

**Utilizing a Multi-Functional Remediation
Framework for the Development and Lifecycle
Assessment of a Novel System for the
Concurrent Removal of Soluble Ocean Carbon
Dioxide and Oil-in-Water Contaminants**

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Utilizing a Multi-Functional Remediation Framework for the Development and Lifecycle Assessment of a Novel System for the Concurrent Removal of Soluble Ocean Carbon Dioxide and Oil-in-Water Contaminants

I. Abstract

The oceans absorb nearly a third of airborne CO₂ emissions, while concurrently, 1.3 million gallons of crude oil are spilled into oceans every year. Both issues continue to detrimentally affect marine biodiversity, and human health. This research provides a highly efficient/practical method for the concurrent removal of CO₂ and soluble oil-in-water contaminants through the creation of a Multi-Functional Remediation Framework (MF-RF) utilizing hypercross-linked polymers (HCPs), synthesized from Styrofoam. First, Styrofoam HCPs were synthesized according to Dong et al. HCPs alone remediated 88% of the 1.7g/L-soluble-benzene in seawater (via measure of benzene's fluorescence). Regarding CO₂ 95% of the contaminant was removed, or $3.12E^{-3}M[CO_2]=[H^+]$ (via pH measure). For the MF-RF, HCP-sponges were constructed on 8x1.3x0.7cm of melamine, with PTFE adhesion, and 450mg HCP for pollutant removal/capture. The MF-RF remediated 92% of the 1.7g/L-benzene contaminant, and 95% of CO₂. Realistic concurrent oceanic experiments with a 0.1pH difference and maximum solubility of benzene highlight 92% remediation of oil, with only 12.6min needed to reach suitable oceanic pH. High-load concurrent removal experiments with 100x more CO₂ demonstrate 71% remediation of oil and 85% remediation of CO₂. Via recycle/reuse studies, the MF-RF may be reapplied until its capacity is reached (5.99g oil/HCP-sponge and 3700ppmCO₂/HCP-sponge) and then simply lifted out for contaminant recovery/recycling.

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III. Key words:

Oil spills, soluble oil, carbon dioxide, ocean acidification, Styrofoam, plastic pollution hyper cross-linked polymers, remediation, multi-functional,

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IV. Abbreviations and Acronyms

| | |
|---|-----------------------------------|
| MF-RF: Multi-Functional Remediation Framework | PTFE: Polytetrafluoroethylene |
| FeCl ₃ : Iron (III) chloride | FDA: Formaldehyde dimethyl acetal |
| SEM: Scanning Electron Microscopy | DCE: 1,2-dichloroethane |
| EDS: Electron Dispersion Spectroscopy | kV: Kilovolt |
| ATR-FTIR: Attenuated Total Reflection Fourier-Transform Infrared Spectroscopy | DI: Deionized |

V. Acknowledgments:

I would like to thank my science research teacher, Mr. Andrew Bramante, for his invaluable guidance and support throughout the research process. His assistance included teaching in the various instrumentation needed to execute the analyses required for this research.

VI. Biography:

Naomi Park is currently a junior at Greenwich High School and has been a part of the GHS Honors Science Research Program since her freshman year. Her interests in science and engineering have been long standing and started in third grade when she tried to combat hand cramps by creating a sensor that would attach to a writing device and emit a red light based on the tightness of one's grip. It was called *Pressure Pen*, and although its impact was seemingly small it lived as the impetus of her interests in scientific research. By experiencing a problem firsthand, and creating an innovative solution, she was inspired to tackle other real-world problems through science.

Additionally, she has a passion for teaching and created a cost-free, eight-week science research after school program at her local elementary school. Beyond science research, she is the President and Founder of Generation Green, a student-led nonprofit organization in Greenwich dedicated to increasing sustainability in her community. Naomi has also been chosen as one out of 100 rising seniors in the world to attend the Research Science Institute (RSI) hosted by MIT to conduct original science research under the tutelage of a current MIT professor this summer. She is particularly interested in nuclear science and the intersection of the field with environmental engineering and hopes to contribute towards significant advancements in this area. In her free time, she loves listening to music and hanging out with friends!

1. Introduction:

1.1 Problem:

The atmospheric concentration of carbon dioxide is increasing at an unprecedented rate due to the burning of fossil fuels such as coal, oil, and gas. The oceans presently absorb nearly a third of all carbon dioxide emissions, and future estimates indicate that by the end of the century, the world's oceans could be nearly 150 percent more acidic, resulting in the lowest known pH for more than 20 million years. This phenomenon is known as ocean acidification and if left unchecked, will continue to detrimentally affect the future of human health, marine biodiversity and function of various ecosystems. Additionally, oil spills release 1.3 million

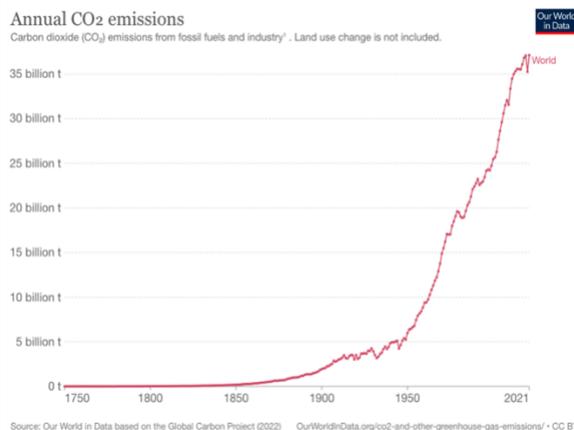


Fig 1, Annual carbon dioxide emissions from 1750-2021 (image courtesy of: Our World in Data)



Fig 2. Oil boom remediation (Image courtesy of: UN environment programme)

gallons of toxic crude oil into the ocean yearly, posing severe health risks to humans, including heart damage, stunted growth, and immune system effects. Aquatic species are also adversely affected, with up to 25,900 animals dying annually due to the heavy pollutants. Traditional methods of crude oil remediation, such as oil booms only remove visible surface contamination. Currently, there is limited research on effective ways to remediate the soluble oil that often gets left behind but is equally as harmful. Finally, plastic pollution continues to cause irreparable damage to ecosystems. More specifically, Styrofoam waste as it is one of the hardest materials to recycle, given its polystyrene content. Hyper cross-linked polymers (HCPs) represent a class of nanoporous materials, which have gained recent attention in the past to be used as environmental sorbents to capture and remove various harmful pollutants. However, the synthesis of HCPs is typically achieved using costly reagents. Recent literature by Dong et. al, demonstrates the development of cost-effective HCPs by using Styrofoam waste. However, there are still many shortcomings with this technology which is primarily why they remain stagnant in

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literature. Most notably is regarding methods of implementation. HCPs currently resemble an insoluble powder indicating that once contaminants are absorbed there is no effective retrieval or removal method for the now contaminated HCPs. Additionally, the creation of a multi-functional remediation system to concurrently remediate more than one pollutant represents an unexplored area of research.

1.2 Engineering Goal:

This primary objective of this research is centered around the creation of a remediation device that is both cost-effective and environmentally friendly via application of Styrofoam HCPs. The created device aims to be practically applicable and meaningful in its implementation, unlike current HCP implementation methods, specifically targeting the removal of crude soluble oil and carbon dioxide pollutants from water, while concurrently lowering the ecological footprint of Styrofoam waste.

1.3 Materials:

- Rigid sound-absorbing melamine foam sheet 1” (*McMaster-Carr*)
- Waste Styrofoam (density of 22.3kg/m³) from product packaging materials
- Iron (III) chloride (FeCl₃)
- 1,2-dichloroethane (DCE)
- Formaldehyde dimethyl acetal (FDA)
- Chloroform
- Acetone
- Methanol
- PTFE Dispersion (15%) in Water (*FuelCell Store, SKU 72500300*)
- Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) Spectrometer
- Scanning Electron Microscope (SEM) with an Energy Dispersive X-Ray Detector (EDS)
- Gyrotory Shaker

1.4 Safety:

All reagents used in this research will be used in strict accordance with the supplier’s MSDS. Specifically, all work will be carried out within a fume hood, while the student researcher wears gloves, goggles, and a lab apron. All waste from this research will be collected, and disposed of along with other organic waste, at the conclusion of the school year, using Clean Harbors Waste Management.

