Bioremediation of Heavy Metals with Waste Lignocellulosic Biomass: Business Analysis

Excerpts from “Bioremediation of Heavy Metals with Waste Lignocellulosic Biomass” by Gabriel Gonsalves Bertho, Albert Manfredi, Christopher Deeley, and Akash Jain

Please refer to the original document for further documentation on any examined cases.

Table of Contents

Executive Summary

This project had the goal of developing a low-cost alternative for removing toxic heavy metals, in particular arsenic, lead, and cadmium, from industrial wastewater. The proposed process involves using a hybrid batch and continuous process mainly consisting of heavy metal removal in a series of 5 adsorption beds packed with coconut coir coated with *P. putida* biofilm, then combustion of the saturated coconut for the production of steam. The process goal was to treat 1 MGD of wastewater at a lower cost than ion-exchange plants which cost $0.02/lb of wastewater treated. The proposed coconut-based bioremediation was estimated to cost $0.00304/lb of wastewater treated, 15.2% of the cost of ion exchange, being economically advantageous. In addition, the energy generation in the biomass boiler led it to have a net-negative GHG emissions footprint of -4640 kg CO2e per day. Profitability analysis with clean water being sold at the pricepoint of ion exchange indicates an ROI of 102.5% and IRR of 96%, over the 17-year project in the base case scenario, resulting in an NPV of $146M. Our results suggest that the use of lignocellulosic biomass, especially coconut coir for large-scale wastewater treatment processes for heavy metal removal is a viable alternative to existing treatment mechanisms, being environmentally friendly and economically advantageous.

Value Proposition

Improper management of industrial waste is a leading source of heavy metal pollution. Waste dumpsites have a significant deleterious impact on the environment, being highly detrimental to the health of the fauna and flora in neighboring areas.[1]

Heavy metals in industrial wastewater can result from processes such as electroplating, municipal waste treatment, metal finishing, and mining. For the cases of liquid waste, chemical precipitation with hydroxides is one of the most widely used methods for heavy metals removal but has been losing popularity due to the associated generation of a toxic sludge that is hard to manage and that, itself, poses an environmental risk.[2] Alternatively, membrane and ion exchange processes have been used as effective methods for heavy metal remediation with lower sludge generation. However, the high costs associated with the operation and the maintenance of membranes and ion-exchange resins are not attractive to the industry, especially at sites with relatively lower generation of metal-contaminated wastewaters.[3] Thus, considering the constraints of current methods and the environmental impact of waste dumpsites, decreasing the costs of heavy metal removal is crucial to encourage companies to treat and reuse their liquid waste.

In the last decades, biosorption of heavy metals with lignocellulosic materials and microbial biofilms has gained attention as a low-cost alternative to synthetic adsorbent materials. The functional groups in cellulose have the capability of complex formation with metals, thus allowing a variety of agricultural waste materials to be applicable for metal removal.[4] Among lignocellulosic materials, coconut fiber (or coir) is a particularly attractive candidate. Coconut fibers have a porous structure that leads to high adsorption capacity, and serves as a site for biofilm formation.[5] The complex microbial consortiums and morphologies present in biofilms have been demonstrated to enhance the efficiency of microbial processes applicable to wastewater treatment.[6] Furthermore, coconut husk has a very low cost as it is an abundant waste in tropical countries.[4]

Stakeholders

Relevant stakeholders for this project include the government, private companies, public and employees, the environment, researchers, and public-private water utilities. Government regulatory bodies and policymakers are responsible for implementing regulations that ensure the safe and sustainable disposal of wastewater containing heavy metals. Government bodies are also responsible for monitoring and evaluating regulation compliance, with an interest to protect public health and prevent further release of heavy metals into the ecosystem. Private companies within industries such as mining and chemical processing facilities that produce wastewater containing heavy metals are also key stakeholders in the management of contaminated effluent as primary producers. These companies have a responsibility to ensure a safe and environmentally responsible disposal regimen within the regulatory framework. The public and employees located in and within reasonable proximity to these facilities are stakeholders due to health risks requiring safe containment and working conditions , as well as reporting of facility practices. Environmental consequences of improper heavy metal handling including contamination of soil and water sources, require stakeholders to maintain ecological balance and ensure that natural resources are protected from pollution. In addition to these direct stakeholders, researchers are critical to development that will enable safer, more efficient and lower cost filtration. Public-private water utilities are responsible for treating and distributing water to the general public and would be adversely affected by downstream heavy metal contamination, possibly requiring more costly treatment methods or more stringent government regulation.

Building Permits and Regulations

It is essential for wastewater treatment processes such as the bioremediation process to understand the legal and regulatory hurdles necessary before construction. As our plant will be co-located with other wastewater treatment plants, many of the permits may already be in possession. In any event, this section lists some of the key permits and regulatory agencies that will be involved in the bioremediation plant, as well as some laws that may pertain to the investments of the plant.

On a national level, the main regulatory body is the Environmental Protection Agency and the Office of Wastewater Management. Specifically, plants must abide by the National Pollutant Discharge Elimination System Permit Program (NPDES).[119] The program outlines the standards for toxic pollutants and requires robust reporting requirements and techniques to monitor effluents to receive a permit. Most state regulations and laws require an NPDES permit as a prerequisite to other important state level permits.

States vary on the level of permits required for wastewater treatment plants. For the purposes of this section, Florida permits will be analyzed, the base case location for the process. According to Chapter 403 of the Florida Statutes, industries and businesses that collect, treat or dispose are required to obtain a wastewater permit from the Florida Department of Environmental Protection (DEP) in addition to NPDES permits.[120] Once licensed by the Florida DEP, there are several additional permits that can be required based on different circumstances. There are significant industrial user wastewater permits, groundwater discharge permits, hauled wastewater discharge permits, and surcharge permits exceeding the characteristics of normal wastewater. As a result, as this wastewater treatment component removes heavy metals, the surcharge permits would be acquired.

