Banana Bark as a Novel Sustainable Oil Sorbent: Dual Functionality of Adsorption and Biodegradation

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This project explores banana bark as a sustainable oil sorbent, comparing its efficiency to moss and activated charcoal. Artificial oil spill simulations demonstrated that crushed banana bark absorbed and retained significantly more oil than traditional sorbents, making it a better alternative. Microscopic examination highlighted potential safety concerns with moss due to insect contamination, whereas banana bark was safer and cost-effective. Moreover, the microflora in banana bark revealed the presence of lipase-producing bacteria capable of degrading absorbed oil, presenting a dual advantage of adsorption and natural biodegradation. Further investigations simulated freshwater and saltwater oil spills to assess the oil-degrading potential of these bacteria. All tested cultures achieved significant oil breakdown within 24 hours, with culture # 6, *Priestia aryabhattai*, maintaining high efficacy in both environments, overcoming salts inhibitory effect on lipase activity. Predictive models indicated near-complete oil degradation within 2.6 days in freshwater and 5 days in saltwater, underscoring the rapid and sustainable nature of this approach. These findings highlight banana bark's multifaceted potential as a safer, biodegradable, and highly effective sorbent, offering a promising foundation for sustainable and versatile oil spill mitigation strategies across diverse environmental conditions.

Introduction

Oil spills are serious environmental disasters that harm ecosystems, wildlife, and people. These spills happen when oil accidentally leaks into the environment, usually due to tanker accidents, pipeline breaks, drilling mishaps, or ship discharges. The effects are immediate and severe, such as water pollution, destruction of habitats, and harm to plants and animals. Over time, the oil can soak into soil and water, causing long-lasting damage to ecosystems and human health[1].

Oil spills affect the environment in many ways. Marine animals are particularly at risk because oil spreads quickly over the water, forming a layer that blocks oxygen and disrupts the lives of animals and birds. Birds coated in oil lose their ability to stay warm, often leading to death. Fish and other marine animals can swallow or absorb toxic chemicals from the oil, which can poison them or cause long-term problems like difficulty reproducing[2]. For example, the 2010 Deepwater Horizon spill in the Gulf of Mexico released millions of barrels of oil, harming thousands of marine species and damaging coral reefs and coastal areas[2].

In freshwater ecosystems like rivers and lakes, oil spills can be just as destructive. These environments are smaller, so the effects of oil contamination can be felt more quickly and severely. One example is the Exxon Valdez spill in 1989, which released about 11 million gallons of oil into Prince William Sound, Alaska. This spill polluted over 1,300 miles of coastline and harmed salmon, otters, and birds[3]. Freshwater species are especially vulnerable because they rely on clean water and cannot easily escape polluted areas[4].

Oil spills also pose risks to human health, especially for cleanup workers and nearby communities. Direct exposure to oil can cause headaches, nausea, breathing problems, and skin irritation. During the Deepwater Horizon spill, many cleanup workers reported symptoms like respiratory problems and skin rashes from chemical exposure[5]. Long-term exposure to oil and cleanup chemicals can lead to serious health issues, including liver and kidney damage, neurological problems, and even cancer. Studies from the Exxon Valdez spill showed that many cleanup workers faced ongoing health problems for years[5,1]. In addition, people who see their environment destroyed or lose their jobs, especially in fishing or tourism, can suffer from anxiety, depression, and PTSD.

Efforts to clean up oil spills include mechanical, chemical, and biological methods. Mechanical tools like booms, skimmers, and absorbents are used to contain and remove oil. Booms prevent oil from spreading, skimmers collect it from the surface, and absorbents soak it up for easy removal[4]. However, these methods often require human workers, putting them at risk of exposure to harmful substances.

Chemical dispersants are used to break oil into smaller droplets, making it easier for natural processes to break it down. However, these dispersants can also harm marine life, and their

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use is often debated[2]. Cleanup workers who handle dispersants may face risks like burns and breathing issues, so protective gear and safety measures are essential[2]. Recently, natural materials like cotton, wool, straw, and kapok have been studied for oil cleanup. These materials are biodegradable, affordable, and good at absorbing oil[6]. For example, kapok fiber can soak up large amounts of oil due to its unique structure. Using these natural materials reduces the need for synthetic options, which can be harder to dispose of safely.

Another promising approach is using microorganisms like bacteria and fungi that naturally break down oil into harmless substances like water and carbon dioxide. This process, called biodegradation, is part of bioremediation. Microbes like *Alcanivorax borkumensis* and *Pseudomonas aeruginosa* are especially good at breaking down oil and can be used to speed up cleanup[7]. These natural methods are a more eco-friendly way to handle spills[8].

In recent years, increasing attention has been given to natural, biodegradable sorbents as environmentally friendly alternatives for oil spill remediation. Several plant-based materials have demonstrated promising oil absorption capabilities due to their fibrous structure, low density, and hydrophobicity. For instance, kapok fiber, with its hollow structure and waxy surface, has shown exceptional oil sorption efficiency while remaining buoyant on water surfaces. Similarly, cotton, straw, sugarcane bagasse, coconut husk, rice husk, and sawdust have been studied for their potential in oil spill cleanup due to their natural abundance and oil-holding capacities[9],[10]. These materials are typically low-cost, widely available agricultural byproducts, making them suitable for large-scale use in developing countries. However, limitations such as microbial contamination, low reusability, or challenges in deployment under field conditions have motivated further research into alternative bio-based sorbents.

This research looks at using banana bark (a waste product from banana cultivation) as an eco-friendly way to clean up oil spills in both freshwater and saltwater. Banana bark, a waste product from banana farming, has a fibrous structure that can trap oil like a sponge[11]. The study compares banana bark's ability to absorb oil with materials like moss and activated charcoal. It also explores whether the natural microorganisms in banana bark can help break down absorbed oil, improving cleanup. The research tests how well banana bark works in freshwater and saltwater. Freshwater environments like rivers and lakes are especially vulnerable to oil pollution because clean water is vital for survival. Similarly, protecting marine environments from oil spills is important, so the study also examines banana barks effectiveness in salty conditions.

In many developing countries, banana bark is often thrown away after farming[11]. Repurposing it for oil cleanup not only helps the environment but also provides economic opportunities. Farmers could sell banana bark as a low-cost oil absorber, creating jobs and boosting local economies. This approach also supports sustainability by reducing waste, protecting the environment, and promoting economic growth[7].

This study aims to show that banana bark can be an effective and sustainable tool for cleaning up oil spills. By combining its ability to soak up oil and support natural oil breakdown, banana bark could reduce the environmental and health impacts of spills. It also offers a low-cost solution that could benefit developing countries where resources for traditional cleanup methods are limited.

Results

The banana bark crushed absorbs significantly more oil from the oil spill simulation than the traditionally used sorbent like moss and activated charcoal. To see the comparative effectiveness of oil absorption of the traditionally used sorbents (moss and activated charcoal) to the banana bark, different weights of sorbents were tested for absorbing the oil in an oil-spill simulation mixture. A two-sample, two-tailed T-test was performed on the collected data (n=6) to evaluate the significance of the differences observed between banana bark and other sorbents. For a sorbent weight of 1 gram, no significant difference is observed in the oil absorption ability of banana bark compared to other sorbents tested. However, for a sorbent weight of 3 grams, the banana bark shredded and crushed both showed a significantly higher oil absorption than moss and activated charcoal ($P < 0.0007$). For the sorbent weight of 5 grams of banana bark shredded and crushed, both showed significantly higher oil absorption than moss but not activated charcoal ($P < 0.01$). Overall, Banana bark sorbents, both the shredded and the crushed, were compatible and worked better in oil absorption when compared to the traditional sorbents (Figure 1, Table 1).

