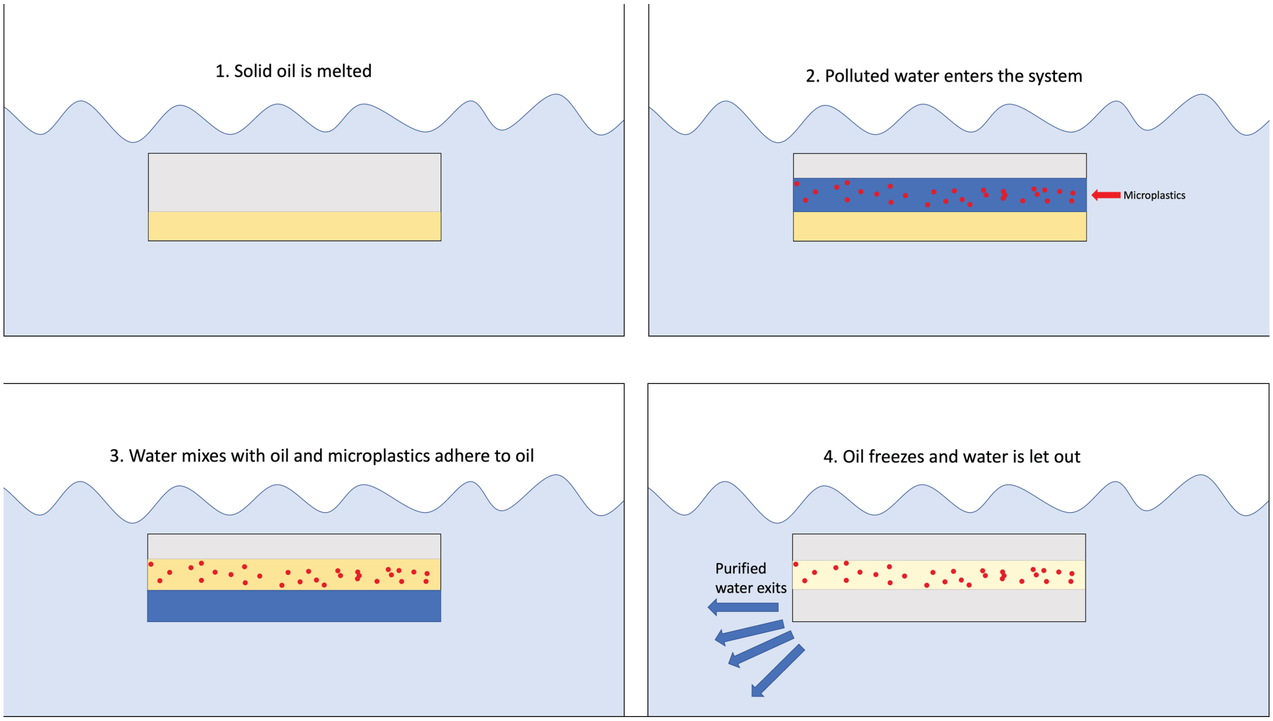

Figure 6: Integration of microplastic filtration into a large-scale system. Solid oil is first melted in the system. Then, polluted water enters the system. Red dots represent microplastics in water. Water mixes with oil, and microplastics adhere to oil. Water and microplastics separate. Lastly, oil solidifies, and water is discharged.

of the garbage patch could be estimated as 5.9 million cubic kilometers. Assuming that the density of microplastics is uniform in the ocean, the concentration of microplastics in the Pacific Ocean is $\rho = \frac{80{,}000 tons}{5{,}900{,}000 km^3} = 1.36 \cdot 10^{-8}$ kg/m³ P_p value can be estimated as 0.95 because the average purification percentage in our experiments was about 95% **(Table 1 and 2)**. If 100 m³ of oil is used to purify water, the amount of microplastics filtered by the system at once would be $2.70 \cdot 10^{-3}$ kg. Sea freight from the port of Hong Kong to the port of Long Beach, California, in the United States crosses the Pacific Ocean. The distance ships travel during the voyage is about 12,424 km, and the average velocity of ships is 24.076 km/hour (12). The system tested in the lab took about 10 minutes to run once. If we assume it takes 1 hour to run the actual system, the amount of microplastics a ship can filter during its entire voyage is 1.40 kg. According to Equation 6, $5.71 \cdot 10^7$ ships need to go through the freight in order to purify all microplastics in the Great Pacific Garbage Patch. Since there are only about 5,300 container ships in the world, it would take thousands of years to purify all plastics in the Pacific Ocean, even if all container ships were to go through the Pacific (13).