2. Fluorescence Detection of Oil-in-Water

Fluorescence spectroscopy can detect as little as 10^{-9} M oil contaminants in water.

The fluorescent properties of Mobil 89 Octane were evaluated on a Perkin Elmer LS50B luminescence spectrometer. Mobil 89 is complex mixture of alkanes ranging from 5-12 carbons, as well as lesser amounts of heavier aromatic hydrocarbons. Each aromatic component would have a specific excitation and emission spectrum:

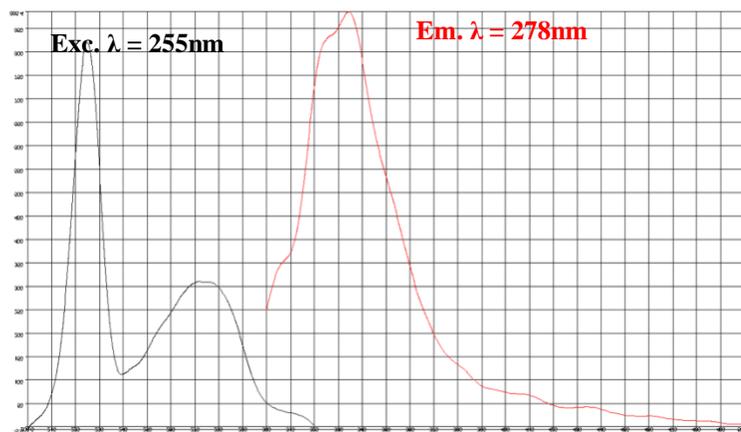


Fig 3. Excitation (black) and Emission (red) spectra of 1.7g/L Benzene from Gasoline contaminated water

deconvolution of these emission spectrum would be difficult. Instead, the fluorescence of benzene, contained in gasoline, was identified, isolated, and used to quantitate the removal of gasoline contaminants from water. The excitation/emission spectral combination of 255 nm and 278 nm, corresponds to that of benzene, and was found to have the highest quantum yield for a saturated solution of gasoline in water (Fig. 3). The emission scans of 0.106-1.7g/L oil-in-water calibration standards were measured (Fig. 4A), and the intensity at 278nm plotted against concentration, to produce the linear relation $y=517.51x$, with an $R^2 = 0.9976$ (Fig. 4B).

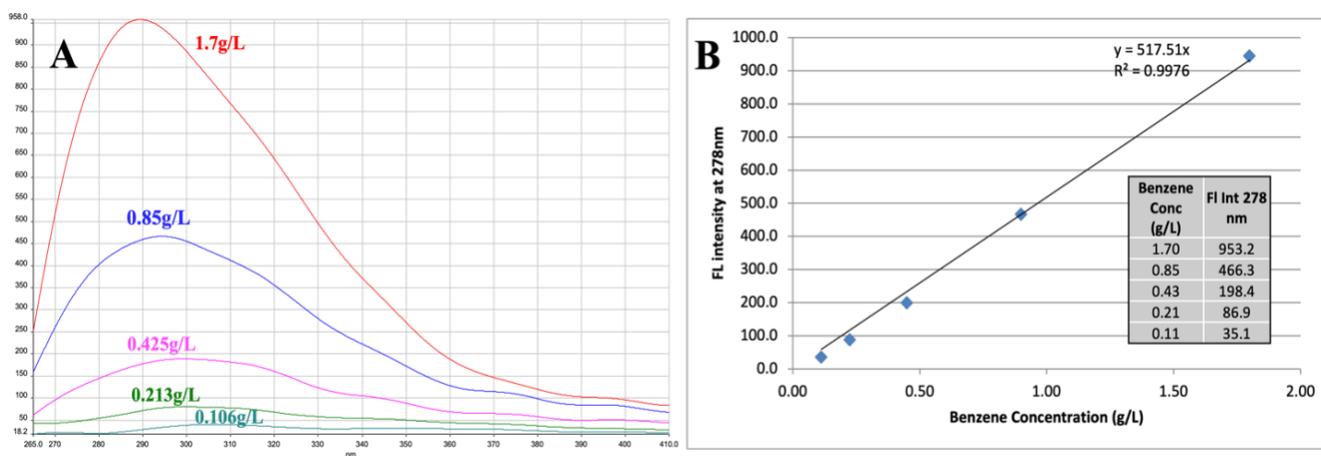


Fig. 4A: Emission Spectra of 0.106 -1.7g/L serial dilution standard of Oil-in-Water. 4B: 278nm emission intensities were plotted against concentration to produce a Benzene in Water Calibration Plot

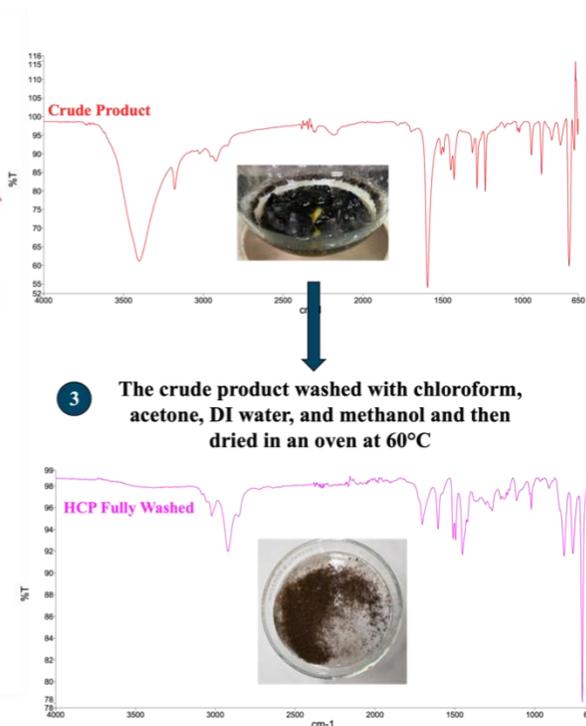
3. Fabrication of Hyper Cross-linked Polymers (HCPs)

1 Addition of:

- 1g FeCl_3
- 1.16mL formaldehyde dimethyl acetal (FDA)
- 1g Styrofoam upon dissolution in 50mL dichloroethane (DCE)



2 Refluxed and stirred for 12 hours at 60°C



3 The crude product washed with chloroform, acetone, DI water, and methanol and then dried in an oven at 60°C

Fig 5. Schematic of the fabrication of the Styrofoam hyper cross-linked polymers outlined by procedures according to Dong et al.

To synthesize the hyper cross-linked polymers (HCPs), 1g of Styrofoam dissolved in 50mL of dichloroethane (DCE), 1g of FeCl_3 , and 1.16mL of formaldehyde dimethyl acetal (FDA) was added to a round-bottom flask and the mixture was stirred and refluxed for 12 hours at 60°C. The crude product was then analyzed via ATR-FTIR Spectroscopy and subsequently washed with chloroform, acetone, deionized water, and methanol. The obtained product was dried in an oven at 60°C, yielding a brown powdery product. Finally, the dried and washed HCPs were analyzed via ATR-FTIR and Energy Dispersive (EDS) X-ray spectroscopies. Comparison to the FTIR spectrum provided in the paper by Dong et al. highlights its successful fabrication. Furthermore, EDS

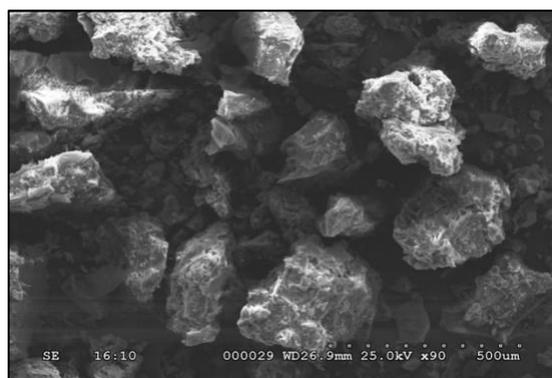
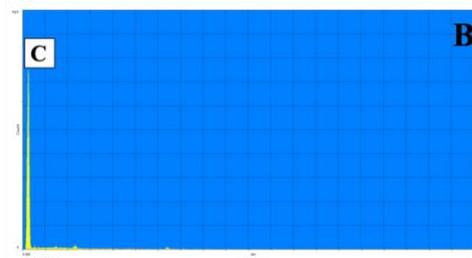


Fig. 6a (above): x400/18kV SEM image of the dried and washed HCPs; Fig. 6b (below): Energy Dispersion Spectrum of HCP highlights carbon content of the HCPs



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analysis highlights the main constituent of the HCPs to be carbon, suggesting that the HCPs are simply a complex C-H, nonpolar compound.