The banana bark samples absorb significantly more water when a higher sorbent weight is used in the oil spill simulation than the traditionally used sorbent, like moss and activated charcoal. When choosing an oil-absorbing sorbent for the oil spill, the preference is obviously towards the material that absorbs more oil and not more water from the oil spill. Banana bark samples showed significantly higher oil absorption than the traditional sorbents, such as moss and activated charcoal. To see the comparative effectiveness of the water absorption ability of the tested sorbents, the remaining water level (ml) in the oil spill simulation was noted for each trial. A two-sample, two-tailed T-test was performed on the collected data (n=6) to evaluate the significance of the differences observed between banana bark and other sorbents. For a sorbent weight of 1 gram, no significant difference is observed in the water absorption ability of banana bark compared to other sorbents tested. However, for a sorbent weight of 3 grams, both the banana bark samples showed a significantly higher water absorption than

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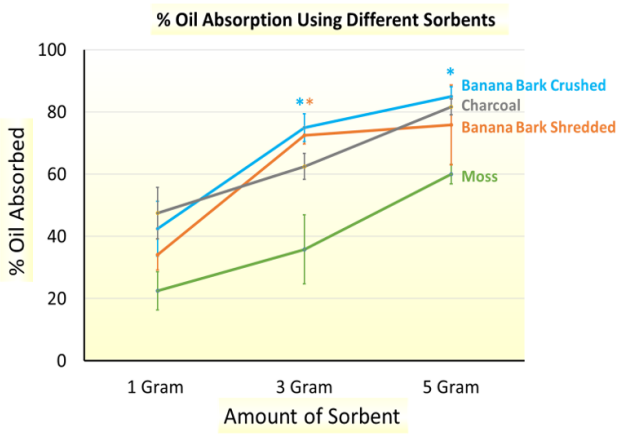

Figure 1: A comparative line graph shows % oil absorption by sorbents (banana bark crushed, shredded, activated charcoal, and moss) with weight- 1, 3, and 5 grams. ** significant difference between banana bark samples and traditional sorbents; * significant difference between banana bark samples and moss.

Sorbant Type	% Total Oil Absorbed by the Sorbant (AVG ± SD)		
Amount of Sorbant (grams)	1 g	3 g	5 g
Moss	22.5 ± 6.12	35.83 ± 11.14	60 ± 3.16
Activated Charcoal	47.5 ± 8.22	62.5 ± 4.18	81.67 ± 2.58
Banana Bark Shredded	34.17 ± 4.92	72.5 ± 2.74	75.83 ± 12.81
Banana Bark Crushed	42.5 ± 8.8	75 ± 4.47	85 ± 3.16

Table 1: The table includes the average standard deviation (n=6) of the percentage of total oil absorbed for each sorbent at different weights.

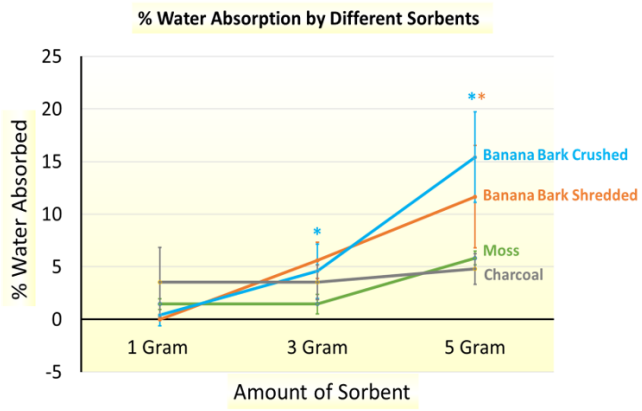

Figure 2: A comparative line graph shows % water absorption by sorbents (banana bark crushed, shredded, activated charcoal, and moss) with weight- 1, 3, and 5 grams. ** significant difference between banana bark samples and traditi onal sorbents; * significant difference between banana bark samples and moss.

Sorbant Type	% Total Water Absorbed by the Sorbant (AVG ± SD)		
Amount of Sorbant (grams)	1 g	3 g	5 g
Moss	1.46 ±0.51	1.46 ± 0.94	5.83 ± 0.65
Activated Charcoal	3.54 ± 3.3	3.54 ± 1.66	4.79 ± 1.46
Banana Bark Shredded	0 ± 0	5.63 ± 1.72	11.67 ± 4.85
Banana Bark Crushed	0.42 ± 1.02	4.58 ± 2.58	15.42 ± 4.31

Table 2: The table includes the average standard deviation (n=6) of the percentage of total water absorbed for each sorbent at different weights.

moss (P <0.02). For the sorbent weight of 5 grams of banana bark samples, both showed significantly higher water absorption than moss and activated charcoal (P <0.016). Overall, banana bark sorbents were found to absorb more water than moss and activated charcoal when the higher weight of samples was used (Figure 2 and Table 2). This difference is likely because banana bark has higher cellulose content, a natural organic material that was dried during processing to remove moisture. It is likely that the recontact with water during the incubation period allowed the banana bark material to absorb the lost moisture during the drying process.

The banana bark samples show significantly higher retention of absorbed materials when compared to moss and activated charcoal. One of the critical aspects of the overall performance of a sorbent is its ability to retain oil after absorption. For example, some materials may rapidly absorb oil but release oil by dripping when they are lifted from the surface. Since banana bark samples absorbed more oil and more water at 3 grams and 5 grams weight levels in the tested oil spill simulation, it was critical to evaluate if the absorbed material stayed retained in the sorbent sample or was released back once separated from the oil spill simulation. Therefore, to evaluate the absorbed material's retention, the sorbent's weight after lifting and draining the liquid was recorded for each trial. To standardize the collected data for comparative analysis, the recorded sorbent weight data was transformed into % weight gain. A two-sample, two-tailed T-test was performed on the collected data (n=6) to evaluate the significance of the differences observed.

First, each sorbent type was compared to itself at different weights. No significant difference was observed between the retention ability of moss and activated charcoal at different weight levels. This means that if more sorbent is used, the absorbed material retention rate will remain the same for the moss and charcoal samples. However, the banana bark crushed sample showed a significant increase in retention of the absorbed material that corresponds to the increase in sorbent's weight (P <0.05) (Figure 3 and Table 3). This indicates that the crushed banana bark sample's ability to retain the absorbed sample increases with weight.

Second, the different sorbents were compared at the same weight level for their ability to retain the absorbed material. For a sorbent weight of 1 gram, no significant difference is observed in the absorbed material retention ability of different sorbents tested. However, for a sorbent weight of 3 grams, both the

banana bark samples showed significantly higher retention of the absorbed material than moss and activated charcoal ($P < 0.02$) (Figure 3 and Table 3).

Thus, banana bark sorbents show higher retention of the absorbed material. This ability is likely due to the higher cellulose content of the banana bark and formation of liposomes by the crushed cell walls during the processing, which can be trapped in the cellulose meshwork. The ability to absorb significantly higher material and retain it better than the traditionally used sorbent places banana bark as a high-potential sorbent for oil spills.

