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Article

Integrated Ocean Cleanup System for Sustainable and Healthy Aquatic Ecosystems

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SUMMARY

In an attempt to find a natural alternative to the commercially used oil-spill adsorbents, we investigated natural adsorbents such as sugarcane, cotton, charcoal, and clay. It has been observed that, up to a certain limit, these materials can be used to clean up oil spills. In addition, particular combinations of these materials could perhaps increase the efficiency of the cleanup. Subsequently, we carefully tested the adsorbing efficiency of each natural adsorbent with oils of different viscosities. By prototyping with a small-scale model, we found that some materials adsorbed oil more than the others, with bentonite and activated charcoal having the highest capacity of up to 100% oil-water mixture adsorption in the first two passes and nearly 90% adsorption in the third pass. Creating different layers of different materials helped to better filtrate the oil-water mixture. Upon testing with seawater, the prototype that we developed was able to adsorb three passes of a mixture of equivalent volume with nearly 100% efficiency. This means that the natural adsorbents tested have comparable efficiency to commercially used nonwoven polypropylene, while being non-toxic to aquatic life and easier to dispose of. Here we describe in detail our studies and prototyping of an effective oil cleanup system.

INTRODUCTION

From their rich biodiversity to their biophysical and chemical buffer systems, aquatic ecosystems play a tremendous role in the biosphere. They comprise the hydrosphere, which houses marine flora and fauna, regulates the water cycle, and provides various resources for civilization. It's therefore essential to maintain a clean and healthy hydrosphere, as these ecosystems provide over half of the breathable oxygen present in air and consists of over 97% of the world's water. These ecosystems also provide nutrition to humans and animals and play a major role in the world's economy from transportation to marine-based investments.

However, the ocean has been contaminated with various kinds of plastics and large patches of oil that mainly collect at five points in the ocean, called the Great Garbage Patches (1). Some of these contaminants, however, do not get collected and are found floating on the ocean and seasides, killing numerous aquatic flora and fauna (2). The floating ocean debris has severely decreased the albatross population and killed over 100,000 marine animals each year (3). Oceanic wastes have been alarming to humans, and the seafood industry is inhibited by the harmful chemicals enclosed in the food chain. Modern non-governmental organizations have taken technological initiatives by using polymer sheets and ocean booms to attract plastic pieces together and destroy them (2). However, recent efforts are focusing on modern and eco-friendly means of ocean cleanup, which are sustainable and have the lowest carbon footprint (4).

With the rising need to clean up the polluted ocean, various methods have incorporated traditional and contemporary technologies. Several popular methods of cleaning up oil spills exist today (5). In-situ burning involves the controlled burning of the oil at the surface of oceans until there is very little or no spilled oil remaining. However, this method isn't always successful, and the fumes released could cause environmental pollution. Another method, natural degradation, also known as bioremediation, comprises the use of certain microorganisms that breaks down these complex oil molecules into non-toxic substances. A physical method is oil collection, which involves using booms to trap the spilled oil over the surface and collecting the oil in a vessel.

One of the most efficient methods of cleaning oil spills is adsorption (5). Adsorbents are materials that trap oil on their surface. For oil adsorption, nonwoven polypropylene has been used repeatedly due to its high water-adsorption capacity and low density. Due to its low cost, polypropylene has been used to clean oil spills around the globe. However, polypropylene disposal became a great issue for the environment as it is either burnt or left in the oceans afterwards (6).

In the wake of this issue, we decided to use natural materials to create a highly efficient ocean cleaner. We hypothesized that in opposition to the commercially used nonwoven polypropylene, a material with high oil affinity and natural origin is likely to have a lesser environmental impact and be sufficiently efficient in terms of the oil it adsorbs. In this paper we describe the efficiency of several adsorbent materials which could potentially be used as viable alternatives for present commercial adsorbents.

RESULTS

In a preliminary test with organic adsorbent materials such as cotton, coconut husk, and jute, the oil adsorbed appeared to be minimal [data not shown]. However, the few inorganic adsorbents that were tested exhibited significantly higher adsorption properties, thus we proceeded to test them with different oils.