2022 Inflation Reduction Act

The Inflation Reduction Act (IRA) of 2022 contained an amalgam of provisions designed to promote green technology investment and reduce GHG emissions. More than reducing inflation, it encourages investments into manufacturing and carbon neutral construction. The Business Energy Investment Tax Credit (ITC) is of relevance to the bioremediation process as it could produce significant financial incentives in the form of tax credits. For projects beginning construction by December 31, 2024, the IRA grants a tax credit of up to 30% on the equipment costs and subsequent bonus credits to all utility facilities with zero or net negative carbon emissions.[121] While the intended target for this bill is power plants and electrical companies, because our bioremediation process is a utility treating wastewater and generates steam that is to be sold for power, it could qualify for the tax credit.[122]

The ITC would drastically improve the profitability of our design as the equipment costs are one of the largest costs associated with it. If the equipment costs can garner a tax credit of up to 30% of the value, it would drastically reduce overall process costs and push the project even more into the green. While the likelihood that the wastewater plant would qualify for the tax credit is still a bit murky, it is worth considering the sake of the project and those looking to adopt the design moving forward. The IRA makes it easier for investors to provide capital to carbon-neutral industrial plants as well; thus, in any event the IRA has had a positive financial impact on our design and process.

Market Research and Competition

The market opportunity for coconut coir-based bioremediation of heavy metals is significant and expected to continue to grow as anthropogenic heavy metal intensive processes are increasingly relied on for industrial production.[7] Given that coconut coir is a renewable and biodegradable material that is abundantly available at an inexpensive price point, and that it has a high affinity for heavy metals[8], it is relevant to explore whether coconut coir can competed can compete with less sustainable resin-based approaches for heavy metal remediation.

The global market for heavy metal remediation is estimated to be worth USD 109.3 billion in 2022 and expected to grow at an 8.4% compound annual growth rate (CAGR) to USD 163.4 billion by 2027.[9] This market growth is driven by the increasing demand for nontoxic wastewater, the rising awareness of the dangers of heavy metal pollution, and the stringent environmental regulations being implemented by governments.[10]

Primary Incumbant: Ion Exchange

Ion exchange is a widely used method to remove heavy metals from wastewater in industrial processes. It consists of the usage of synthetic resins to remove the undesired metals from wastewater by exchanging them with non-toxic ions of the same charge, and its application is very similar to that of adsorption. Saturated resins can be regenerated with highly concentrated solutions of a suitable ionic species, such as sodium chloride, which releases the heavy metals and replaces them with the ions from the regenerating stream. Some of the most commonly used ion-exchange resins for heavy metal filtration include strong acid cation (SAC) resins, weak acid cation (WAC) resins, and chelating resins.[11,12]

The contaminated effluent from regenerating streams should be disposed of safely. However, disposal methods depend on the government regulations. Historically, heavy metal waste has sometimes been dumped directly into the environment.[10] The most commonly recommended method of disposal is in a properly lined landfill or incineration. While processes to recover the metals have been proposed, the high separation costs have not made such processes feasible thus far. Ion exchange processes can range from a few cents to several dollars per gallon of wastewater treated, depending on the specific conditions. Thus, ion-exchange can be more expensive than other methods, such as chemical precipitation or sedimentation, which typically cost a few cents per gallon.

Resins fabricated for specific applications tend to range anywhere from \$500 to \$2,000 and up per cubic foot, while SAC/WAC resins are \$40 to \$200 per cubic foot. In addition to the resin purchase cost, storage tanks, metering pumps, and forwarding pumps, cost can cost from \$100,000 to \$300,000 depending on the size of the plant.[13] At the end of the resin life, recycling is unfeasible since there are few facilities capable of processing polystyrene or acrylic spent resins. In order to process 1 million gallons of heavy metal waste a day, industry sources suggest a counter-current system at about 2,000 gallons per minute using a proprietary packed-bed technology, such as DOW's ADVANCED AMBERPACK™ or UPCORE™ Ion Exchange technology. The cost is estimated to be between \$7 M and \$10M. This estimate does not account for solid handling systems and additional safety equipment. Volatile costs are mainly due to disposal fees for the regeneration streams contaminated with heavy metals (usually brine). How often the resins must be regenerated is highly dependent on the wastewater and the conditions of the ion-exchange resins. Eventually, the resins will also have to be disposed, being usually done every four to ten years after installation.[14]

The problem statement of this project estimated a cost of $0.02 per lb of wastewater treated for ion-exchange processes, which is a high-end estimate. Nonetheless, any process with a lower cost will be competitive to ion-exchange due to its environmental issues related to regeneration streams.

Coconut Fiber Market Analysis

Coconut coir is a natural fiber obtained from the outer husk of coconuts. It can be used in agriculture/horticulture, packaging, construction, and wastewater treatment. Given the fast growth rate of coconut, it is essential to carbon sequestration and has a marker that is expected to grow at a CAGR of 8.2% during the forecast period of 2021-2028.[15] The agricultural sector is the largest end-user of coconut coir, utilizing it for soil amendment, mulch, and as a pith basis for a growing medium used for potting mixes, seed starting medium, and rooting medium.[16] It is also used to make coco coir logs, which are used as a growing medium for many flowering plants. The packaging industry uses coco coir as a cushioning material, filler material, and absorbent material in coco coir mats, which are used to protect products during transportation.[17] Finally, coco coir is used in construction as a binder, filler, and insulation material. It is also used to make cement and particle coco coir boards, which are used as a building material in low-cost housing and other construction applications.[18,19]

Despite the numerous applications of coconut coir, a great portion of coconut waste ends up in landfills, taking a considerable volume. For instance, Brazil is estimated to landfill 7 million tons of coconut husk per year.[20] As new applications for coconut husk are developed, this market is expected to grow significantly. Any application of coconut coir reduces the amount of waste landfilled, thus decreasing its carbon footprint and overall environmental impacts, being highly encouraged by the industry.

Bacterial Growth Market Analysis

The microbial growth culture market is currently valued at USD $2.3 billion.[21] Due to the rise in biologics-based biotechnology and pharmaceutical research coupled with heightened demand for fermented consumer products, many vendors suppliers have emerged in this booming and competitive industry. The current CAGR is 5% and the market is expected to reach USD 2.91 billion by 2030.[22] The microbial growth culture market is divided into two distinct parts: agar for plating and liquid broths for bacterial growths.