For practicality, a device specific to purifying microplastics should be built. Then, the system could roam around the garbage patch and purify water continuously. In addition, the size of the system can be larger since it does not have to perform tasks other than purifying water. For example, if a system has dimensions of 3 km in length and 1 km in width and height, the capacity of the system is $3 \cdot 10^9$ m³. If 10^8 m³ of oil is used, the amount of plastics filtered at once would be 37.468 kg. If it takes two hours to run the system once, the system can run about 12 times a day. It would take about 177,930 days, which is about 487 years. However, if there are 10 of these systems running in the Pacific Ocean, it would only take 48.7 years to filter all microplastics from the Pacific. Therefore, it would be more practical to build a system that exclusively purifies microplastics in the ocean rather than integrating it into existing ships. We can also estimate the amount of oil that would be used during the filtering process. If you consider the volume of the oceans to be $1 \cdot 10^{21}$ liters, at a 20:1 ratio $7 \cdot 10^{21}$ liters of palm oil is needed. This equates to $6 \cdot 10^{16}$ tons of palm oil. As only $7.55 \cdot 10^7$ tons of palm oil was produced during the past year (14), it is practically impossible to filter the entire ocean. The system should work in areas where microplastic concentration is the highest to maximize efficiency with a limited amount of palm oil supplied. In addition, further research on recycling the used oil is essential for the sustainability of our proposed system.

DISCUSSION

In this research, we hypothesized that nonpolar solvents with freezing point higher than that of water can remove the microplastics from the contaminated water. We set up a lab scale experiment to test the effectiveness of the proposed system. The experiment yielded successful results, with all filtration percentages being 94.2% or higher. We conducted another experiment to compare the energy consumption of palm oil and palm kernel oil. The result showed palm kernel oil to be the more energy efficient medium of filtration. This section discusses the possible limitations of our research and suggests topics for future research.

Comparing palm oil to palm kernel oil

Since the amount of energy needed to liquefy palm kernel oil is much lower than that of palm oil, palm kernel oil is more energy-efficient than palm oil. On the other hand, it is true that palm kernel oil does not freeze as easily as palm oil. As palm kernel has a melting point of 25˚C, it freezes at temperatures under 25˚C (7). The temperature of the ocean varies from 30˚C at sea surface to -2˚C at the seabed (15). Palm kernel oil would remain liquid on the surface of the ocean while palm oil would be solid at any depth in the ocean. Therefore, if palm oil were to be used as a filter medium, there would need to be a heating system that allows palm oil to remain liquid. Constantly applying heat is not only a waste of energy, but also an environmental threat as it can raise the ocean temperature and exacerbate global warming. In the case of palm kernel oil, a constant heating system is not necessary if the ocean temperature is above 25˚C. If the ocean temperature is below 25˚C, a heater would be needed, but the amount of energy required to liquefy palm kernel oil is much lower than that of palm oil. Therefore, the energy needs for a palm kernel filtration system are much less than that of palm oil. However, palm kernel oil would need a cooling system to solidify the oil after purifying polluted water since some ocean temperature is higher than 25˚C. Instead of using freezing technology to cool the oil, a water pump can be used to raise ocean water at the seabed to cool the oil since ocean temperature at seabed can drop to about -1˚C. Many existing ships already have marine cooling pumps, so it would be feasible to integrate them into our proposed filtering system. Overall, palm kernel oil is more energy efficient and poses less environmental threat than palm oil.

Limitations and implications

The box we used to model our filtration system in lab-scale was made of plastic. As a result, some oil adhered to the inner surface of the box. When the oil solidified in the cooling system, some oil adhered near the water drain. When the drain seal was removed to discharge purified water, small pieces of solid oil that formed around the drain came out with the purified water. Since the oil impurities did not pass through the filter paper, they were calculated as the mass of the unfiltered microplastics. This led to an artificially decreased percentage of microplastics filtered relative to the actual value. Therefore, the percentage of microplastics actually filtered would be higher than the calculated percentages. To resolve this error, a real scale system can adopt materials other than plastics such as metals to be used as filtration reservoirs. Further research is needed to devise methods to disallow oil from exiting the system, as this method of purification yields a solid mixture of oil and microplastics.