We calculated the efficiency of each inorganic material in adsorbing kerosene, petrol, diesel, and engine oil as the ratio

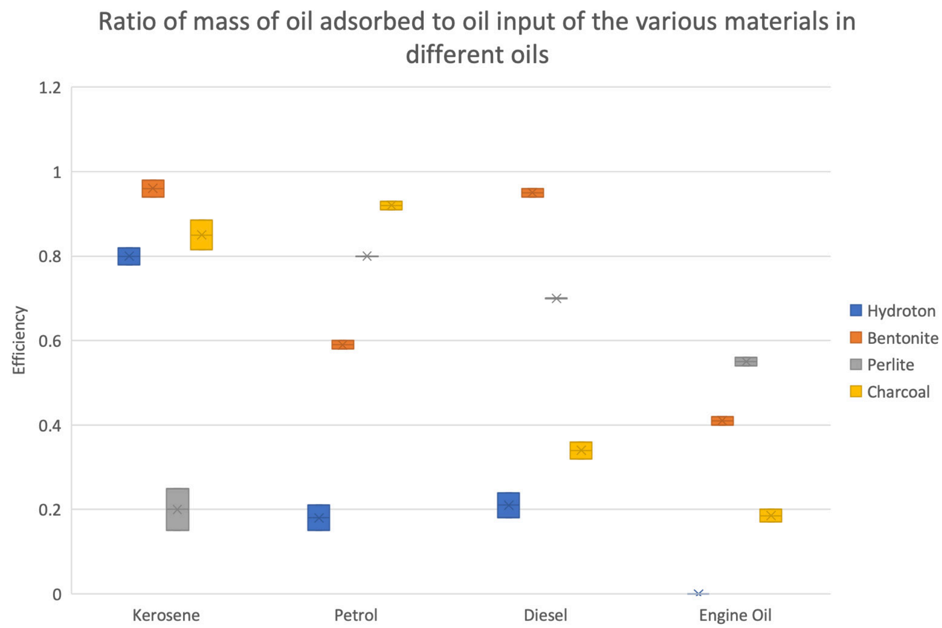

Figure 1. Efficiency of the various components of our prototype in oils of varying viscosities. The graph displays the percentage of oil-adsorbed to oil-input when bentonite, perlite, hydroton, and activated charcoal are introduced with four oils kerosene, engine oil, diesel, and petrol. The data from this figure was used to determine the order of materials incorporated into the prototype. On average, bentonite and activated charcoal displayed high oil-adsorption capacities overall.

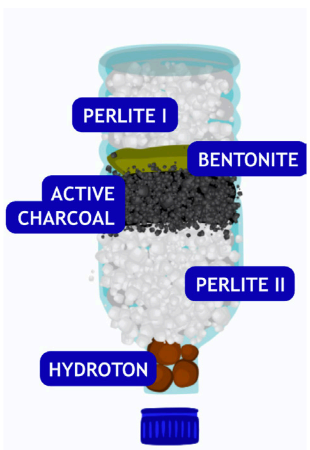

Figure 2. Prototype design. The prototype consisted of perlite, bentonite, activated charcoal, and hydroton layered in the order perlite-bentonite-activated charcoal-perlite-hydroton in the ratio 3:1:2:3:2. Results from Figure 1 and economic feasibility of each material were used to determine order and ratio.

of oil-adsorbed to oil-input (**Figure 1**). Bentonite on average showed the highest oil adsorption efficiency, while hydroton exhibited the least. Additionally, perlite served as a midline. Hence with all this data, we constructed a prototype composed of perlite-bentonite-activated charcoal-perlite-hydroton in the ratio 3:1:2:3:2 (**Figure 2**). The order of materials was decided based on their adsorption, placing the higher adsorbing materials towards the middle. The ratio composition was based on the economic feasibility of each material. For further experiments, the oil was an equal mixture of the three oils kerosene, petrol, and diesel since engine oil is much denser and viscous in comparison to crude oil (7).

As part of the oil-water emulsion test, we passed the equivalent weight (33 g) of oil-seawater emulsion through the apparatus. The first two passes were completely adsorbed by the apparatus. During the third pass, the apparatus collected 25 g of water, which was determined to be pure enough for household use. We inferred that the water adsorption capacity may have reached the maximum limit, meaning that the apparatus had successfully taken up 99 g of oil-water emulsion, but upon reaching the limit of adsorption, released 25 g of water as residue. For confirmation, we added 33 g of water once again to the apparatus following the end of the third pass, after removing the leftover residue from the conical flask. This experiment released 20 g of water into the conical flask, with infinitesimal but observable traces of oil.

To confirm the potential absence of oil in the filtrate from the third pass, we conducted a flame test. A filter paper dipped into the oil-seawater emulsion caught on fire almost immediately once introduced into a flame. The flame test with newspaper dipped in the filtrate from the third pass, however, did not catch fire, likely due to the considerably less or negligible amount of oil.