Liquid broths are of interest for bacterial growth as a part of the feedstock for the biofilm development. Microbial growth media is to be formulated on site for two reasons: first to reduce costs of the raw materials and second to modify the broth to improve biofilm development and make the coconut coir more favorable for adsorption of heavy metals. The raw materials for our microbial growth broth include those similar to LB growth media: yeast, tryptone, H_2O, and NaCl. The current costs and supplier information are displayed in **Table 7.1.**

Table 7.1 Price of Raw Materials for Biofilm Growth Broth and their suppliers. The sum of the total per ton LB Growth culture is totaled to demonstrate the overall raw material cost.

Raw Material	**Cost per metric ton (USD)**	**Source / Supplier**
Yeast Extract	$1000	BCC[23]
NaCl	$8.5	USGS[24]
Glucose	$580	Selina Wamucii[25]
DI Water	$1.5	Seider et al.[26]
Tryptone	$12800	OurBio[27]
Total LB Growth Culture	**$461**	

Geographically, North America accounts for the largest part of the market for microbial growth culture with the major competitors and suppliers Becton, Dickinson and Company, Bio-Rad Laboratories, Inc., bioMérieux S.A., Eiken Chemical Co., Ltd., Hi-Media Laboratories Pvt. Ltd., Merck & Co., Inc. (MilliporeSigma/ Merck KGaA), Neogen Corporation, Scharlab, S.L., Sigma-Aldrich, and Thermo Fisher Scientific, Inc.[21] There are also a growing number of suppliers in Asia that are able to produce high quality raw

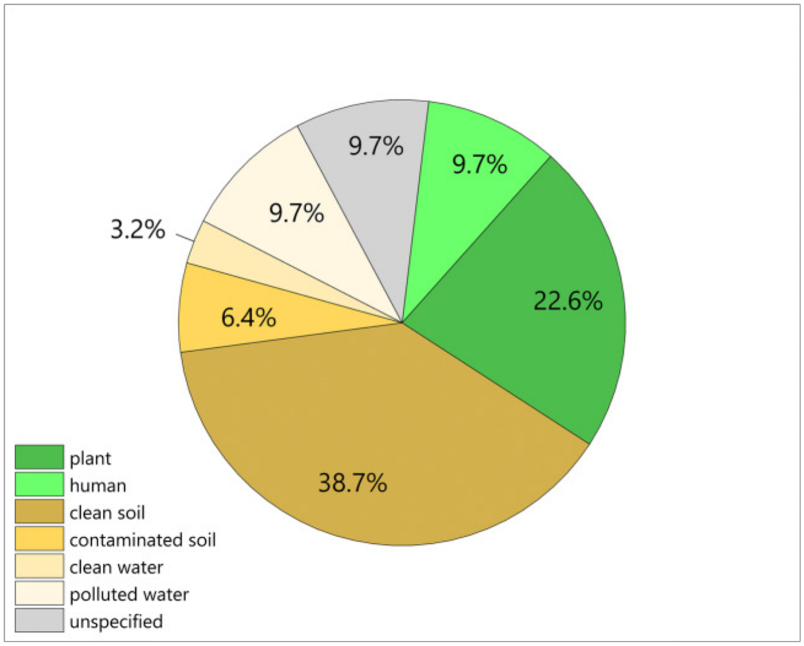

Figure 7.1. Source distribution of *P. putida* from the wild sources of plants, humans, clean soil, contaminated soil, clean water, and polluted water. Most notably, *P. putida* are derived from clean soil (38.7%) and plants (22.6%).

materials at a relatively low cost such as OurBio which we use to supply tryptone in our biofilm growth feedstock.[27]

Pseudomonas putida (P. putida) is often used in industry as a cell factory due to its versatile metabolism, hardiness against shear and chemical stress, and its resilience in large-scale production.[28] *P. putida* grows well on lignocellulosic biomaterials, making it well suited to grow on the coconut coir. These bacteria are also readily engineered for use in various applications. Notably our strain has been modified to improve its biofilm growth characteristics. These strains are tabulated in **Appendix F**. *P. putida* is isolated by suppliers from diverse sources summarized in **Figure 7.1**[29]**;** the bacteria are then purchased and grown in industry.[28] The 6.4% and 9.7% prevalence in contaminated soil and water, respectively, result from relatively idealized growth conditions in those settings. *P. putida* can be purchased for a low fixed cost of $13.35 and then readily stored as a bacterial starter.[29] As a result, *P. putida* is cheaply available, readily purchased and easily used for our biofilm development process.

Competitive Patent Analysis

This section presents an analysis of previous and active patents relating to wastewater treatment using coconut coir, microorganisms, or similar processes to the one described in this report that could warrant a competitive or legal challenge and creates a strategy to address those threats. Patent CN217188071 was filed in China by Anhui Ocean Green Technology LLC in 2022 and is currently active.[31] This patent creates filters of composite organic media and develops a bump filter to pass through multiple cavities to treat wastewater. Most notably, the packing layers are comprised of zeolite, coarse sand, soil, and coconut coir. It is a utility patent specifically for sewage systems, so our design that focuses on heavy metal wastewater is still novel, especially when considering the addition of a biofilm. However, close attention should be paid to competitor filtration systems such as these as they are decentralized filter systems and not wastewater process plants with different markets. While they address different markets, the technologies are related in some sense.

Patent CN211471008U is another Chinese patent filed by Guangdon Ruisheng Environmental Protection.[32] This utility model involves another filter for wastewater treatment using multiple boxes. Interestingly, it uses a filter core of activated carbon and coconut husk granules to adsorb poisonous substances. This marks a patent that specifically highlights coconut husk adsorption properties. While this patent was filed in 2019, it expired as the inventors failed to pay the fee, meaning there is no competitive effect on our process.