4. HCP Remediation of CO₂ and Oil in Seawater

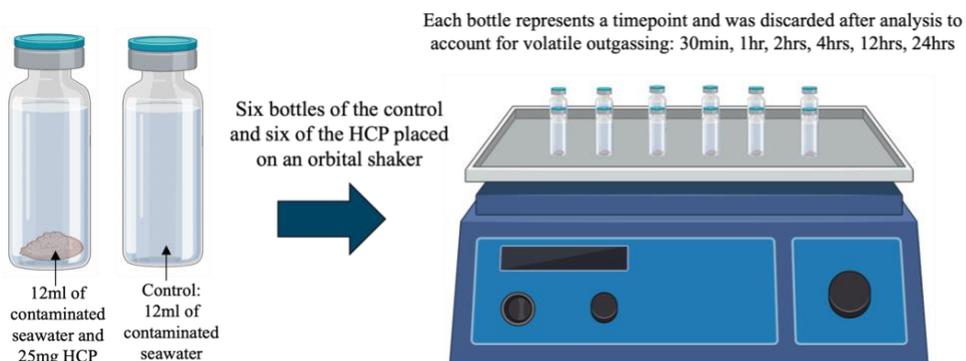


Fig 7. Schematic of the Experimental Setup

CO₂ and crude soluble oil experiments were carried out with six, 12ml bottles of just the contaminated water as the control and six 12ml bottles of the contaminated water and 25mg of the washed HCP. Each bottle represented a time point: 30min, 1hr, 2hrs, 4hrs, 12hrs, and 24hrs and was discarded after analysis to account for volatile outgassing. To simulate ocean waves and movement, each bottle was taped onto an orbital shaker for continuous movement throughout the testing period. Regarding soluble oil remediation, at each timepoint, the solution was analyzed via fluorescence spectroscopy whereas CO₂ remediation was quantified via a relative increase in pH.

4.1 Oil in Seawater Remediation:

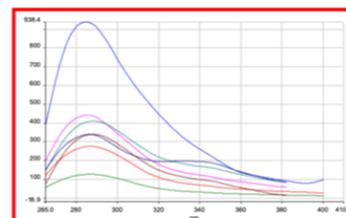
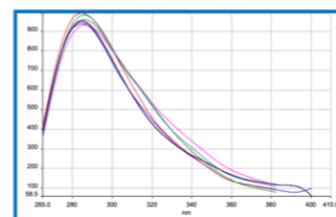
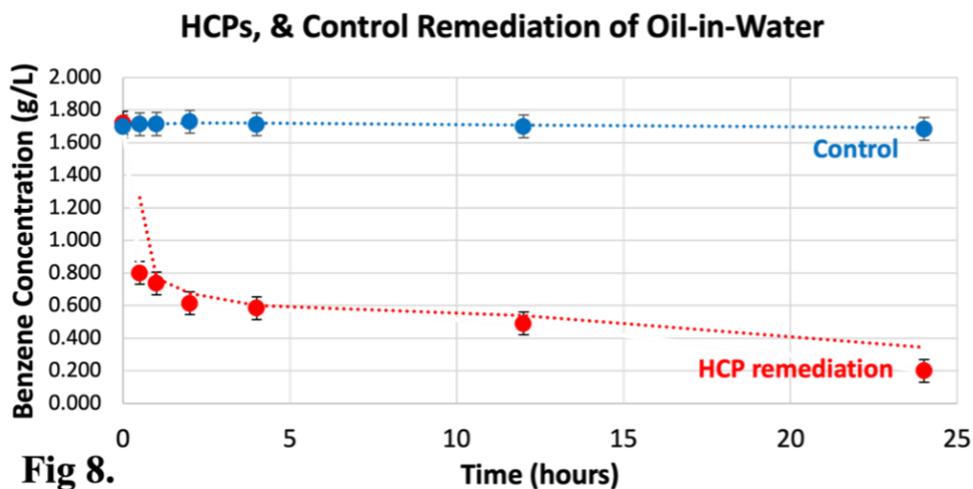


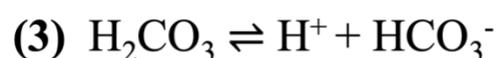
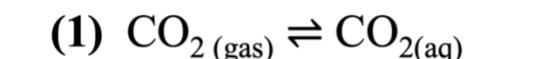
Fig 8.

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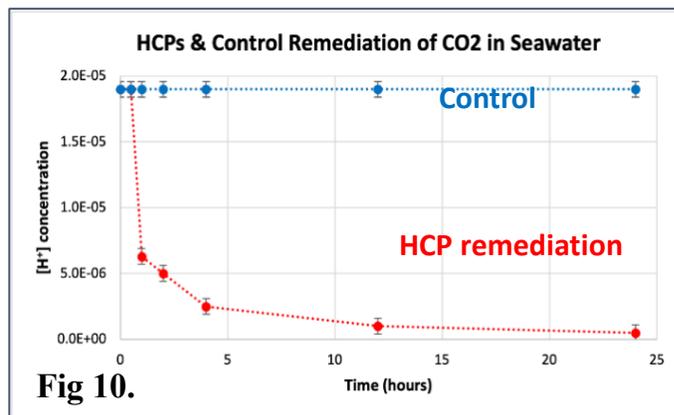
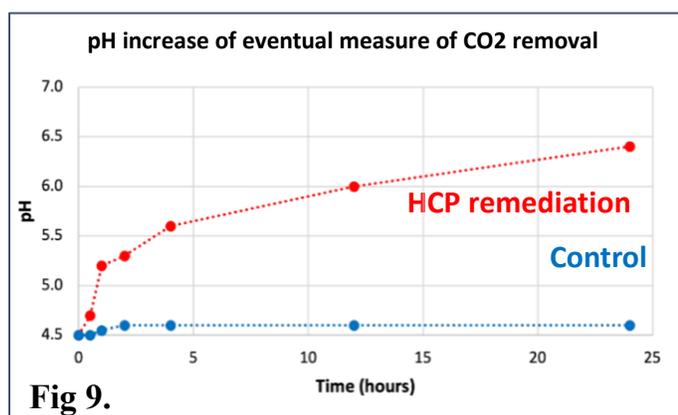
At each time point, the solution was analyzed for benzene content via its fluorescent emission at 278nm, with a 255nm excitation. In the first 30 minutes of water treatment, more than ½ of the oil contaminant was removed, with up to 88% remediation in 24 hrs. As expected, there was no decrease in the control over 24 hrs highlighting the effectiveness of the newly-created measurement methodologies (Fig. 8).

4.2 CO₂ in Seawater Remediation

As can be seen in the mechanism, as CO₂ is removed, based on Le Chatelier's principle, the H⁺ concentration would in turn decrease, causing the pH to increase. Furthermore, CO₂ remediation was measured indirectly as a function of H⁺. At each time point, the solution was analyzed with a pH meter for a relative pH



increase. As expected, there was little to no increase in the control over the testing period. Adversely, for the HCPs, the pH increased from 4.5-6.4 over 24 hours, indicating 95% remediation (Figs. 9-10).