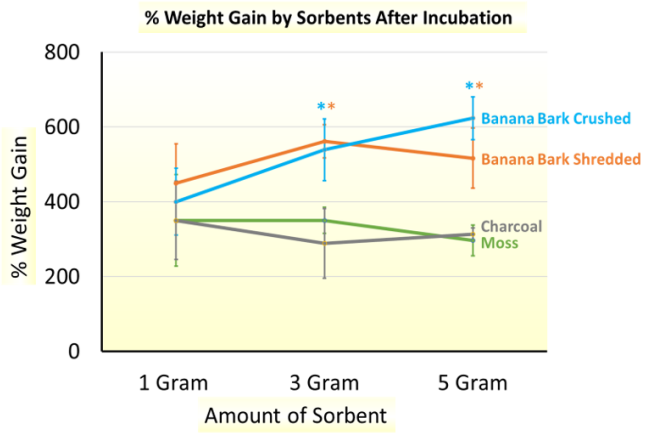

Figure 3: A comparative line graph shows % weight gain by each sorbent (banana bark crushed, shredded, activated charcoal, and moss) with weight- 1, 3, and 5 grams. ** significant difference between banana bark samples and traditional sorbents; * significant difference between banana bark samples and moss.

Sorbant Type	% Increase in Sorbant's Weight After Incubation (grams) (AVG ± SD)		
Amount of Sorbant (grams)	1 g	3 g	5 g
Moss	350 ± 122.47	350 ± 34.96	296.67 ± 40.82
Activated Charcoal	350 ± 104.9	288.89 ± 93.5	313.33 ± 16.33
Banana Bark Shredded	450 ± 104.9	561.11 ± 44.31	516.67 ± 80.42
Banana Bark Crushed	400 ± 89.44	538.89 ± 82.78	623.33 ± 57.75

Table 3: The table includes the average standard deviation (n=6) of the total percentage weight gain by each sorbent at different tested weights

The microscopic examination reveals that the banana bark sorbent is safer than the moss sorbent. Both organic samples tested in the project were examined under a microscope to observe the microscopic changes that occurred in the sample during the experimentation. During the microscopic examination, as seen in figure 4, the moss sample showed the presence of microscopic insects or bugs with an exoskeleton. Although the identity of these organisms is not investigated in this project, the presence of insects that can potentially pose a threat to human health when gathering moss samples is concerning. Thus, banana bark collection and processing is much safer than working with moss.

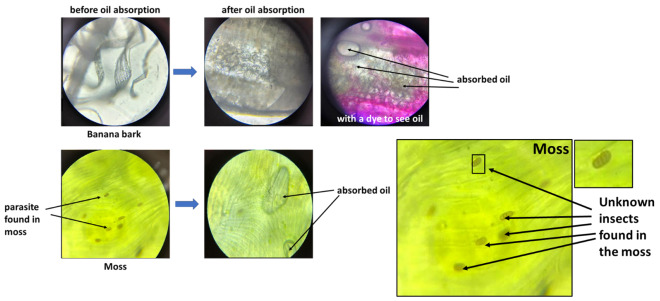

Figure 4: The image shows a microscopic view of banana bark crushed sample (top panel) and moss sample (bottom panel) at 400X. The enlarged image on the bottom panel shows the insects found within the moss sample.

The banana bark samples contain microflora to biodegrade absorbed oil naturally. Transportation, storage, and disposal of the sorbent after the oil absorption is a significant concern for the sorbents used today. Additionally, options such as landfill and incineration pose potential environmental threats by releasing and contaminating surroundings with toxins. Biodegradation is a potential option when using organic material such as banana bark as a sorbent for oil spills. To evaluate the potential biodegradation of oil trapped in the sorbent, samples were collected from the organic sorbents before and after the oil absorption. These samples were first streaked on a general-purpose media (trypticase soy agar - TSA) to isolate microflora present in the material (Figure 5). After incubation of the agar plates, many different bacterial colonies were selected based on the colony characteristics and restreaked on the media with lipid-tributyrin agar (TBA) to evaluate the bacteria's ability to degrade lipids/oil by producing enzyme lipase (Figure 6, 7). TBA media appears opaque due to the oil mixed in the agar. If bacterial cells produce enzyme lipase and degrade oil, the media around the bacterial growth will show a clear zone, as seen in Figure 7. Many bacterial colonies (Table 4) obtained from banana bark samples, both before and after the oil absorption, showed the presence of enzyme lipase and the ability to degrade the oil. Thus, banana bark used as an oil sorbent has a high potential to degrade oil naturally without hurting the environment.

All the cultures isolated from banana bark successfully degraded oil in the freshwater oil spill simulation. Based on the qualitative observed results for the freshwater oil spill simulation, the amount of oil in the sample tubes with inoculated cultures showed relatively less leftover oil as compared to the control tubes upon incubation. The amount of oil left (out of 1 ml added) after the incubation (24, 48, and 72 hrs.) in reactions was measured as the height of the oil column (mm). The data collected was transformed into a percentage for standardization and relative comparison. To see the comparative ability of these bacterial cultures, the percentage of leftover oil from the six

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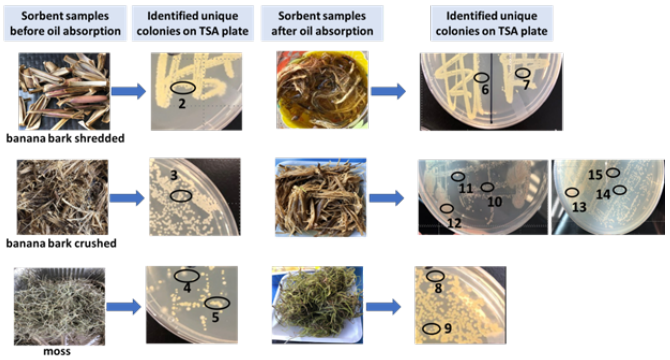


Figure 5: Pictures of sorbent samples before and after the oil absorption and various microbial colonies obtained from sampling the sorbent on the TSA plate after 48-hour incubation. The selected colonies are marked and numbered in the images.

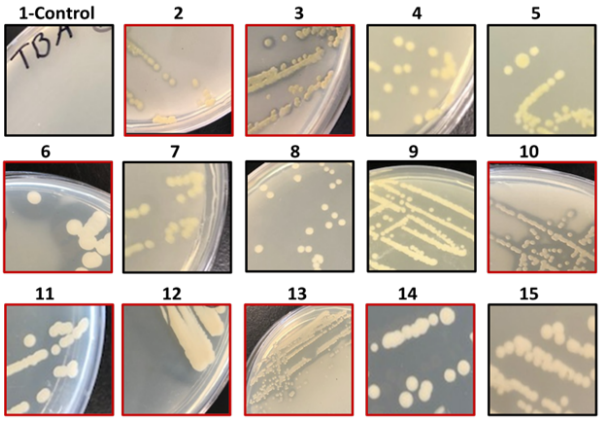


Figure 6: A close-up view of the tributyrin agar plates streaked with the selected colonies. The clearing around the microbial growth indicates lipase enzyme secretion that degrades the lipids in the media. The red box images show cultures (colony # 2, 3, 6, 10, 11, 12, 13, and 14) that have lipase activity and can degrade lipids. (Colony # 1: control; 2: banana bark shredded before oil absorption; 3: banana bark crushed before oil absorption; 4, 5: moss before oil absorption; 6, 7: banana bark shredded after oil absorption; 8, 9: moss after oil absorption; 10, 11, 12, 13, 14, 15: banana bark crushed after oil absorption).

freshwater oil spill simulation trials for each culture was averaged for each incubation time point. Figure 8 table and line graph illustration provides the % average standard deviation (error bars) for each data point. All the tested cultures (Culture # 2, 3, 6, 10, 11, 12, 13, and 14) showed significant oil degradation just in 24 hours of incubation ($P < 0.0001$, two sample independent Student's t-test). No such decrease in oil was measured in the control tube (no culture tube). This result supports the observation of the previous year's data and confirms that banana bark can degrade oil naturally using its microbial flora after oil