We conducted a Baeyer's reagent test, which is an experiment used to test the presence of oil in a solution. When testing the oil-seawater emulsion with Baeyer's reagent, we obtained a brown precipitate and clear purple supernatant. Hence, the presence of oil was confirmed by brown precipitate and the purple supernatant indicated clear water. With the filtrate-Baeyer's reagent mixture, the test

Media	Refractive Index
Pure distilled water	1.333
Seawater	1.349
Filtrate produced in the experiment	1.35
Crude oil	1.46

Table 1. Mean refractive index of the various tested media. This table displays the average of the calculated values of refractive indices we have measured in the refracting index test. The refractive index was calculated by passing a laser beam through a hollow rectangular prism containing the media and measuring the change in position of an object when placed in front of the prism.

NON-WOVEN PROPYLENE	RESEARCH PROTOTYPE
(C3H6)n Polypropylene	69% Perlite 13% Charcoal 7% Bentonite 11% Hydroton
Non-biodegradable	Highly biodegradable
Disposable / One-time use	Can be used as fuel
Artificial / man-made product	Natural / eco-friendly product
Can adsorb up to 15 times its weight theoretically. (9)	Experimentally could adsorb up to 3 times its weight before releasing some of the adsorbed water.
Hydrophobic and oleophilic	More oleophilic and less hydrophilic. Adsorbs both water and oil. Releases water, as the prototype has more affinity towards oil.
Harms aquatic ecosystem and harmful when consumed by animals.	Not harmful to animals, if large-scale model is implemented.

Table 2. Comparison between commercially used adsorbents to the prototype we constructed. We have used the data collected from our experiments as well as references from other research to compare our small-scale prototype and non-woven polypropylene.

produced a purple colored clear solution, with no precipitate. Typically, a brown precipitate is formed even when there are trace quantities of oil, and hence this experiment indicates that the presence of oil in the solution is <5%, making it safe for domestic usage (8).

Next, we performed an acrolein test, which tests for the presence of oil in a solution. In this test, when we added potassium bisulfate to the oil-seawater emulsion and heated the mixture, a potent smell was released. On the other hand, when only a mixture of seawater and potassium bisulfate was heated, the residue was odorless. When we performed the experiment on oil alone, it released a potent smell. When the filtered water from the third pass was tested with potassium bisulfate, the residue, again was odorless.

Lastly, we conducted a Refractive Index Experiment (**Table 1**). This provides a quantitative analysis which further supports the results of the qualitative experiments performed earlier.

DISCUSSION

Dense oils include grease, diesel, and petrol variants (5). Heavier oil particles are separated by oil booms having larger molecular surfaces. As each adsorbent material has a certain inherent adsorption capacity, we had to carefully select materials in order to maintain the efficiency and integrity of our apparatus.

Dense oil layers are selectively adsorbed by coconut husk, a natural oil-adsorbing material. Coconut husks have both oil- and water-adsorbing capacity; however, adsorbed water evaporates in the atmosphere relatively quicker than oil. Thinner oils pass through the husk layer to the internal layers. However, due to its poor capability in the preliminary test, coconut husk was not considered as an addendum to the prototype. In addition, the last layer of the prototype featured common clinical filter paper, to contain the internal layers of components.

Perlite is a natural metamorphic-igneous rock, which is similar in its properties to the commonly found pumice. Perlite is an amorphous volcanic glass that has a relatively high water content, typically formed by the hydration of obsidian. It occurs naturally and has the unusual property of greatly expanding when heated sufficiently. It is an industrial mineral and a commercial product useful for its low density after processing (6).

Activated carbon, carbon, and its derivatives are powerful absorbents of oil spills. In comparison to the commercially used polystyrene sheets are less powerful than carbon, charcoal, and ash as organic absorbent. Activated charcoal, adsorbs the oil molecules, and being oleophilic in nature, water-suspended charcoal particles attach itself to the oil molecules, making filtration easier. Moreover, perlite adsorbs the activated carbon particles, increasing its net efficiency. Activated charcoal has a high bonding area of 2,000 m^2 per gram, which attracts organic molecules to itself making it an excellent adsorbent (6).