There are two South Korean patents that utilize biofilms as a means of treating wastewater. Patent KR101422528B1 uses a wastewater treatment system that includes a biofilm reactor that is used to remove toxins from the water supply.[33] Another patent, KR20050012876A, utilizes a concoction of microorganisms adhered to an activated carbon adsorber to enhance the adsorption capacities of the filtration system.[34] However the latter patent is no longer active and was filed in 2005. Both of these patents use microbes to create a reaction packed with other layers of filtration material to remove a variety of contaminants and toxins. While these patents demonstrate other inventors have envisioned using microbes as a means to enhance adsorption, other patents can be crafted specific to *P. putida* upon a raw biomaterial and non-activated carbon filter like our process to ensure it is patent protected.

There are two active patents in the United States that share similarities with our proposed bioremediation process. Patent US11053147B2 was filed in 2019 and is currently active claiming the design of a horizontal flow biofilter system. Its novelty is in maximizing the surface area for water to be treated by the biofilter.[35] A second patent, US20070170115A1, is more similar to our process in using a powdered natural lignocellulosic materials (including that of coconut husk) to remove colloidal volatile solids and adsorbing toxic substances that harm biological life and bacteria.[36] This patent contains a continuous wastewater treatment process, but it is different as it uses a completely fluidized bed with powderized lignocellulosic material of a variety of sources. However, there are once again no specifications of the type of microbe used in the biofilter process and no combination of a biofilm with pure coconut husk as the lignocellulosic support.

As a result of the gaps and over-specificity in existing patents, the bioremediation process of this report has a clear path forward to pursue its own intellectual property if it is able to highlight three novel ideas. First, highlight the combination of *P. putida* biofilm and coconut coir as an adsorption packing. Second, emphasize the heavy metals specifically being treated in sewage or wastewater. Third, warrant a utility patent based on the complete process design of the adsorption system and batch and continuous processes to complete the patent.

Raw Material Cost Summary

The costs of the raw materials used in this bioremediation process are presented in **Table 14.1.1** These costs include international freight costs for materials that are unlikely to be available at quantities in the U.S.

Table 14.1.1: Raw Material Costs and Suppliers in USD per metric ton.

Material	Function	Cost per metric ton	Source
Raw Coconut Coir	Heavy metal Adsorption	$285	Dailoc Vina[72]
Glucose	Biofilm Formation	$580	Selina Wamucii[25]
Tryptone	Biofilm Formation	$12800	OurBio[27]
Yeast Extract	Biofilm Formation	$1000	BCC[23]
Brine	Biofilm Formation	$8.5	USGS[24]
D.I Water	Biofilm Formation	$1.5	Seider et al.[26]
Pseudomonas Starter	Biofilm Formation	$13.35 per bed	Carolina Science[29]
Ash	Byproduct	$318 (disposal)	Seider et al.[26]

In addition, excess 50 psig steam from the biomass boiler is considered to be sold at $13.2/metric ton.[26] The availability of coconut coir varies significantly according to location, India being the largest producer. For that reason, an analysis of coconut coir cost per location and its associated freight costs to the U.S are listed in **Table 14.1.2.**

Table 14.1.2: Coconut coir cost per location.

Supplier Location	Cost per metric ton	Freight Cost to the U.S per metric ton of coir	Total Cost per metric ton of coir
Vietnam[72]	$7	$278	$285
Brazil[73]	$200	$71	$271
India[74]	$130	$420	$550
U.S (Distributor which imports from Indonesia)[75]	$353	-	$353

The Vietnam distributor was selected for the base case due to its cost and its appropriate monthly capacity. The freight and material costs are in the high-end due to the effects of the COVID-19 pandemic and are expected to decrease in the following years. The data collected indicates that depending on where the wastewater treatment plant is located, there would be much lower costs of coconut coir.

Equipments Cost Summary

Economic analysis was integrated with equipment sizing to obtain optimum values that minimized costs.. The total bare module cost for all equipment is $16.94 M, and is summarized in Tables 20.1 ~ 3. This value includes subordinate parts specified in section 19 of this report. Adsorption beds are the main bulk of the cost, contributing 61% of the total. Stainless steel is used for the main equipment of the bioremediation portion of the process (AP-1 ~ 5, AB-1 ~ 5, HX-1, HX-2) to increase their lifespan. **Table 20.1** summarizes the process equipment, which constitutes 95% of the total equipment cost.

Table 20.1: Processing Equipment Costs Table

ID	Equipment Name	Purchase Cost (USD)	Bare Module Factor	Bare Module Cost (USD)
A-P-1	Adsorption Column 1	$249,204	4.16	$1,036,687
A-P-2	Adsorption Column 2	$249,204	4.16	$1,036,687
A-P-3	Adsorption Column 3	$249,204	4.16	$1,036,687
A-P-4	Adsorption Column 4	$249,204	4.16	$1,036,687
A-P-5	Adsorption Column 5	$249,204	4.16	$1,036,687
A-B-1	Adsorption Column Backup 1	$249,204	4.16	$1,036,687
A-B-2	Adsorption Column Backup 2	$249,204	4.16	$1,036,687
A-B-3	Adsorption Column Backup 3	$249,204	4.16	$1,036,687
A-B-4	Adsorption Column Backup 4	$249,204	4.16	$1,036,687
A-B-5	Adsorption Column Backup 5	$249,204	4.16	$1,036,687
DA-1	Deaerator	$20,000	3.21	$64,200
P-1	Pump 1	$11,993	3.30	$39,577
P-2	Pump 2	$11,588	3.30	$38,242
P-3	Pump 3	$11,588	3.30	$38,242
P-4	Pump 4	$11,588	3.30	$38,242
P-5	Pump 5	$11,588	3.30	$38,242
P-6	Pump 6	$8,201	3.30	$27,064
P-7	Pump 7	$10,349	3.30	$34,153
BTC-1	Belt Conveyor 1	$32,478 (4 units)	3.21	$417,020
BTC-2	Belt Conveyor 2	$17,661 (4 units)	3.21	$222,164
BTC-3	Belt Conveyor 3	$6,986 (2 units)	3.21	$44,596