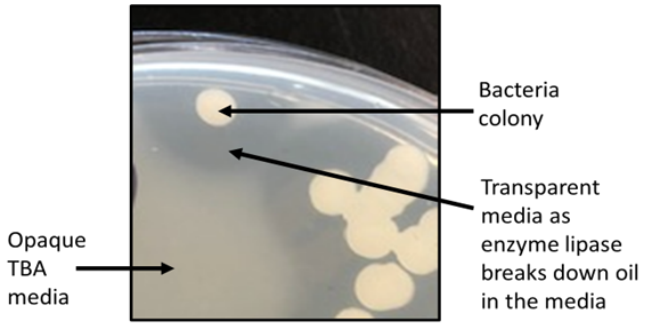


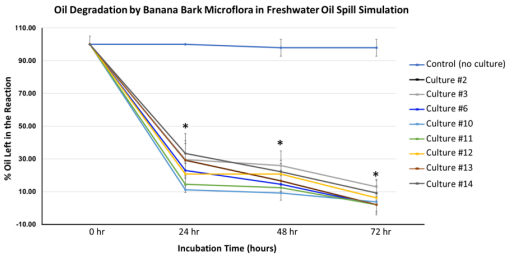
Figure 7: The image demonstrates the growth of lipase-producing bacteria that clears the opaque media by degrading oil around the bacterial growth.

Sample	Colony #	Lipase Activity
Control: oil and water mixture	1	No
banana bark shredded before oil absorption	2	Yes
banana bark crushed before oil absorption	3	Yes
moss before oil absorption	4	No
	5	No
banana bark shredded after oil absorption	6	Yes
	7	No
moss after oil absorption	8	No
	9	No
banana bark crushed after oil absorption	10	Yes
	11	Yes
	12	Yes
	13	Yes
	14	Yes
	15	No

Table 4: The table shows colony numbers identified based on the colony characteristics from different samples and their ability to produce enzyme lipase to degrade the oil. The light red color fill indicates lipase activity.

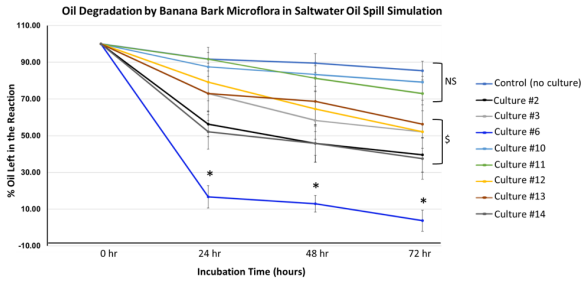
absorption.

All the cultures isolated from banana bark, except for cultures # 10 and 11, showed a significant degradation of oil in the saltwater oil spill simulation. For the saltwater oil spill simulation, the control tube showed a slight decrease in the left-over oil upon incubation, which was consistent with that of the other culture tubes. However, the sample tubes inoculated with culture #6 showed very little remaining oil after the incubation time. To see the comparative ability of each lipase-producing bacterial culture isolated from the banana bark, the percentage of oil left from the six-saltwater oil spill simulation trials for each culture was averaged for each incubation time point. Figure 9 provides a summary view of the % average oil left with the standard deviation to compare each culture's ability to degrade oil. Cultures # 10 and 11 did not show any significantly different oil degradation compared to the control sample in the saltwater oil spill simulation. The rest of the cultures (cultures # 2, 3,



% Oil Left in the Reaction After Incubation (% average ± standard deviation) in Freshwater Simulation										
	Culture #	Control (no culture)	Culture # 2	Culture # 3	Culture # 6	Culture # 10	Culture # 11	Culture # 12	Culture # 13	Culture # 14
Incubation	0 hour	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0
	24 hours	100 ± 0	29.17 ± 10.2	29.63 ± 11.5	22.92 ± 9.4	11.11 ± 0	14.58 ± 5.1	20.8 ± 6.4	29.17 ± 10.2	33.33 ± 12.2
	48 hours	97.92 ± 5.1	16.67 ± 6.5	25.93 ± 9.1	14.58 ± 5.1	9.26 ± 4.5	12.5 ± 0	20.8 ± 6.4	16.67 ± 6.5	22.22 ± 7
	72 hours	97.92 ± 5.1	2.08 ± 5.1	12.96 ± 4.5	2.08 ± 5.1	3.7 ± 5.7	2.1 ± 5.1	6.25 ± 10.5	2.1 ± 5.1	9.26 ± 4.5

Figure 8: The line graph illustrates the average percentage of leftover oil after incubation of 0, 24, 48, and 72 hours in the freshwater oil spill simulations for the control and for all the tested cultures (#2, 3, 6, 10, 11, 12, 13, and 14) from the banana bark. The error bars depict the % standard deviation. * Indicates a statistically significant difference in the degradation of oil as compared to the control group for all the cultures tested ($P<0.0001$, t-test). The table depicts the line graph data. N=6.



% Oil Left in the Reaction After Incubation (% average ± standard deviation) in Saltwater Simulation										
	Culture #	Control (no culture)	Culture # 2	Culture # 3	Culture # 6	Culture # 10	Culture # 11	Culture # 12	Culture # 13	Culture # 14
Incubation	0 hour	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0
	24 hours	91.67 ± 6.5	56.25 ± 6.8	72.92 ± 9.4	16.67 ± 6.1	87.5 ± 7.9	91.67 ± 6.4	79.17 ± 10.2	72.92 ± 14.6	52.1 ± 9.4
	48 hours	89.58 ± 5.1	45.83 ± 10.2	58.33 ± 10.2	12.96 ± 4.5	83.33 ± 6.4	81.25 ± 6.8	64.58 ± 9.4	68.75 ± 13.1	45.83 ± 6.5
	72 hours	85.42 ± 5.1	39.58 ± 9.4	52.08 ± 4.5	3.7 ± 5.7	79.17 ± 6.4	72.92 ± 9.4	52.1 ± 14.6	56.25 ± 13.1	37.5 ± 11.2

Figure 9: The line graph illustrates the average percentage of leftover oil after incubation of 0, 24, 48, and 72 hours in the saltwater oil spill simulations for the control sample and for all the tested cultures (#2, 3, 6, 10, 11, 12, 13, and 14) from the banana bark. The error bars depict the % standard deviation for each data point. * Indicates a statistically significant difference at $P<0.0001$; $ indicates a statistically significant difference at $P<0.05$; NS indicates no difference in the degradation of oil as compared to the control group (t-test). The table depicts the line graph data. N=6.

6, 12, 13, and 14) showed significant oil degradation just in 24 hours of incubation ($P<0.05$, two sample independent Student's t-test). Similar to the freshwater oil spill simulation, the rate of oil degradation reduced after the first 24 hours. Culture # 6 showed the most oil degradation ability compared to the other cultures tested in the saltwater oil spill simulation. This result supports the observation of the previous year's data and confirms that banana bark can degrade oil naturally using some species of its microbial flora after oil absorption.

Most lipase-producing bacterial cultures isolated from banana bark can degrade oil at a better rate in freshwater than in saltwater. To see the comparative effect of the different isolated lipase-producing bacterial cultures from banana bark for degrading oil in freshwater vs. saltwater oil spill simulation, the % oil left in the reaction tube after each of the incubation times (0, 24, 48, and 72 hours) was plotted for each of the cultures independently (Figure 10). A statistical comparison between oil degradation of freshwater vs. saltwater oil spill shows that cultures # 2, 3, 10, 11, 12, 13, and 14 (all cultures except culture # 6) degrade oil at a higher rate in the freshwater oil spill simulation as compared to saltwater oil spill simulation ($P<0.05$, two samples independent Students t-test) (Figure 10). This indicates that the salt interferes with the bacterial lipase enzyme responsible for degrading oil in oil spill simulation.