5. Construction of Multi-Functional Remediation Framework

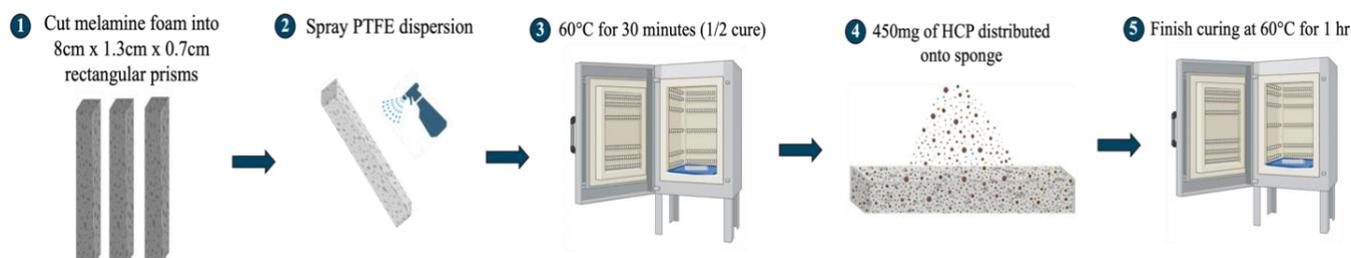


Fig. 11: Schematic of the construction of the HCP-sponges

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The proposed design of the Multi-Functional Remediation Framework (MF-RF) includes: a melamine sponge to act as the base, a 15% polytetrafluoroethylene dispersion to act as the binding agent and the hyper cross-linked polymers for pollutant removal and capture. To synthesize the MF-RF, melamine foam sheets with pore sizes of $\sim 150 \mu\text{m}$ were cut into rectangular prisms with the dimensions of 8cm x 1.3cm x 0.7cm. The PTFE dispersion was then liberally applied via spraying and the layer (on sponges) was half-cured for 30 minutes. After the first cure, 450 mg of the HCP were distributed onto the sponge and placed back in the oven for the final curing of 1 hour at 60°C . Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy (ATR-FTIR) and Scanning Electron Microscopy (SEM) were used to provide evidence for the successful development of the MF-RF, at each step of its construction. First, comparison of the ATR-FTIR spectra of Figs. 12A-C (*insets*) highlight the coverage of the melamine sponge first with PTFE (12A vs. 12B), then the successful inclusion of HCP on the surface of the completed MF-RF (*noted by red circles in 12C*). Similarly, SEM images demonstrate PTFE coverage, and surface HCP inclusion.

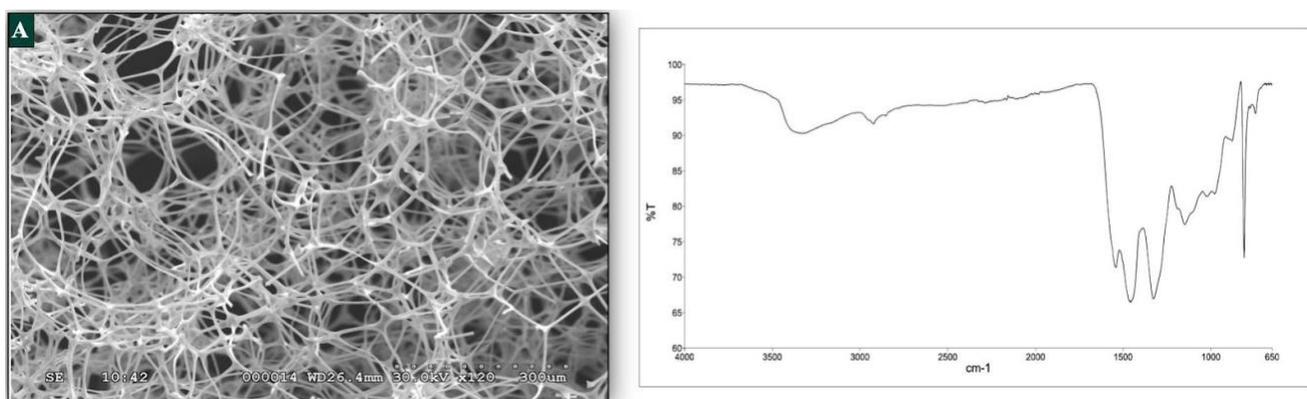


Fig. 12A: $x120/30kV$ SEM image and ATR-FTIR spectrum of the clean melamine sponge.

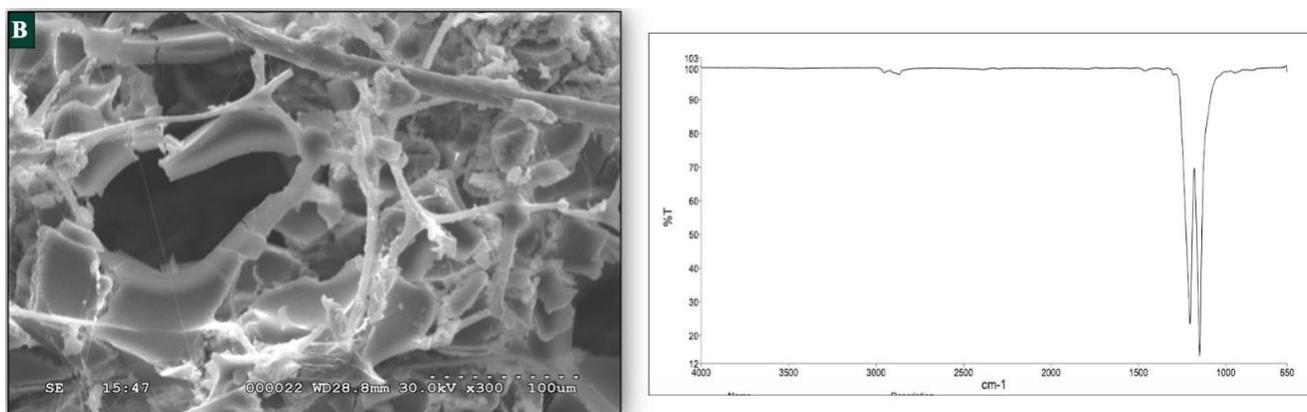


Fig. 12B: $x300/30kV$ SEM image and ATR-FTIR spectrum of the melamine sponge coated with PTFE

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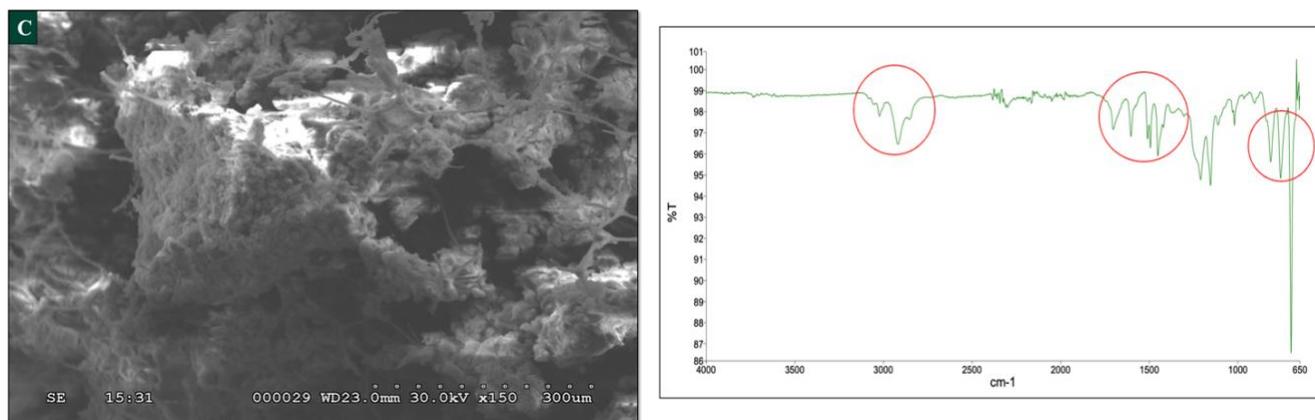


Fig. 12C: x150/30kV SEM image and ATR-FTIR spectrum of the HCP, PTFE, and melamine sponge