ID	Equipment Name	Purchase Cost (USD)	Bare Module Factor	Bare Module Cost (USD)
BTC-4	Belt Conveyor 4	$39,382	3.21	$126,416
BTC-5	Belt Conveyor 5	$9,345	3.21	$29,999
PC-1	Pneumatic Conveyor	$145,456	3.21	$466,913
PC-2	Pneumatic Conveyor	$145,456	3.21	$466,913
BF-1	Belt Filter 1	$28,000	3.21	$89,880
BF-2	Belt Filter 2	$28,000	3.21	$89,880
BB-1	Biomass Boiler	$495,000	4.00	$1,980,000
HX-1	Heat Exchanger 1	$147,737	3.29	$486,201
HX-2	Heat Exchanger 2	$179,954	3.29	$592,228
HX-3	Heat Exchanger 3	$52,567	3.29	$172,997
HX-4	Heat Exchanger 4	$49,375	3.29	$162,493
BP-1	Bale Processor	$35,550	1.09	$38,750
Total				**$16,071,282**

The biomass boiler BB-1 was considered to have a bare module factor of 4 to account for the costs of flue gas filters that can retain fly ash contaminated with heavy metals, and other equipment to avoid environmental contamination. Furthermore, as the bale processor BP-1 is a portable equipment, only freight, taxes, and insurance were accounted for in the bare module factor. **Table 20.2** summarizes the storage equipment costs. It is important to note that the SC-1 is a warehouse and not an equipment, being the reason it has a bare module factor of 1. To account for construction costs of SC-1, an increased cost of service facilities was factored (**Table 21.1**). A bare module factor of 3.21 for SL-1 was considered due to its special ancillary equipment.

Table 20.2: Storage Equipment Costs Table

ID	Equipment Name	Purchase Cost (USD)	Bare Module Factor	Bare Module Cost (USD)
SL-1	Spent Coconut Storage Silo	$110,991	3.21	$356,280
SC-1	Dry Coconut Storage Shed	$40,364	1.00	$40,364
TK-1	Ash Storage Tank	$63,286	3.00	$189,858
TK-2	Tryptone Storage Tank	$6,519	3.00	$19,556
TK-3	Yeast Extract Storage Tank	$4,568	3.00	$13,704
TK-4	Brine Storage Tank	$2,600	3.00	$7,800
TK-5	Glucose Storage Tank	$6,519	3.00	$19,556
SK-1	Ash SuperSacks	$6000	1.00	$6000
Total				**$653,118**

Considering that the main equipment units (adsorption beds) are highly expensive, that the streams consisted mainly of nearly-pure liquid water, and that stainless steel was used as construction material, only spares for the pumps were considered and are summarized in **Table 20.3**.

Table 20.3 Spare Equipment Costs Table

Equipment Name	Purchase Cost (USD)	Bare Module Factor	Bare Module Cost (USD)
Spare Pump 1	$11,993	3.30	$39,577
Spare Pump 2	$11,588	3.30	$38,242
Spare Pump 3	$11,588	3.30	$38,242
Spare Pump 4	$11,588	3.30	$38,242
Spare Pump 5	$11,588	3.30	$38,242
Spare Pump 6	$8,201	3.30	$27,064

Equipment Name	Purchase Cost (USD)	Bare Module Factor	Bare Module Cost (USD)
Total			**$219,609**

All equipment costs except biomass boiler, storage shed, bale processor, belt filters, and deaerator were estimated following the methods described in Chapter 16 of Seider et al.[26] A CEPCI of 820 was used.

Fixed Cost Summary

The total permanent investment of the process was estimated to be $ 24.7 M. It was calculated following the methodologies in Chapter 16 of the Seider et al. textbook integrated into a Python code to optimize equipment sizing (more info in **Appendix A**). Costs of service facilities were assumed to be higher than default to account for the coconut coir shed. **Table 21.1** presents the assumptions made for the calculation of total permanent investment.

Table 21.1 Assumptions for Total Permanent Investment.

Site Factor:	1.0 U.S Gulf Coast
Year of Total Permanent Investment:	100% in 2024
Cost of Site Preparation:	5.00%
Cost of Service Facilities:	5.50%
Allocated Costs for Utility Plants:	$0
Cost of Contingencies and Contractor’s Fees:	18.00%
Cost of Land:	2.00%
Cost of Royalties:	$0
Cost of Plant Startup:	10.00%

Following these assumptions, **Table 21.2** summarizes all the costs calculated for the total permanent investment.

Table 21.2 Summary of Total Permanent Investment

Investment Summary

Total Bare Module Costs:		
Fabricated Equipment	$ -	
Process Machinery	$ 16,071,281	
Spares	$ 219,608	
Storage	$ 653,119	
Other Equipment	$ -	
Catalysts	$ -	
Computers, Software, Etc.	$ -	
Total Bare Module Costs:		**$ 16,944,008**
Direct Permanent Investment:		
Cost of Site Preparations:	$ 847,200	
Cost of Service Facilities:	$ 931,920	
Allocated Costs for utility plants and related facilities:	$ -	
Direct Permanent Investment		**$ 18,723,129**
Total Depreciable Capital:		
Cost of Contingencies & Contractor Fees	$ 3,370,163	
Total Depreciable Capital - Unadjusted		**$ 22,093,292**
Site Factor		1.00
Total Depreciable Capital		**$ 22,093,292**
Total Permanent Investment		
Cost of Land:	$ 441,866	
Cost of Royalties:	$ -	
Cost of Plant Start-Up:	$ 2,209,329	
Total Permanent Investment - Unadjusted		$ 24,744,487
Site Factor		1.00
Total Permanent Investment		**$ 24,744,487**

Operating Cost Summary

Process Material

The feed to this process is wastewater contaminated with heavy metals from a process facility. Coconut coir is the feed material for adsorption, and LB growth media is the substrate needed for biofilm growth. All materials in **Table 22.1** except coconut coir are constituents of the L.B growth media. The costs of the raw materials are shown in **Table 22.1.**

Table 22.1: Cost of Raw Material in 2024 dollars

Raw Materials

	Raw Material:	Unit:	Required Ratio:		Cost of Raw Material (per ton):
1	Coconut Coir	Tons	7.47E-07	Tons per lb of Clean Water	$285.000
2	Glucose	Tons	2.49E-09	Tons per lb of Clean Water	$580.000
3	Salt	Tons	2.79E-09	Tons per lb of Clean Water	$8.500
4	Yeast	Tons	6.23E-10	Tons per lb of Clean Water	$1000.000
5	Tryptone	Tons	1.25E-09	Tons per lb of Clean Water	$12800.000
6	DI Water	Tons	4.98E-06	Tons per lb of Clean Water	$1.500
7	Pseudomonas Starter	Tube	3.13E-08	Tube per lb of Clean Water	$13.350
	Total Weighted Average:			$2.389E-04 per lb of Clean Water	

Product Costs

In order to compare the process described in this report to ion-exchange, the selling price of clean water was considered to be $0.02/lb, which is the cost of ion-exchange provided in the problem statement. This project focuses on cost minimization of wastewater treatment. In reality, the application of the process described in this report would not generate revenue as sales. **Table 22.2** summarizes the selling price or cost of the product and byproducts.