In addition, linear approximation of the oil degradation was modeled to obtain equations for each cultures ability to degrade oil. Comparing slopes for each plot cultures # 2, 3, 10, 11, 12, 13, and 14 showed that bacteria could degrade oil in freshwater oil spill simulation at a better rate than in the saltwater oil spill simulation (Table 5). The difference in the slope of freshwater vs saltwater oil spill simulation reflects the differences in the lipase enzyme reaction rates due to the presence of salt. It is important to note that while linear models were selected here for simplicity and consistency with the measured data points, the non-linear nature of biodegradation (particularly the rapid initial phase) suggests that future modeling using exponential decay or first-order kinetics could yield more accurate representations.

Lipase-producing culture # 6 isolated from banana bark can degrade oil at the same rate irrespective of the presence or absence of salt. The oil-degrading ability of culture #6 was not affected by the presence or absence of salt in the oil spill simulation (Figure 10, Table 5). This suggests that culture #6 will be able to degrade oil with the same effectiveness in freshwater oil spills or saltwater (marine) oil spills. The slope of the linear approximation equation of oil degradation in the freshwater and saltwater oil spill simulation was the same (m = 1.6). This suggests that lipase produced by culture # 6 is effective for its oil breakdown activity in the presence of salt. Therefore, the presence of culture #6 makes banana bark an effective oil sorbent in both freshwater and marine water oil spill situations to naturally degrade the absorbed oil.

Modeling a collective effect of lipase producing microbial flora of banana bark indicates complete degradation of the absorbed oil in 2.6 day in freshwater oil spill and 5 days in saltwater oil spill. To calculate the number of hours (or number of days) required for a relative complete degradation of the absorbed oil by banana bark, the slopes of the modeled linear approximation equation were averaged for freshwater

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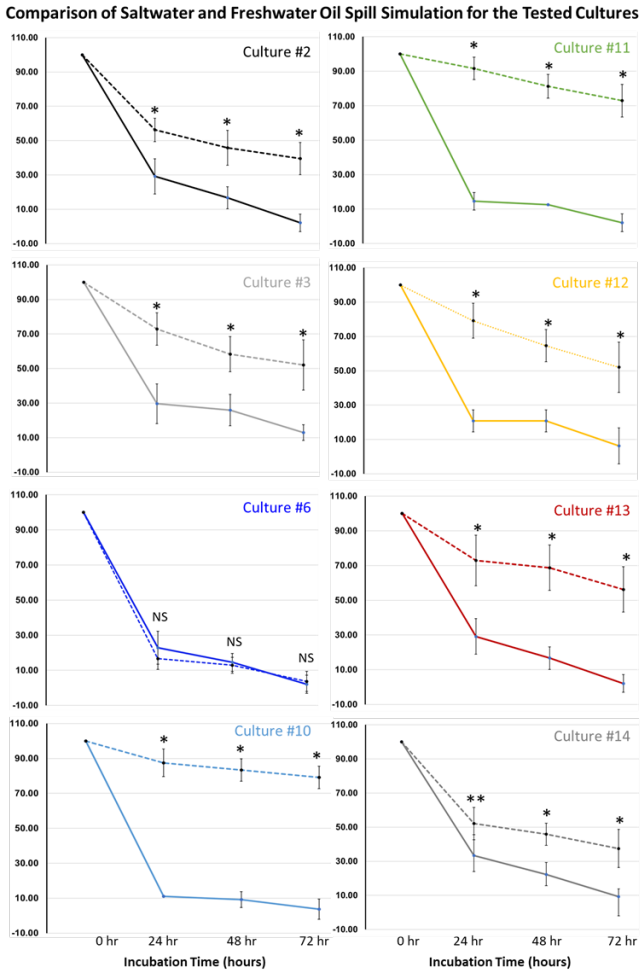

Figure 10: The line graph illustrates the effect of cultures #2, 3, 6, 10, 11, 12, 13, and 14 in the degradation of oil after incubation of 0, 24, 48, and 72 hours in the saltwater (dotted line) vs freshwater (solid line) oil spill simulations. The error bars depict the % standard deviation for each data point. * Indicates a statistically significant difference at $P<0.001$; ** indicates a statistically significant difference at $P<0.05$; NS indicates no statistical difference (two sample independent Students t-test). N=6.

(m=1.57) and saltwater (m=0.8). Using the average slope, which indicates the collective rate of oil degradation in freshwater, the equation for oil degradation in the freshwater oil spill is y = -1.57x. Similarly, the equation for the saltwater oil spill is y = -0.8x. Calculating the value of x when y=100 (near 100% degradation) provides the number of hours for relative complete degradation (degradation time is estimated using the equation: slope time = 100%). For the freshwater oil spill, 63 hours or 2.6 days is a calculated time value for complete degradation of the absorbed oil. Likewise, the complete degradation would require

Linear Aproximation Equation with R^2 value		
Oil Spill Simulation Type	Freshwater	Saltwater
Culture # 2	y = -1.5811x; R^2 = 0.8281	y = -0.9921x; R^2 = 0.8233
Culture # 3	y = -1.4275x; R^2 = 0.7592	y = -0.7564x; R^2 = 0.9197
Culture # 6	y = -1.6121x; R^2 = 0.7771	y = -1.6259x; R^2 = 0.7116
Culture # 10	y = -1.6645x; R^2 = 0.6631	y = -0.3224x; R^2 = 0.9143
Culture # 11	y = -1.6493x; R^2 = 0.7055	y = -0.3782x; R^2 = 0.9979
Culture # 12	y = -1.5439x; R^2 = 0.7274	y = -0.7006x; R^2 = 0.9857
Culture # 13	y = -1.5811x; R^2 = 0.8281	y = -0.6572x; R^2 = 0.8999
Culture # 14	y = -1.4716x; R^2 = 0.8192	y = -1.0231x; R^2 = 0.7939

Table 5: The table depicts linear approximation equations of oil degradation by each isolated lipase-producing bacterial culture in freshwater (green color) and saltwater (blue color) oil spill simulation. Slope values represent the linear degradation rate calculated from data points. The R2 value with each equation represents the goodness of fit for the modeled linear approximation with the actual measured data.

124 hours or 5 days for the saltwater oil spill. These calculations assume that the oil degradation rate stays constant and that the density of lipase-producing microbial flora in banana bark is at the same concentration used in this study. Since this study is performed as an in-vitro assay, many confounding factors, such as microbial antagonism, resources available for microbial growth, effect of microbial metabolites etc., are not considered in the current calculation.

Comprehensive Phenotypic and Molecular Characterization of Culture #6 Identifies It as *Priestia aryabhattai*. Among all tested cultures, Culture #6 was the only isolate that maintained a consistent rate of oil degradation in both freshwater and saltwater simulations. This salt-independent performance was not observed in any other lipase-producing isolates and suggests that Culture #6 possesses a uniquely salt-tolerant phenotype. Due to this consistency across varying salinities, Culture #6 was prioritized for further phenotypic, biochemical, and molecular characterization to evaluate its potential for broad-spectrum bioremediation applications.