5.1 Air-tight Modeling of MF-RF Function:

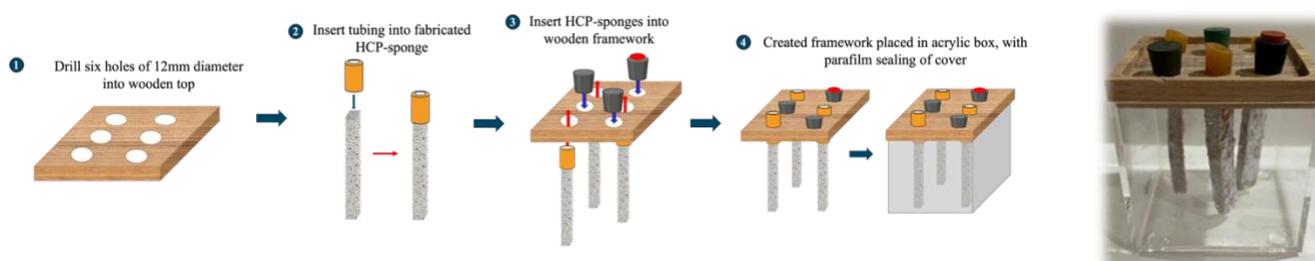


Fig 13: Schematic of the construction of the air-tight modeling of MF-RF function

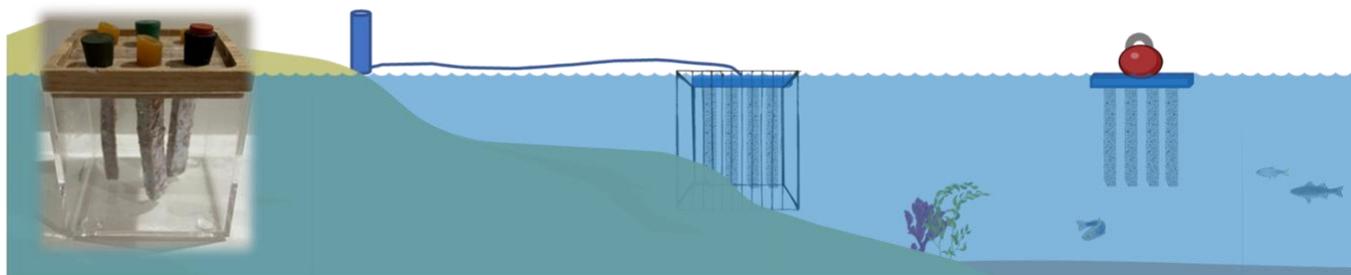
To construct the testing receptacle, six holes of 12mm diameter were drilled into a wooden top. Then, the HCP-sponges were inserted into tubing of the same diameter to then be inserted into the constructed wooden framework. A red rubber septum, or liquid draw port was glued onto a rubber stopper with a hole for access to the solution for analysis to prevent volatile outgassing.

6. Proposed Design of the Multi-Functional Remediation Framework

The completed MF-RF device can be implemented either at the shoreline (via tethering), or at deep sea depths, using a buoy. Additionally, an eco-friendly enclosure will be built around the device to prevent MF-RF disruption and consumption (Fig. 14).

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Fig. 14: Schematic of the proposed implementation of the MF-RF



7. Measure of MF-RF Remediation in Seawater

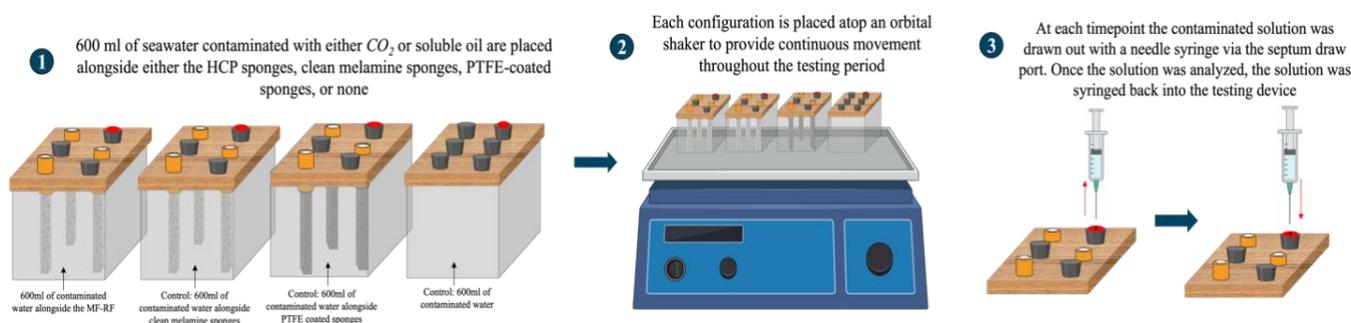
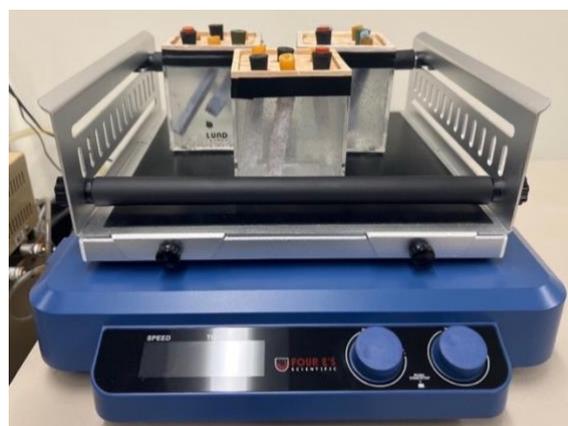
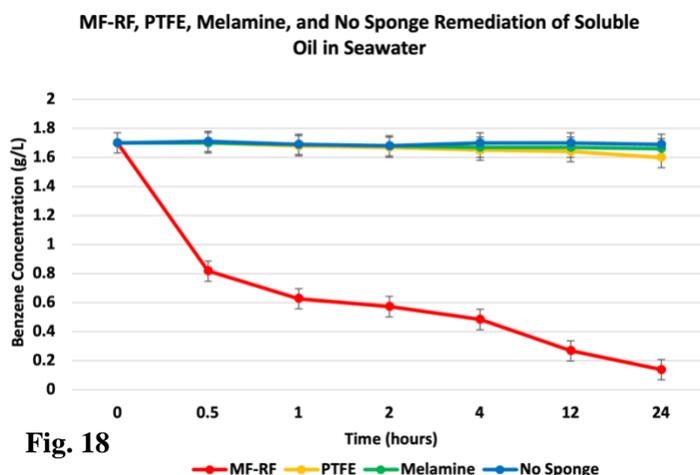
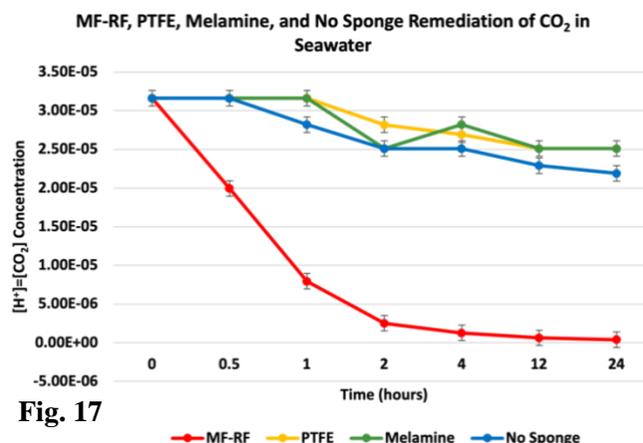
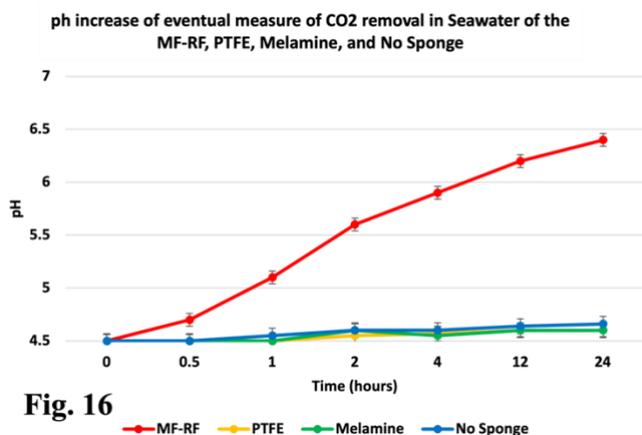


Fig. 15: Schematic of the Experimental Process

Remediation experiments were carried out with HCP-sponges, PTFE coated sponges, a plain melamine sponge, and no treatment. For each configuration, the constructed air-tight modeling receptacles were filled with 600ml of respective contaminated water (soluble oil or CO_2). To simulate ocean currents, each trial was placed on an orbital shaker, for continuous movement over the testing period. At specific time intervals, the contaminated solution was drawn out using a needle syringe from the designated liquid draw port, analyzed, and then reintroduced into the testing device. The analysis was performed at time 0, 0.5, 1, 2, 4, 12, and 24 hours to monitor the remediation progress. As expected, for the untreated and PTFE controls, there were no or $\sim 5\%$ (respectively) remediation of solution. However, the HCP-sponge treatment in seawater resulted in significant remediation, with a removal efficiency of approximately 92% for 1.7 g/L of benzene contaminant and 95% for CO_2 (equivalent to $3.12E^{-5}M [CO_2] = [H^+]$).