Table 22.2: Cost of Products and Byproducts in 2024 dollars

Products

Product:	Unit:	Byproduct Selling Price	
Clean Water	lb	$0.02	per lb
		8,345,391	lb per Day

Byproducts

	Byproduct:	Unit:	Ratio to Product		Byproduct Selling Price	
1	Excess Steam	Ton	4.45E-06	Ton per lb of Clean Water	$19.090	per Ton
2	Ash	Ton	1.49E-07	Ton per lb of Clean Water	-$3.188E+02	per Ton

Utilities Costs

As the biomass boiler of this process produces enough heat for all the heating utilities in this project, only electricity is needed. **Table 22.3** summarizes the cost of utilities.

Table 22.3: Utilities Costs Summary

Utilities

	Utility:	Unit:	Required Ratio		Utility Cost	
1	High Pressure Steam	lb	0	lb per lb of Clean Water		per lb
2	Low Pressure Steam	lb	0	lb per lb of Clean Water		per lb
3	Process Water	gal	0	gal per lb of Clean Water		per gal
4	Cooling Water	lb	0	lb per lb of Clean Water		per lb
5	Electricity	kWh	0.0002421265442	kWh per lb of Clean Water	$0.0101	per kWh

Other Variable Costs

Other variable costs were maintained as default according to the Economic Analysis v5 spreadsheet. The plant will be designed over one year and constructed an additional one. **Table 22.4** shows the values input for the general expenses.

Table 22.4: Other Variable Costs Summary

Other Variable Costs		
General Expenses		
Selling / Transfer Expenses:	3.00%	of Sales
Direct Research:	4.80%	of Sales
Allocated Research:	0.50%	of Sales
Administrative Expense:	2.00%	of Sales
Management Incentive Compensation:	1.25%	of Sales

Total Variable Costs

Following the assumptions listed in **Table 22.4, Table 22.5** presents the calculation of total variable costs.

Table 22.5: Variable Costs Summary

Variable Cost Summary		
Variable Costs at 100% Capacity:		
General Expenses		
Selling / Transfer Expenses:		$ 1,652,187
Direct Research:		$ 2,643,499
Allocated Research:		$ 275,365
Administrative Expense:		$ 1,101,458
Management Incentive Compensation:		$ 688,411
Total General Expenses		$ 6,360,920
Raw Materials	$0.000239per lb of wastewater	$657,774

Byproducts	$0.000037per lb of wastewater	($102,758)
Utilities	$0.000025per lb of wastewater	$67,496
Total Variable Costs		**$ 6,983,432**

Fixed Costs

Fixed costs were kept as default values into spreadsheet. The process will require 2 operators per shift, each earning $40 per hour, for 5 shifts. There will also be 2 technical assistance engineers and 1 control laboratory engineer, each earning a salary of $200,000 per year, including benefits. **Table 22.6** shows the fixed costs..

Table 22.6: Fixed Capital Costs Summary

Fixed Cost Summary	
Operations	
Direct Wages and Benefits	$ 832,000
Direct Salaries and Benefits	$ 124,800
Operating Supplies and Services	$ 49,920
Technical Assistance to Manufacturing	$ 20,000
Control Laboratory	$ 10,000
Total Operations	**$ 1,036,720**
Maintenance	
Wages and Benefits	$ 994,198
Salaries and Benefits	$ 248,550
Materials and Services	$ 994,198
Maintenance Overhead	$ 49,710
Total Maintenance	**$ 2,286,656**
Operating Overhead	

General Plant Overhead:	$ 156,168
Mechanical Department Services:	$ 52,789
Employee Relations Department:	$ 129,773
Business Services:	$ 162,767
Total Operating Overhead	**$ 501,497**
Property Taxes and Insurance	
Property Taxes and Insurance:	$ 441,866
Other Annual Expenses	
Rental Fees (Office and Laboratory Space):	$ -
Licensing Fees:	$ -
Miscellaneous:	$ -
Total Other Annual Expenses	**$ -**
Total Fixed Costs	**$ 4,266,738**

Working Capital and Total Capital Investment

Table 22.7 shows the tabulation of working capital changes from 2024 to 2026. The total capital investment is $28.8 M.

Table 22.7: Working Capital Required in First 3 Years of Operation

Working Capital

	2024	2025	2026
Accounts Receivable	$ 3,259,109	$ 407,389	$ 407,389
Cash Reserves	$ 256,492	$ 32,061	$ 32,061
Accounts Payable	$ (42,920)	$ (5,365)	$ (5,365)
Insert Product Here Inventory	$ 434,548	$ 54,318	$ 54,318
Raw Materials	$ 2,595	$ 324	$ 324
Total	**$ 3,909,823**	**$ 488,728**	**$ 488,728**
Present Value at 15%	*$ 3,399,846*	*$ 369,549*	*$ 321,347*
Total Capital Investment		**$ 28,835,228**	

Revenue Model and Sensitivity Analysis

The purpose of this process is to mitigate the prohibitive high cost of heavy metal removal from wastewater. In order to perform a profitability analysis and meet the constraints of the design project statement, the treated wastewater is assumed to be sold at the market price of wastewater treatment with ion-exchange at $0.02 per pound. The profit margins for use in the profitability analysis are the difference between the overall cost per pound of wastewater treated compared to the competitor price of ion exchange. For example, if the overall cost is 15% of the ion exchange treatment price, selling the wastewater treatment for $0.02 per pound would result in 75% profit for the plant. With this model in mind, the results of the profitability analysis are explained below in further detail.