The phenotypic characteristics of culture #6 were examined through microscopy and biochemical assays. Gram staining confirmed the cell morphology as Gram-positive bacilli. Microscopic examination also revealed a thick glycocalyx layer,

indicative of biofilm-forming potential. Further growth assays were conducted using mannitol salt agar media containing increasing concentrations of NaCl (up to 7.5%), which confirmed salt tolerance and mannitol fermentation ability of culture #6. This ability to grow in high-salt conditions confirms the cultures adaptation to saline environments and supports its role as a key contributor to the biodegradation potential of banana bark in both freshwater and marine oil spill scenarios. Further biochemical tests revealed catalase enzyme activity, where effervescence was observed using hydrogen peroxide. An oxidase test reagent showed a color change indicative of oxidase activity and confirmed cellular respiration as a primary method of metabolic mechanisms. Lipase production was tested on tributyrin agar plates, which showed clear zones around colonies and confirmed lipase enzyme production.

For further genus and species level identification, the sample was analyzed for unique protein spectral fingerprint and sequence-based analysis of protein-coding genes. Protein Spectral Fingerprint Analysis helped identify culture #6 using a matrix-assisted laser desorption/ionization-time of flight (MALDI-TOF) mass spectrometry approach. The samples were analyzed using a calibrated MALDI-TOF mass spectrometer to yield a unique protein spectral fingerprint, and the obtained spectra were compared against a comprehensive reference database of bacterial profiles for species-level identification. This approach helped narrow down the culture identification to *Priestia aryabhattai* or *Priestia megaterium* (Figure 11). For accurate species-level identification and for further confirmation, sequence-based analysis of protein-coding genes was performed. Culture #6 chromosomal DNA served as a template for amplifying protein-coding genes using polymerase chain reaction (PCR) with specific primers targeting conserved bacterial sequences. The PCR products were purified and sequenced using Sanger sequencing. The resulting sequences were aligned and compared with entries in the National Center for Biotechnology Information (NCBI) database using the Basic Local Alignment Search Tool (BLAST). The identification of culture #6 as *Priestia aryabhattai* was confirmed through a high sequence similarity to known entries (Figure 12).

Rank (Quality)	Top Ten Matched Patterns	Score	NCBI ID
1 (+++)	Priestia megaterium DSM 1668 DSM	2.080	1404
2 (+++)	Bacillus aryabhattai ACC 1231945 ext ACC	2.040	412384
3 (+++)	Priestia megaterium DSM 2894 DSM	2.010	1404
4 (+++)	Bacillus aryabhattai JCM 13839T ext ACC	1.990	412384
5 (+++)	Bacillus megaterium ACC 1036886 ext ACC	1.960	1404
6 (+++)	Priestia megaterium DSM 32T DSM	1.890	1404
7 (-)	Colletotrichum gloeosporioides CBS 100471 CBS	1.320	474922
8 (-)	Priestia flexa ACC 4937793 ext ACC	1.290	86664
9 (-)	Proteus mirabilis 9482_2 CHB	1.280	584
10 (-)	Citrobacter koseri MB_8260_05 THL	1.260	545

Figure 11: Using testing process to yield a unique protein spectral fingerprint (MALDI-TOF) that was compared to the existing database helped narrow down identification of culture #6 as *Priestia aryabhattai* or *Priestia megaterium*.

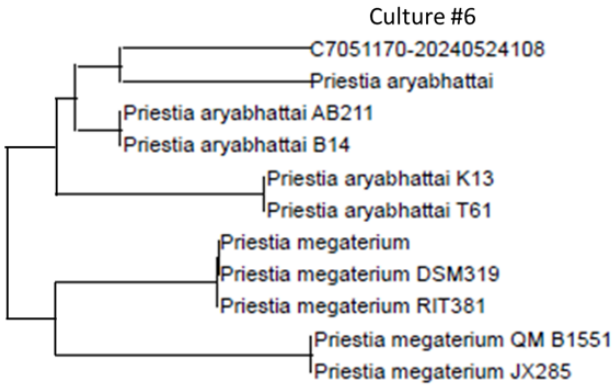

Figure 12: Using sequenced based analysis of protein coding genes that was compared to the existing database helped species-level identification of culture #6 as *Priestia aryabhattai*.

Discussion

This study underscores the significant potential of banana bark as a dual-function sorbent that offers both physical oil adsorption and biological degradation via its native microbiota. The study explored two processing methods for banana bark (dried and shredded versus dried, shredded, and pressed) and tested their performance in an artificial oil spill simulation. Using motor oil, selected for its moderately high viscosity to challenge the sorbents, the investigation measured oil absorption, water absorption, and % weight gain across three weight levels (1, 3, and 5 grams) with six trials per condition. Compared to traditional sorbents like moss and activated charcoal, banana bark (especially in its crushed form) demonstrated significantly higher oil absorption and material retention. Moreover, microscopic examinations identified a critical advantage of banana bark over mossthe absence of potential contaminants such as insects or bugs, which were found in moss samples. Additionally, some of banana barks natural microflora showed lipase activity, enabling the breakdown of absorbed oil, making it a uniquely multifunctional as a biodegradable sorbent that can absorb oil and degrade the absorbed oil.

Further investigation provided additional evidence for banana bark's potential, focusing on the biodegradation capabilities of its microbiota in freshwater and saltwater oil spill simulations. While oil degradation was rapid in freshwater, the presence of salt reduced efficacy for most bacterial strains. Among the microbial isolates, culture #6, identified as *Priestia aryabhattai*, stood out for its salt-independent oil degradation. The identification of culture #6 (*Priestia aryabhattai*) involved a comprehensive approach combining protein spectral fingerprinting and sequence-based analysis. Protein fingerprinting was performed using matrix-assisted laser desorption/ionization-time of flight (MALDI-TOF) mass spectrometry, yielding a unique spectral

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signature for the bacterial strain. Subsequent sequence-based analysis of protein-coding genes confirmed *Priestia aryabhattai* as the species with high sequence similarity in the NCBI database, validating its identity and role in oil degradation.

Priestia aryabhattai (formerly classified *Bacillus aryabhattai*) is an environmentally resilient, Gram-positive bacterium commonly isolated from diverse ecological niches such as soil, air, plant rhizospheres, and even extreme environments like the stratosphere[12,13]. It has been reported to possess significant biotechnological and ecological relevance, particularly due to its enzymatic versatility and tolerance to stress conditions, including salinity, UV exposure, and oxidative stress[12,14,15]. In recent studies, *P. aryabhattai* has shown potential for bioremediation by degrading a variety of hydrocarbons, including those found in crude oil, and producing biosurfactants that enhance the bioavailability of hydrophobic pollutants[16]. Its ability to tolerate and function in saltwater environments also makes it a promising candidate for marine bioremediation applications. The consistent oil degradation performance of *P. aryabhattai* in both freshwater and saltwater conditions observed in this study aligns with previous reports of its stress adaptability and hydrocarbon degradation capacity. This culture has never been reported in association with banana trees and thus contributes to the novelty of this study. Given these attributes, the identification of *P. aryabhattai* as part of the banana bark microbiota strengthens the case for its use in future field-scale bioremediation systems targeting oil-contaminated aquatic environments using banana bark as an oil sorbent.