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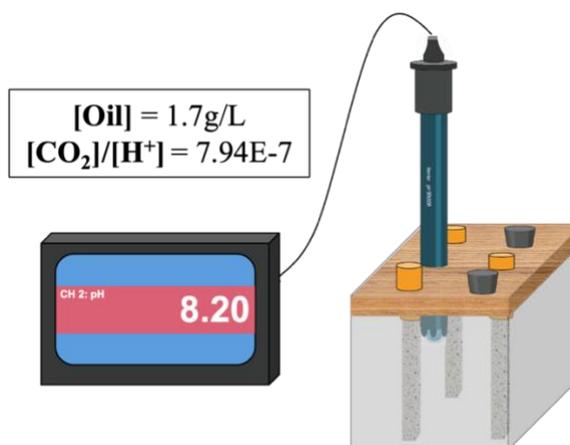


8. Concurrent removal of CO₂ and Oil in Seawater

8.1 Realistic Concurrent Remediation:

The development of a device to simultaneously remove multiple contaminants is an area of research that has not been thoroughly explored. To address this gap, experiments were conducted to assess the effectiveness of the HCP-sponge in remediating both soluble oil and CO₂ under realistic oceanic conditions. The oceanic CO₂ concentration increased from 310 ppm in 1955 to 400 ppm in 2015, resulting in a 0.1 decrease in seawater pH. Although a small difference, each pH unit decrease represents a ten-fold increase in acidity. As such, realistic oceanic experiments with a 0.1 pH difference

Fig 19a: Schematic of the Experimental Setup of the Concurrent Realistic Oceanic Trials



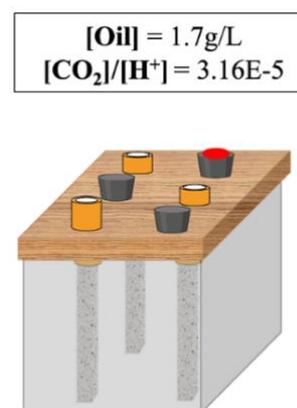
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and maximum solubility of benzene were carried out. The MF-RF remediated 92% of the oil in 24 hours, with only 12.6 minutes to reach a normal a pH of 8.2. Unlike past remediation trials, where pH measurements were obtained by withdrawing solution, the recent trial employed a Vernier pH sensor within the solution to obtain real-time measurements of the pH levels. This approach was necessary because the difference in pH that needed to be measured was only 0.1.

8.2 High-load Concurrent Remediation

With the efficacy of both contaminants established, high-load concurrent remediation was conducted. The concentration of soluble oil was kept the same, however, the concentration of CO₂ was increased 100x to push the device to its limits in a shorter amount of time. The results indicate that even when the concentration of CO₂ increased by two orders of magnitude, the device was able to remediate 71% of the oil contaminant (1.2g oil) and 85% of the CO₂ (3.09E⁻⁵M [CO₂]). These experiments demonstrate that while having duality of function, even when concentrations are significantly increased, the device still performs efficiently.

Fig 19b: Schematic of the Experimental Setup of High-load Concurrent Remediation Trials



9. Reuse Study

9.1 Recycling of HCPs



- 1 HCPs post oil remediation was taken out of the testing bottle and placed atop the diamond of an ATR-FTIR spectrometer

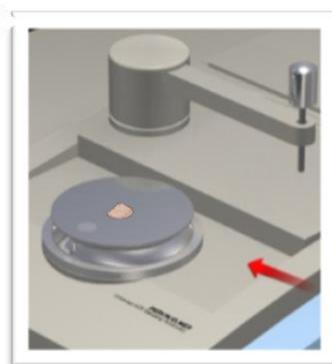


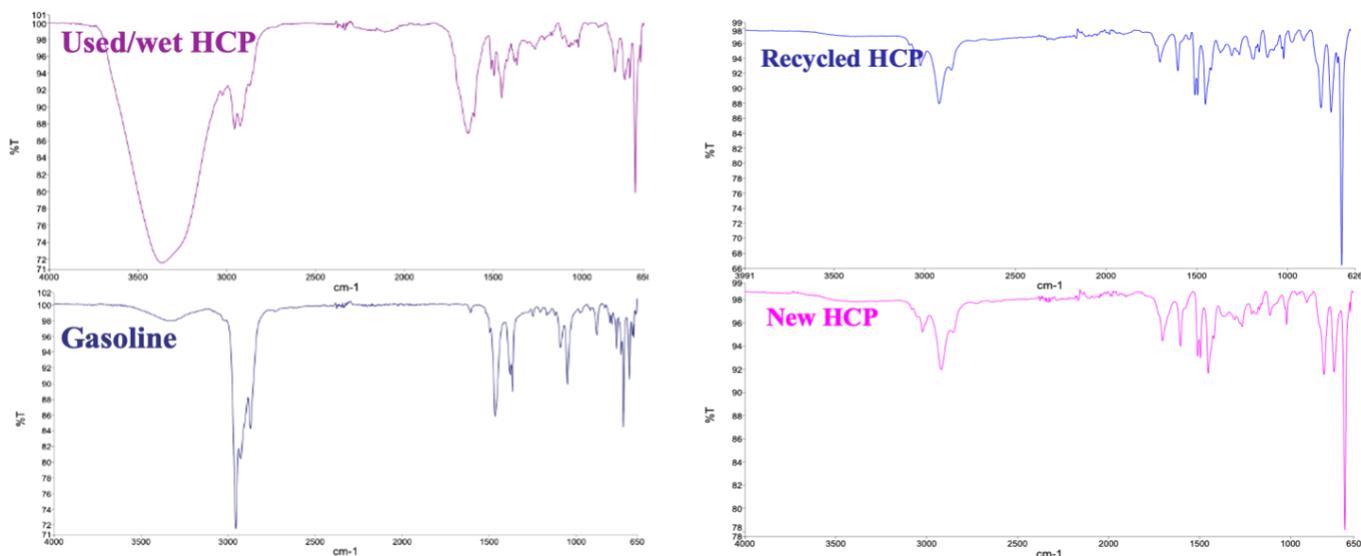
Fig 20. Recycling of Used HCPs

- 2 Once the spectrum of the used/wet HCP was taken, the HCP was then dried, and its spectrum taken

To test the recyclability of the HCPs itself, a post oil remediation trial HCP was taken out, placed atop an ATR-FTIR spectrometer and its spectrum was taken. Then, the spectrum of the dried HCP was taken. FTIR analyses highlight that following the removal of crude soluble oil, the spectrum of the dried HCPs

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closely resembled that of new HCPs. This demonstrates that the HCPs were not significantly altered or degraded by the remediation process and remain viable for potential reuse and recycling.