Base Case Profitability Scenario

Profitability analysis was completed using a spreadsheet prepared by Brian K. Downey, Equity Research - US Royal Gas Exploration / Production, Sanford C. Bernstein & Co., LLC, and revised by Prof. Bruce Vrana, UPenn. **Table 24.1.1** outlines the key assumptions that served as inputs for the base-case profitability scenario including the location and key process decisions such as disposal operation and product pricing.

Table 24.1.1: Assumptions for base-case profitability analysis.

Location	Florida
Sale of Excess Steam	Yes
Number of Operators	2
Capacity of Operation	80%

Inflation Rate	3%
Cost of Capital	15%
Hazardous Disposal Costs for Ash	Yes
Product wastewater price	$0.02

The heavy metal bioremediation plant will begin construction in 2024 and commence operation at 80% capacity in 2025. Total capacity will be reached in 2025. A conservative general inflation rate of 3% is assumed in addition to a cost of capital of 15%. For the base-case calculation, the plant location is assumed to be co-located in Florida, using the gulf-coast site factor. Two operators are needed and limited lab support is provided by the existing wastewater facility. In the base case, bricks are not created by a partner organization to sequester the heavy metal, and instead a hazardous waste fee is levied to dispose of the ash produced by this process at the end of the adsorption packing life. High-pressure steam is assumed to be sold to the existing wastewater treatment plant. In exchange, the plant provides D.I water produced on site. Under base case utilities, feedstock and product prices, capital investment, and fixed costs, the plant will have an NPV of $146M, an ROI of 102.5%, and an IRR of 96.35% over the 17-year project.

Table 24.1.2 tabulates the base-case ROI analysis as a function of the annual sales, annual costs, depreciation, income tax, net earnings, and total capital investment. It also contains a key parameter recommended by the industrial consultants: the price to sell the wastewater treatment per pound to achieve 15% ROI. A 15% ROI is more reasonably what the project would target. While this profitability analysis was conducted assuming the treatment costs the same as competitors, pragmatic implementation of this design co-located to a wastewater treatment plant would mean charging a substantially lower price than competitors. As a result, a price of treatment of $0.0053 per pound of water would generate a 15% ROI on the base case scenario for the process.

Table 24.1.2: ROI Analysis Results for Base Case Year 3.

Annual Sales	52,584,157
Annual Costs	(11,194,517)
Depreciation	(1,944,261)
Income Tax	(9,072,437)
Net Earnings	30,372,942
Total Capital Investment	29,632,421
IRR	**96.34%**
NPV	**$146,672,800**
ROI	**102.50%**
Price for 15% minimum ROI	**$0.00524**

Table 24.1.3 shows the profitability measures in year 3 and cash flow statements for the lifetime of the project. Positive cash flows of $23M are attained in the second year of operation, and by the third year net earnings exceed $28M.

Table 24.1.3: Cash Flow Statement for Base Case.

Year	Design Cap	Unit Price	Sales	Capital Costs	Working Capital	Var Costs	Fixed Costs	Depreciation	Taxable Income	Taxes	Net Earn	Cash Flow	Cum NPV at 15%
2023	0%		-	-	-	-	-	-	-	-	-	-	-
2024	0%		-	(24,744,500)	(3,909,800)	-	-	-	-	-	-	(28,655,000)	(24,917,400)
2025	72%	$0.02	39,652,500	-	(488,700)	(5,028,100)	(4,266,700)	(4,418,700)	25,939,000	(5,966,000)	19,972,900	23,902,900	(6,843,300)
2026	81%	$0.02	45,947,300	-	(488,700)	(5,826,300)	(4,394,700)	(7,069,900)	28,656,500	(6,591,000)	22,065,300	28,646,600	11,992,300
2027	90%	$0.02	52,584,200	-	-	(6,667,900)	(4,526,600)	(4,241,900)	37,147,800	(8,544,000)	28,603,700	32,845,700	30,771,900
2028	90%	$0.02	54,161,700	-	-	(6,867,900)	(4,662,400)	(2,545,100)	40,086,300	(9,219,800)	30,866,300	33,411,500	47,383,300
2029	90%	$0.02	55,786,500	-	-	(7,073,900)	(4,802,300)	(2,545,100)	41,365,200	(9,514,000)	31,851,100	34,396,300	62,253,800
2030	90%	$0.02	57,460,100	-	-	(7,286,100)	(4,946,300)	(1,272,600)	43,955,100	(10,109,700)	33,845,300	35,117,900	75,455,900
2031	90%	$0.02	59,183,900	-	-	(7,504,700)	(5,094,700)	-	46,584,500	(10,714,400)	35,870,000	35,870,000	87,181,900
2032	90%	$0.02	60,959,500	-	-	(7,729,900)	(5,247,600)	-	47,982,000	(11,035,900)	36,946,100	36,946,100	97,684,300
2033	90%	$0.03	62,788,200	-	-	(7,961,800)	(5,405,000)	-	49,421,500	(11,366,900)	38,054,500	38,054,500	107,090,800
2034	90%	$0.03	64,671,900	-	-	(8,200,600)	(5,567,100)	-	50,904,100	(11,708,000)	39,196,100	39,196,100	115,515,700
2035	90%	$0.03	66,612,000	-	-	(8,446,600)	(5,734,100)	-	52,431,300	(12,059,200)	40,372,000	40,372,000	123,061,500
2036	90%	$0.03	68,610,400	-	-	(8,700,000)	(5,906,200)	-	54,004,200	(12,421,000)	41,583,200	41,583,200	129,820,000
2037	90%	$0.03	70,668,700	-	-	(8,961,000)	(6,083,300)	-	55,624,300	(12,793,600)	42,830,600	42,830,600	135,873,200
2038	90%	$0.03	72,788,800	-	-	(9,229,900)	(6,265,800)	-	57,293,100	(13,177,400)	44,115,600	44,115,600	141,294,700
2039	90%	$0.03	74,972,400	-	4,887,300	(9,506,800)	(6,453,800)	-	59,011,800	(13,572,700)	45,439,000	50,326,300	146,672,800