A few existing studies on natural sorbents have been reported in the literature. Kapok fiber, due to its hollow structure and hydrophobic wax coating, has been widely studied and reported to absorb approximately 35 - 40 g of oil per gram of fiber[10,17]. Straw, another readily available agricultural byproduct, shows relatively lower oil sorption capacity, ranging from 5 - 10 g/g depending on the oil type and pretreatment[18]. Reed canary grass, ax, and hemp bers absorb 2 - 4 g/g oil[19]. Cotton fibers can absorb around 25 - 30 g/g of oil under optimal conditions but often retain significant amounts of water when used in oil-water mixtures[20]. In our study of crushed banana bark samples, we observed better absorption than activated charcoal and moss samples. We focused on calculating percentage-based absorption, which was 42.5% for 1 gram of sample, 75% for 3 grams of sample, and 85% for 5 grams of sample. 1ml of motor oil usually weighs about 0.9 grams. Therefore, the average absorption amount for the crushed banana bark sample was $\tilde{5}$ g/g, which is relatively lower than other reported sorbents. However, it is noteworthy that the banana bark sample hold on to the absorbed material after testing period. Although not the most superior absorbent, banana bark demonstrates additional capacity to support oil degradation by native lipase-producing microbes and offers a dual functionality that is not reported for most plant-based sorbents. This highlights banana bark as not only an effective oil absorber but also a potential platform for in-situ biodegradation.

When oil degradation trends are compared, a collective model, using linear approximation, suggests that banana bark could achieve near-complete oil degradation within approximately 2.6 days in freshwater and 5 days in saltwater. While linear models simplify these predictions and may not account for real-world factors such as microbial interactions or resource limitations, they do provide a promising framework for understanding banana barks capabilities. While in this study degradation rates were modeled linearly for simplicity, it is noteworthy that a real-world microbial degradation often follows non-linear kinetics due to factors such as substrate limitation, enzyme saturation, or metabolite accumulation. Therefore, future studies should incorporate long-term monitoring and fit non-linear models (such as first-order kinetics or Michaelis-Menten enzyme dynamics) to better reflect the complexities of biodegradation in dynamic ecosystems. Additionally, this study evaluated individual bacterial strains isolated from banana bark for their oil-degrading capabilities, however, it is important to recognize that in natural environments, microbial communities do not function in isolation; interactions such as competition, cooperation and often synergism can significantly affect the rate and extent of biodegradation. These microbial dynamics may either enhance or inhibit the degradation of motor oil, making it difficult to attribute observed effects to a single species or treatment. Synergistic effects between bacterial strains (such as cooperative substrate breakdown, cross-feeding, or biosurfactant production) can enhance the overall efficiency of oil biodegradation. Previous studies have shown that microbial consortia can outperform individual strains in degrading complex hydrocarbons due to complementary metabolic pathways[7]. Although culture #6 (*Priestia aryabhattai*) showed robust degradation performance independently, future studies should explore the interaction between multiple lipases producing strains from banana bark to determine whether co-culturing leads to additive or synergistic effects. This would provide a more ecologically relevant model of in-situ biodegradation and may further improve the efficiency of banana bark as a dual-function sorbent. Additionally, variations in environmental conditions, such as pH, temperature, and nutrient availability, can further modulate microbial behavior, introducing additional complexity to data interpretation. Future studies should consider the inclusion of controlled microbial consortia or metagenomic profiling to account for and better understand these microbial interactions. Moreover, to improve quantification accuracy, future experiments should adopt mass-based or concentration-based methods, such as gravimetric or spectrophotometric analysis (such as GC-MS), to measure oil degradation and would complement the dimensional estimates (e.g., oil column height) used in this study and enhance reproducibility. Techniques like GC-MS would provide precise identification and quantification of motor oil components be-

fore and after degradation, enabling the tracking of intermediate metabolites and confirmation of complete mineralization. Such analytical refinement could also reveal degradation efficiencies across hydrocarbon classes (alkanes, aromatics, cycloalkanes), providing molecular-level insights into the metabolic pathways involved.

From an economic perspective, banana bark offers a scalable and cost-effective solution for oil spill remediation, especially in developing countries with significant banana production. These nations can repurpose discarded banana plants, often wasted after fruiting, into valuable oil sorbents, potentially boosting GDP through export opportunities while offering an environmentally friendly solution to oil spill remediation. From a cost perspective, banana bark presents a highly affordable alternative to conventional sorbents. Activated charcoal, one of the traditionally used commercial sorbents, typically costs between $2.50 - $6.00 per 100 grams depending on purity and grade, while sphagnum moss and kapok fiber range between $3.00 - $5.00 per 100 grams in raw or processed form. In contrast, banana bark is an agricultural byproduct that is often discarded post-harvest, resulting in negligible acquisition costs in banana-producing regions. The primary expenses involve basic processing (drying, shredding, and packaging), which can be implemented locally with minimal infrastructure, particularly in rural farming communities. Additionally, valorizing banana agricultural waste can reduce rural poverty by generating new income streams and fostering small-scale circular economies [11]. This highlights banana barks potential not only as an environmentally sustainable solution but also as a cost-effective and socially beneficial one, especially for low-resource or developing regions impacted by oil spills.

In conclusion, banana bark not only absorbs and retains oil efficiently but also supports rapid microbial degradation of the absorbed oil, particularly due to the presence of *P. aryabhattai* in both freshwater and saltwater environment. Future research that expands kinetic modeling, incorporates advanced analytical techniques, tests broader environmental variables, and characterizes microbial synergy will further enhance its promise as a low-cost, scalable, and sustainable tool for oil spill remediation. These efforts will further refine banana barks applications, advancing sustainable and effective strategies for environmental conservation and economic development.

Methods

Preparation of sorbents:

Fresh pieces of banana bark were harvested from a banana tree. To prepare a shredded banana bark sample, pieces of banana bark were harvested from a tree and dried in a metal tray under direct sunlight for three days. After drying, the bark was shredded into thread-like structures, with care taken to keep the cellulose intact. For the crushed banana bark sample, the dried bark pieces were placed between sheets of transparency film (previously cleaned with 70% alcohol) and then mechanically compressed using a weighted press to create a compact mat. This mat was further pounded with a mallet to disrupt the cell structure and achieve a crushed texture. The processed mats were then dried again under direct sunlight for three days. Moss samples were collected from a tree and dried in a metal tray under direct sunlight for three days. Activated charcoal capsules were purchased and opened, and the charcoal powder was collected for use.

Oil absorption by sorbents:

Oil spill simulations were created by using 20% motor oil in water. Motor oil was selected due to its relevance in real-world oil spill scenarios, particularly from transportation and industrial sources, and its moderately high viscosity. In addition, Motor oil is a readily available and provide an easy visual representation of oil spill. The viscosity was standardized by using oil from the same manufacturer and batch, pre-mixed thoroughly before each experiment to ensure homogeneity and consistency across trials. Eighty milliliters of water were added to clean cups, with 18 cups prepared for each sorbent type and an additional 18 cups prepared for control reactions. Twenty milliliters of oil were carefully measured using a pipette and dispensed into each cup. One gram, three grams, and five grams of each sorbent material (banana bark crushed, banana bark shredded, moss, and activated charcoal) were weighed for the trials. The weighed sorbents were added to labeled oil-spill cups, with six cups of each weight prepared for all sorbent types. Control cups with no sorbent were also set up. All reactions were incubated for two hours at room temperature. To measure the oil absorbed by each of the sorbents tested, a clean graduated cylinder with a sieve inside a funnel was set up. The reaction mixture from each cup was decanted into the cylinder after the incubation period. The remaining water and oil levels were measured and recorded using the graduated markings on the cylinder. The sorbent material was weighed after the reaction incubation to determine its mass increase. These steps were repeated for all six trials, and the data were recorded. For data analysis, quantitative data were organized into tables using Microsoft Excel. Averages and standard deviations for the six trials in each setup were calculated. The data were plotted as line graphs with error bars to visualize trends. A two-tailed T-test was performed to evaluate significant differences between groups. The use of T-test over traditional ANOVA was chosen, because ANOVA can compare the four tested groups simultaneously to determine if at least one group differs, but it does not specify which groups are significantly different from each other. In contrast, the two-tailed t-test, although limited to pairwise comparisons, allowed a more detailed and direct evaluation of specific group differences.