9.2 MF-RF Reuse

To test the reusability/recyclability of the device itself as well as corroborate the HCP-sponge's capability in remediating crude soluble oil and carbon dioxide, a used HCP-sponge was transferred to a 250ml bottle and heated at 30°C for 15 minutes. 20ml of the headspace was drawn

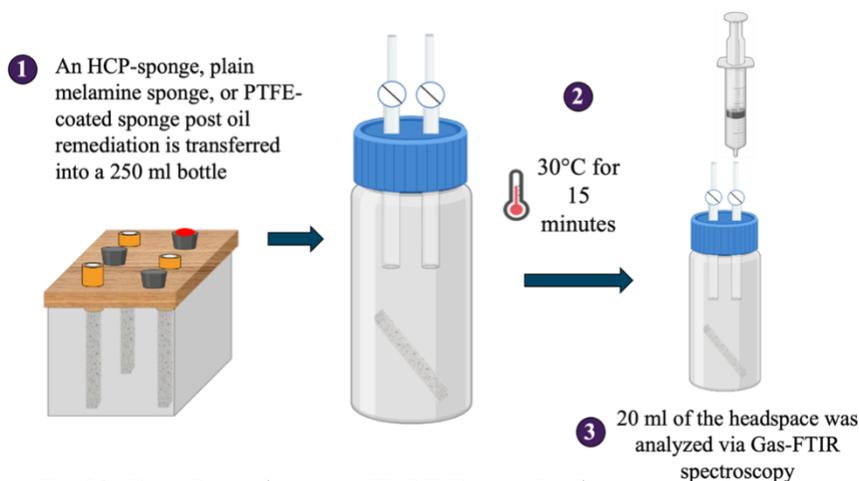
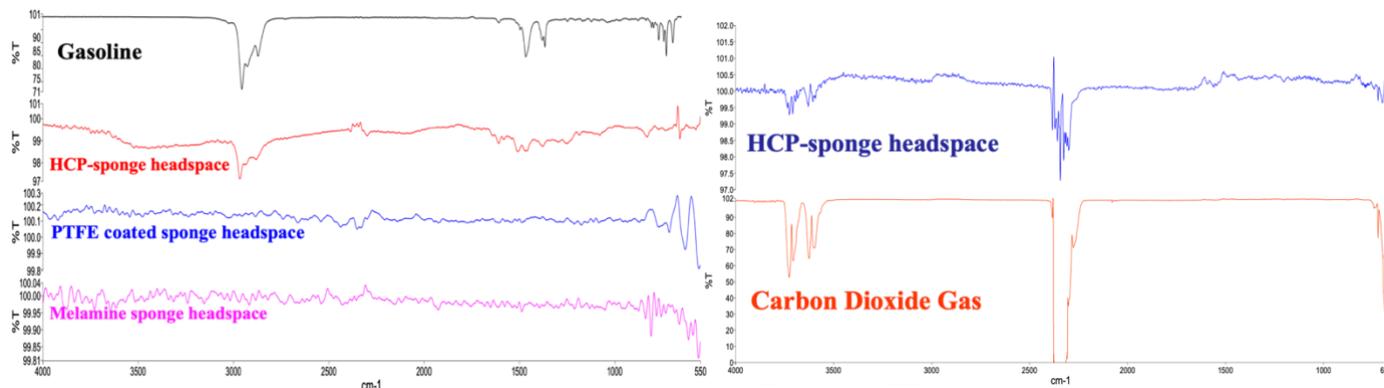


Fig 21. Post Remediation MF-RF Reuse Study

out with a syringe and injected into an FTIR Gas cell. This process was repeated with the melamine sponge and a PTFE-coated sponge. Gas-FTIR analyses of the HCP-sponge headspace demonstrate that, following the heating process, only the contaminant was detected (gasoline and carbon dioxide), suggesting that none of the other components of the sponge were lost or degraded, which highlights the durability and potential for reuse of the HCP-sponge. Furthermore, given that no gasoline or carbon dioxide was detected in the headspace of the PTFE-coated sponge and melamine sponge, it can be inferred that the gasoline

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was selectively adsorbed to the HCPs within the HCP-sponge, providing further evidence of its efficacy in remediation.



10. MF-RF Longevity

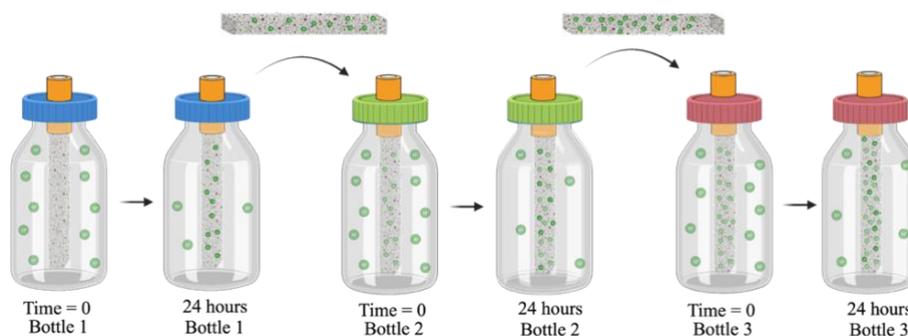
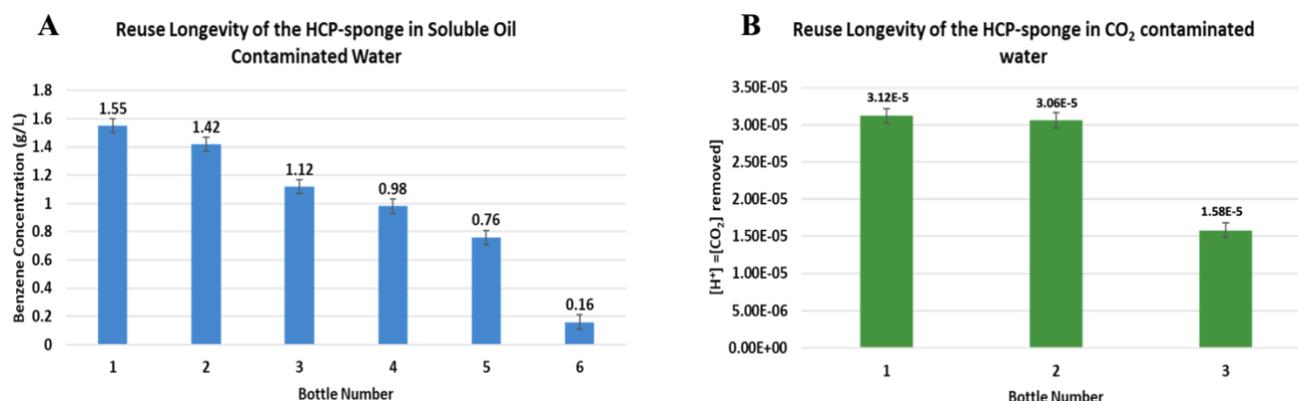


Fig. 22 Schematic of CO₂ Longevity Trials to Reach Extended Remediation Capacity

To examine extended remediation capacity, an HCP-sponge was first put into contaminated seawater (CO₂ or soluble oil) and left on the gyratory shaker for one day. The solution was analyzed via fluorescence spectroscopy or pH meter, dependent on the type of contaminant being tested at the end of the 24 hours. The sponge was then transferred to another, fresh contaminated solution for similar t_0 and 24-hour analyses. This cycle was repeated separately for each contaminant, until no further remediation was exhibited by the sponge.