Control experiments without using oil showed about 30% filtration percentage for both 500 μm and 13 μm diameter microplastics. Although the filtration percentage is significantly less than when palm oil and palm kernel oil were used, this indicates that the system's structure itself has some filtration ability. As mentioned previously, this is likely due to using a plastic box to model the system. Microplastic particles can adhere to the plastic box and artificially increase the filtration percentage. Future research should incorporate a type of material that disallows microplastic adhesion to the modeled system.

In order for this method to be more practical, the oil used for purification must be able to be reused. There is a limited amount of oil available, so it is unsustainable to use new oil every time for purification. Further research is needed to devise a method to separate microplastics from oil.

In addition, the filter paper used in this research was grade 1 filter paper, which has pore size of 11 μm. Since some microplastics can be as small as 10 nm, microplastics smaller than 11 μm might not have been collected in this experiment. Further research is needed to verify the effectiveness of this purification method for filtering microplastics smaller than 11 μm.

Moreover, a major conflict with the use of palm oil has been the deforestation associated with its manufacturing. Cultivation of palm oil requires formation of palm oil plantations, which destroys forests and endangers animals inhabiting the area. Palm oil plantations cover more than 27 million hectares of the Earth's surface (16). Methods to reuse palm oil should be further researched to limit contributions to deforestation. Although this research used palm oil as a filter medium, there could be other nonpolar solvents that are easier to produce and pose less environmental threats than palm oil that can work as a filter medium. Further research is recommended to search for a more suitable nonpolar solvent that could be used as a filter medium.

MATERIALS AND METHODS

Filtering microplastics using a lab-scale system

A plastic box was prepared to model the system in lab-scale. Small holes were drilled at one corner of the box for water discharge. Waterproof tape and a glue gun were used to seal the holes. 500 mL of water was measured using a volumetric flask. Approximately 17.5 grams of NaCl were weighed using a scale. The water and NaCl were mixed in a 1 L beaker until all salt was dissolved. A hot plate was prepared at 70˚C. Two hundred grams of oil were measured in a beaker and melted on the hot plate. Another hot plate was prepared at 50˚C. The plastic box was placed on the hot plate without its bottom corner directly touching the hot plate to prevent the glue from melting. Five grams of microplastics were measured. The prepared water solution and microplastics were added to the box. The mixture was stirred for 1 minute. The liquid oil was added in the box, and the mixture was stirred for another minute. After mixing, the hot plate was turned off, and the box was moved to a cooling bath or a refrigerator. The box was cooled until the oil solidified. The tape was removed from the box, and the purified water was collected with a beaker.

Qualitative analysis

To qualitatively verify the effectiveness of the purification process, the solid oil after purification was obtained and melted to see if microplastics were present. Solution with microplastics is milky white while pure palm kernel oil has a gold transparent color. Although numeric calculation was not performed, the color differences pre- and post-filtration were observed.

Determining heat of fusion values for oil

Two 300 mL beakers of the same size with known mass were prepared. The beakers were placed on a hot plate set to 80˚C. A small amount of solid oil between 4 and 5 grams was prepared. One hundred milliliters of water were prepared. The temperature of the water at room temperature was measured using a thermometer. The prepared oil sample and water were simultaneously poured in each beaker on the hot plate. The thermometer was fixed with a ring stand and a metal clamp so that it measured the temperature of the water without touching the beaker. As soon as all oil became liquid, the temperature of the water was recorded. The mass of the beaker with oil was obtained using a scale. The amount of energy needed to liquefy 1 gram of solid oil was calculated using the heat transfer equation $q = m \cdot c \cdot \Delta T$. The diameters of the two beakers were identical and small enough for both beakers to completely fit on the hot plate. This allowed the amount of heat applied to each beaker to be almost identical, which was checked by using a thermometer to measure the temperature at different positions on the hot plate.

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