Bentonite is an absorbed aluminum phyllosilicate clay, which is known for its natural healing properties. Bentonite particles are the finest among the ones present in the prototype, but they are very porous with a large surface area. This increased surface area contributes to larger oil adsorption. Since the density of oil is less than water, it adsorbs the oil molecules more than water. Research has shown that bentonite clay can adsorb up to 100% oil in relative quantity, in barely the first pass itself, while other materials can achieve 100% only after many passes (6).

The refractive index of the filtrate from the third pass lies very close to that of seawater, and there is a tremendous displacement from the refractive index of crude oil (**Table 1**). This again shows that the filtrate contains negligible amounts of oil.

Our prototype was made of 100% natural materials potentially lessening harm to the aquatic organisms and marine biome (10, 11). These natural adsorbents are very efficient in combating oil spills. In addition, our prototype is also more oleophilic as compared to commercial adsorbents. The materials used in our prototype are highly biodegradable and can be used as fuel once served its purpose (**Table 2**). Based on tests and research of various sorbents on various oils, we decided to form a layer-by-layer filtration unit. The ease to build and cost-effectiveness makes it an even advantageous alternative to models used commercially. We could use an integrated system that could be used as a microcontroller or mini-CPU for propelling the rover. Solar power could be used to fuel this mechatronic and thereby makes it an eco-friendly module.

Here we've proposed a new model of a sustainable ocean cleanup module that can be used for cleaning up oil spills in oceans. It incorporates completely natural components such as bentonite, activated charcoal, perlite, and hydroton arranged in layers within a prototype (**Figure 2**), and these components adsorb the oil-seawater emulsion with an adsorption capacity of up to 100% in the first two passes of water, and with nearly 90% adsorption rate in the third pass. The model proposed was tested in terms of efficiency and a set of experiments were performed to describe the purity of the seawater that was released from the third pass thereby demonstrating its efficiency. Further developments and ideas were also proposed to further advance the project.

If our model was implemented on a large scale, there could be an immediate response system to an oil spill; the once spilled oil that was deemed unusable could be reused as a source of fuel, and it would make the vast deep blue ocean into a sustainable marine biome.

MATERIALS AND METHODS

A number of natural materials including cotton, coconut husk, jute, activated charcoal, bentonite, hay, vegetable fibers, sand, hydroton, and perlite were tested for oil adsorption by passing oil equivalent to the weight of the adsorbent used. This experiment was performed twice.

After the finalization of the adsorbents, testing was conducted to furnish a rough analysis of the volume of each adsorbent that needs to be used in the prototype. Four types of oils were used, namely kerosene, petrol, diesel, and engine oil. The test consisted of passing equivalent mass of each oil through each of the adsorbents and finding the ratio of oil adsorbed to oil input. This test was performed twice.

For the oil-water emulsion test, a mixture of oil and seawater was passed through the prototype shown in Figure 2. The oil used was a combination of diesel, petrol, and kerosene. To begin with the experimentation, 33 g (equivalent weight of the apparatus), where 30 g was seawater and 3g was oil (about 9.1% of the emulsion was oleic), was added to the laboratory prototype. This was recorded as Pass I. A second pass of the same 33 g of the oil-water emulsion was added into the prototype from the end of the first pass. The third pass was tested with 33 g of the oil-water emulsion, added to the prototype from the end of the second pass. This whole experiment was carried out twice, with two nearly identical prototypes, and the average data was reported.

In the flame test, a sheet of newspaper was dipped into both the oil-seawater mixture and the filtrate received after Pass III, and then burnt. We also performed the Baeyer's reagent test with the oil-seawater mixture as well as the filtrate. We added Baeyer's reagent equivalent to the volume of the sample used. In the presence of unsaturated compounds, the color of the solution turns to brown, and finally disappears, otherwise remains purple, in accordance with the color of potassium permanganate ($KMnO_4$). Next, we performed the acrolein test. According to this experiment, a solution to which potassium hydrogen sulfate is added, releases an irritating odor when heated in the presence of organic compounds. We performed this test by adding potassium hydrogen sulfate equivalent to volume of the sample used to oil-seawater emulsion, seawater, oil, and the filtrate from Pass III. The final test for confirmation is to check the refractive indices (12) of the filtrate, oil, and seawater. We did this by passing a laser beam through a hollow rectangular prism containing the filtrate and oil-water emulsion and measuring the change in position of an object when placed in front of the prism. The flame test and acrolein test were performed only once, however, the Baeyer's reagent test and the refractive index test was conducted thrice; the refractive index test was precise up to 0.01 and the average data was reported.

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