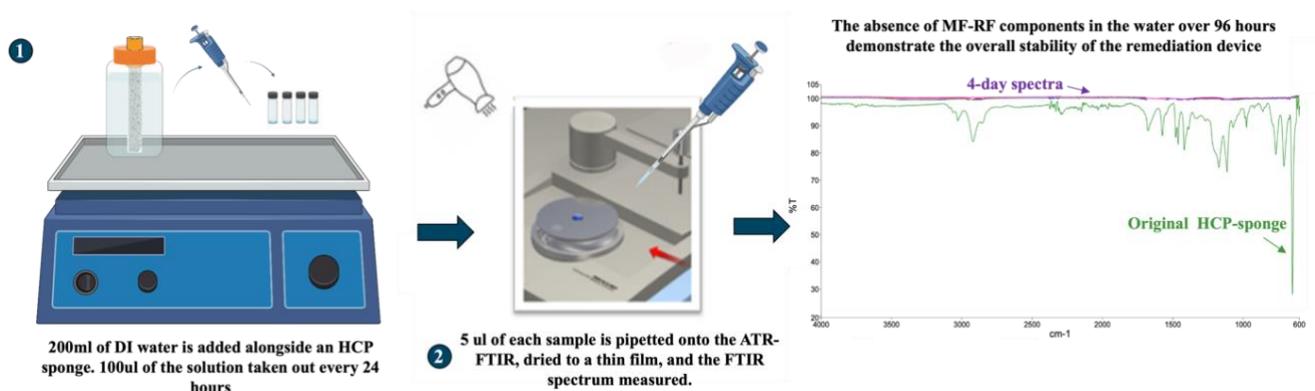
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Fig. 23A: Possible Reuse Longevity of the HCP-sponge in soluble oil contaminated water demonstrated in six “Reuse” cycles. Fig. 23B: Possible Reuse Longevity of the HCP-sponge in CO₂ contaminated water demonstrated in three “Reuse” cycles

Experiments evaluating the reuse and longevity of the HCP-sponge device indicate that, when deployed in seawater contaminated with soluble oil, each 7.3cm² HCP-sponge can effectively remove up to a maximum of 5.99g of oil. Additionally, when the HCP-sponge is exposed to seawater contaminated with CO₂, it exhibits a maximum removal capacity of 3700ppm of CO₂.

11. Stability and Integrity of HCP-sponge

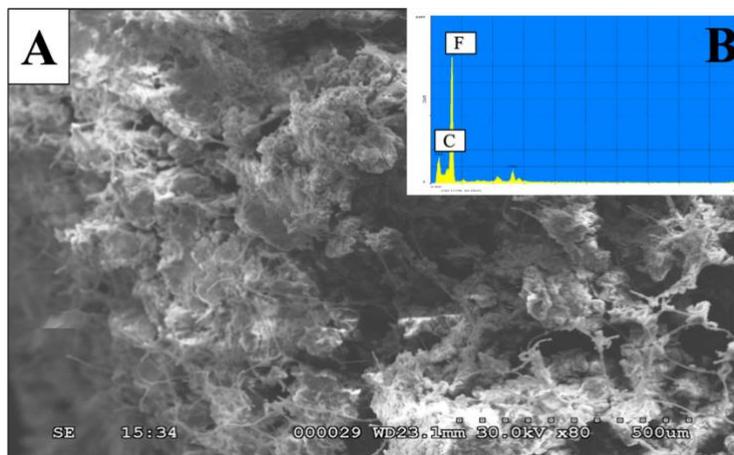
Fig. 24: Schematic for the evaluation of HCP-sponge stability



In order to test the stability of the HCP-sponge and its constituents, an HCP sponge was placed in 200ml deionized water, and placed on a gyratory shaker to simulate ocean waves/currents for a total of 4 days (Fig. 21). At 24-hour intervals, 100µl of the solution was removed, and for each time point/sample, 5µl was placed atop the diamond of an ATR-FTIR spectrometer and dried to a thin film. The FTIR spectrum was measured for each timepoint. The resulting ATR-FTIR spectra up to 96 hours are free of HCP sponge components, suggesting that the remediation device is stable over time, and safe for marine life.

SEM analyses were conducted post remediation and longevity trials. EDS analyses confirm the consistent presence of fluorine and carbon, the HCP-sponge components of PTFE and Styrofoam HCPs, highlighting the continued HCP-sponge stability over prolonged use (Figs. 25a-b).

Fig. 25A-B (right): (A): x80/300kV SEM of the HCP-sponge post remediation and longevity trials; (B): EDS spectrum of figure 25A.



12. Discussions and Conclusions

The detrimental threat and danger CO₂ emissions and oil spills have on oceans has already been well established in literature. The research presented herein provides a highly efficient/practical method for the concurrent removal of CO₂ and soluble oil-in-water contaminants through the creation of a Multi-Functional Remediation Framework (MF-RF) utilizing hypercross-linked polymers (HCPs), synthesized from plastic waste. First, Styrofoam HCPs were synthesized through a one-pot Friedel–Crafts reaction according to Dong et al. HCPs alone remediated 88% of the 1.7g/L-soluble-benzene in seawater (via measure of benzene’s fluorescence). Regarding CO₂, 95% of the contaminant was removed, or $3.12 \times 10^{-5} \text{M}[\text{CO}_2]=[\text{H}^+]$ (via pH measure). For the MF-RF, HCP-sponges were constructed on $8 \times 1.3 \times 0.7 \text{cm}$ (7.3cm^2) of melamine with with PTFE adhesion, and 450mg HCP for pollutant removal/capture. The MF-RF remediated 92% of the 1.7g/L-benzene contaminant, and 95% of the CO₂. Realistic concurrent oceanic experiments with a 0.1 pH difference and maximum solubility of benzene highlight 92% remediation of oil, with only 12.6min needed to reach suitable oceanic pH. High-load concurrent removal experiments

with 100x more CO₂ demonstrate 71% remediation of oil and 85% remediation of CO₂ highlighting duality of function. Via recycle/reuse studies, the MF-RF may be reapplied in contaminated water until its capacity is reached (5.99g-oil/HCP-sponge and 3700ppmCO₂/HCP-sponge). Additionally,

regarding possible implementation, oil booms only remove visible surface contamination. The oil on top is constantly releasing toxic soluble oil into the surrounding water. To mitigate this, the

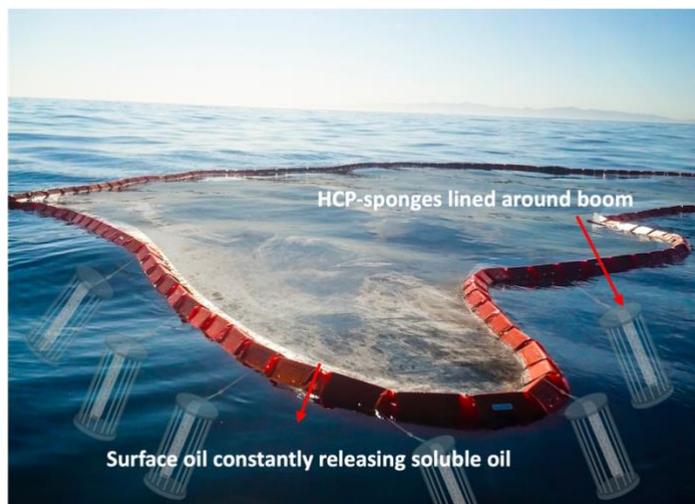


Fig. 26. Possible implementation of HCP-sponge for oil recovery and remediation

HCP-sponges will be lined around the boom to capture the soluble oil before it contaminates the surrounding water. As such, modeled by previous experiments, it would take five days for the sponges to reach capacity and subsequently taken out. Reuse studies highlight that once saturated, the soluble oil in the sponges can be reused and repurposed for its intended use of home heating or transportation. In terms of CO₂, based on concurrent and maximum capacity trials, it would take six tested HCP-sponges (2 frameworks) to increase the pH of ocean water by 0.1 in 57.2KL of water (roughly the size of a backyard pool). Implementation of the MF-RF for CO₂ remediation is envisioned for ocean acidification hotspots

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which inhabit a myriad of calcifying organisms that have been the most detrimentally affected by ocean acidification. All while the MF-RF is remediating, Styrofoam waste would be further prevented from ending up in a landfill. Stability studies demonstrate prolonged MF-RF integrity, as a marine-safe, easy-to-use oil and CO₂-remediation tool, costing \$1.50/framework which is simply lowered into contaminated water, left until saturated, and then lifted out for contaminant recovery/recycling.

| | Styrofoam HCPs | | MF-RF | | High-load concurrent | |
|---------------------|----------------|----------------------------|--------|----------------------------|----------------------|----------------------------|
| Contaminant | Oil | CO ₂ | Oil | CO ₂ | Oil | CO ₂ |
| % Remediation | 88% | 95% | 92% | 95% | 71% | 85% |
| Quantity remediated | 1.496g | 3.12E-5 M[H ⁺] | 1.564g | 3.12E-5 M[H ⁺] | 1.207g | 3.09E-5 M[H ⁺] |

Table 1: Summary of remediation efficiencies exhibited by tested devices

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