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Evaluating microscopic changes in organic sorbents:

Microscopic slides of moss and banana bark samples were prepared before and after oil absorption. The samples were observed under a microscope (400X) to identify microscopic changes in the materials caused by oil absorption. A water-soluble dye (1 drop) was added to samples after oil absorption to visualize the contrast between oil and water.

Evaluating Lipase Production:

Multiple samples were collected from moss and banana bark using sterile cotton swabs before and after oil absorption. The collected samples were streaked onto sterile trypticase soy agar (TSA) plates and incubated at 25°C for 48 hours. After incubation, distinct colonies (that must appear at least three times from three independent samples) were selected and streaked onto tributyrin agar (TBA) plates to assess lipase production and lipid degradation. The TBA plates were incubated at 25°C for 48 hours. Observations were recorded, and photographs were taken of the colonies showing lipid hydrolysis.

Preparing solutions:

To Prepare LB media for freshwater simulation, 2% LB broth was prepared by dissolving 7 grams of LB media powder in 200 ml distilled water and then making up the final volume to 350 ml. The solution was sterilized in a 500 ml capacity conical flask using an autoclave (121 degrees Celsius, with 15 psi pressure, for 20 minutes). To prepare LB media with NaCl for saltwater simulation, 2% LB with 3.5% NaCl was prepared by dissolving 7 g of LB media powder and 8.75 g of NaCl in 200 ml distilled water and then making up the final volume to 350 ml. The solution was sterilized in a 500 ml capacity conical flask using an autoclave. To prepare motor oil for simulations: 110 ml of motor oil in a 500 ml conical flask was sterilized using an autoclave

Formulating oil spill simulations and setting up reactions for assessing oil degradation:

Freshwater simulation was prepared by aseptically pipetting 4 ml of the 2% LB media overlayed with 1 ml of sterilized motor oil in a sterile 15 ml sterile tube. Saltwater simulation was prepared by aseptically pipetting 4 ml of the LB media with NaCl overlayed with 1 ml of sterilized motor oil in a sterile 15 ml sterile tube. This simulates a 20% concentration of oil in an oil spill simulation. A total of 6 tubes in each freshwater and saltwater simulation were used for control (no bacterial inoculation) and 6 tubes were used for each of the cultures tested in freshwater and saltwater simulation. A total of 108 tubes were prepared for 6 trials of each category. Qualified Scientist revived bacterial cultures #2, 3, 6, 10, 11, 12, 13, 14 from -800°C and grew each culture to obtain logarithmic phase growth until OD 600 was one. Each culture was added to the labeled tube at 5 million bacteria per tube density. All the reaction test tubes were incubated at 250°C (to mimic room temperature) using an incubator shaker (all tubes will be labeled, tightly capped, and taped). For data collection, all tubes were marked and labeled, and the height of the oil column in a tube was measured as millimeters (mm) of leftover oil at time 0 hours (before incubation). After each incubation point (24, 48, and 72 hours), the reaction tubes were taken out of the incubator shaker and centrifuged at 3000 rpm for 5 minutes to clear the border between oil, foam, and medium. The height of the oil column in the reaction tube was measured. After the data collection, all the biohazardous material was discarded by the qualified scientist. All incubated media with growing bacteria was collected in a large 2-liter conical flask and autoclaved. Then, all the liquid was transferred to the Laboratory Media Discard Canister. The empty test tubes were discarded in biohazard trash. For data analysis, the amount of oil left (out of 1 ml added) after the incubation (24, 48, and 72 hrs.) in reactions was measured as the height of the oil column (mm). The data collected was transformed into a percentage for standardization and relative comparison with 0-hour incubation. The objective is to assess the rate of motor oil consumption over time (0-72 hours) in freshwater and saltwater. To accomplish this, all data (in millimeters) will be recorded in a table and converted into several linear models to analyze. T-test statistical analysis will be employed, which allows for the comparison of group averages, all of which will be used to draw conclusions.

Identification of culture:

To identify culture #6, a matrix-assisted laser desorption/ionization-time of flight (MALDI-TOF) mass spectrometry approach was employed. The live bacterial sample was submitted to the Charles River processing lab at Newark, DE. Protein extracts from culture #6 were analyzed using a calibrated MALDI-TOF mass spectrometer to yield a unique protein spectral fingerprint. The obtained spectra were compared against a comprehensive reference database of bacterial profiles for species-level identification. For further confirmation, sequence-based analysis of protein-coding genes was performed. Total DNA extracted from culture #6 was used as a template for amplifying protein-coding genes using polymerase chain reaction (PCR) with specific primers targeting conserved bacterial sequences. The PCR products were purified and sequenced using Sanger sequencing. The resulting sequences were aligned and compared with entries in the National Center for Biotechnology Information (NCBI) database using the Basic Local Alignment Search Tool (BLAST). The identification of culture #6 was confirmed through a high sequence similarity to known entries. Additional phenotypic characteristics of culture #6 were examined through

microscopy and biochemical assays. Culture #6 was stained using a standard Gram staining protocol to visualize the cell morphology and arrangement. For the salt tolerance test, growth assays were conducted in media containing increasing concentrations of NaCl (up to 10%) to confirm salt tolerance using mannitol salt agar media. Additional enzymatic activity biochemical tests were performed to assess the production of key enzymes. For catalase activity, hydrogen peroxide was added to a colony to observe effervescence. An oxidase test strip was used to observe color change indicative of oxidase activity.

Risk/Safety:

All procedures were conducted using appropriate personal protective equipment (PPE), including lab coats, face shields, heat-resistant gloves, and closed-toed shoes, in compliance with BSL-2 laboratory standards. The use of car motor oil in experimentation presented potential health and environmental risks. Direct contact with motor oil can cause skin irritation, and improper disposal may result in soil and water contamination. To address these concerns, all experiments were performed in a well-ventilated area and used motor oil was disposed of following local environmental regulations and safety guidelines. When operating the autoclave, safety protocols such as pressure and temperature monitoring, automatic interlocking systems, and safety valves were followed to prevent hazards during sterilization. The laboratory was equipped with appropriate containment facilities, including biosafety cabinets, to support safe handling of materials. All personnel received training from a designated supervisor or qualified scientist on potential hazards, proper handling techniques, autoclave usage, disposal of biohazardous waste, and emergency procedures. By adhering to these established safety protocols and fostering a culture of safety, the potential risks associated with the experimental procedures were effectively minimized, ensuring the protection of both researchers and the environment.

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Authors

Mahie Patil, a high school student from Orlando, Florida, is driven by a deep interest in solving real-world challenges through interdisciplinary science. Her research projects reflect a passion for innovation in biological sciences, environmental microbiology, human behavior, and artificial intelligence. Through these endeavors, she combines curiosity with creativity to solve problems in STEM fields. Shivani Persaud (Mentor) brings over 15 years of experience in scientific education and laboratory supervision. She holds a Bachelor of Science in Medical Laboratory Science and a Master of Arts in Biology (Biotechnology) from Hunter College. Her professional background includes leadership roles at Valencia College, Olympia High School, and Columbia University Medical Center. She is committed to mentoring aspiring scientists and advancing STEM education.

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