Robust Sensitivity Analyses

Multiple sensitivity analyses were run across key process variables to determine their effects on the overall profitability metrics of the bioremediation plant. Importantly, the sensitivity analysis was robust and distinct from the sensitivity operations available in the equity research spreadsheet that was utilized for base-case calculations. The python code in **Appendix A** optimized each profitability input and scenario, redesigning the equipment and process to output the best financial scenario with each variable change. As a result, the sensitivity analysis is robustly applied to plants of different sizes that best fit the criteria and design restrictions. The variables that were tested in the robust sensitivity analysis are as follows: the inflation rate, the adsorption capacity of the coconut coir, raw material cost of the coconut coir, plant location, and qualification for the IRA tax credit. The sensitivity analysis supported a best and worst case financial scenario that is further detailed in Section 24.3.

As a first case sensitivity analysis, the inflation rate was manipulated to determine its impact on costs. **Table 24.2.1** contains a matrix detailing how the varying inflation rate impacts fixed costs, variable costs, and total permanent investment costs and the percentage by which they increase. Ultimately, this sensitivity analysis is important to predict how macroeconomic factors will affect the plant's profitability, especially given the recent inflationary trend in the United States economy. While inflation rates do inflate the other costs of the plant, performing sensitivity on key process variables is more important to understand the drivers of plant costs.

Table 24.2.1: Sensitivity Analysis on inflation rate and its impact on fixed, variable, and total permanent investment costs.

		Inflation										
		1.50%	1.80%	2.10%	2.40%	2.70%	***3.00%***	3.30%	3.60%	3.90%	4.20%	4.50%
	$2,133,369	102.06%	102.00%	101.93%	101.87%	101.81%	101.75%	101.68%	101.62%	101.55%	101.49%	101.42%
	$2,560,043	101.00%	100.93%	100.86%	100.80%	100.73%	100.66%	100.60%	100.53%	100.46%	100.39%	100.32%
	$2,986,717	99.93%	99.86%	99.79%	99.72%	99.65%	99.58%	99.51%	99.44%	99.36%	99.29%	99.22%
	$3,413,391	98.87%	98.80%	98.73%	98.65%	98.58%	98.50%	98.42%	98.35%	98.27%	98.19%	98.11%
	$3,840,065	97.81%	97.74%	97.66%	97.58%	97.50%	97.42%	97.34%	97.26%	97.18%	97.09%	97.01%
	$4,266,738	96.75%	96.67%	96.59%	96.51%	96.42%	96.34%	96.26%	96.17%	96.08%	96.00%	95.91%
	$4,693,412	95.70%	95.61%	95.52%	95.44%	95.35%	95.26%	95.17%	95.08%	94.99%	94.90%	94.81%
	$5,120,086	94.64%	94.55%	94.46%	94.37%	94.28%	94.18%	94.09%	93.99%	93.90%	93.80%	93.70%
	$5,546,760	93.59%	93.49%	93.40%	93.30%	93.20%	93.11%	93.01%	92.91%	92.81%	92.71%	92.60%
	$5,973,434	92.53%	92.43%	92.33%	92.23%	92.13%	92.03%	91.93%	91.82%	91.72%	91.61%	91.50%
Fixed Costs	$6,400,108	91.48%	91.38%	91.27%	91.17%	91.06%	90.95%	90.85%	90.74%	90.63%	90.51%	90.40%

		Total Permanent Investment										
		$12,372,243	$14,846,692	$17,321,141	$19,795,589	$22,270,038	***$24,744,487***	$27,218,935	$29,693,384	$32,167,833	$34,642,281	$37,116,730
	$3,491,710	178.56%	155.66%	138.07%	124.11%	112.75%	103.32%	95.36%	88.54%	82.62%	77.44%	72.86%
	$4,190,052	176.15%	153.56%	136.20%	122.44%	111.23%	101.93%	94.07%	87.34%	81.50%	76.38%	71.86%
	$4,888,394	173.73%	151.46%	134.34%	120.76%	109.71%	100.53%	92.78%	86.13%	80.37%	75.33%	70.86%
	$5,586,735	171.32%	149.36%	132.48%	119.09%	108.19%	99.14%	91.49%	84.93%	79.25%	74.27%	69.86%
	$6,285,077	168.90%	147.25%	130.62%	117.41%	106.67%	97.74%	90.19%	83.73%	78.12%	73.21%	68.86%
	$6,983,419	166.48%	145.15%	128.75%	115.74%	105.14%	96.34%	88.90%	82.53%	77.00%	72.15%	67.86%
	$7,681,761	164.07%	143.05%	126.89%	114.06%	103.62%	94.94%	87.61%	81.32%	75.87%	71.09%	66.86%
	$8,380,103	161.65%	140.94%	125.02%	112.38%	102.09%	93.54%	86.31%	80.11%	74.74%	70.02%	65.85%
	$9,078,445	159.23%	138.84%	123.16%	110.71%	100.57%	92.14%	85.01%	78.91%	73.60%	68.96%	64.84%
Variable Costs	$9,776,787	156.81%	136.73%	121.29%	109.03%	99.04%	90.73%	83.71%	77.70%	72.47%	67.89%	63.84%
	$10,475,129	154.39%	134.62%	119.42%	107.34%	97.51%	89.33%	82.41%	76.48%	71.34%	66.82%	62.83%

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Sensitivity analyses on other process variables provided important insights into the key drivers of the costs of the bioremediation plant. **Figure 24.2.1** depicts the results of the sensitivity analysis on the effect the packing material adsorption capacity has on overall profitability. Importantly, there is a clear relationship between the amount of heavy metals the process is able to adsorb and the overall profitability of the venture. The code optimizes material with lower adsorption capacities by adding additional raw material costs and larger equipment costs. As equipment and capital costs are the largest source of expenses, reducing the adsorption capacity had a profound effect on ROI. If the adsorption capacity of the packing can be increased to 150 % the base case, ROI sky-rockets to 173% and increases more slowly afterwards due to the equipment sizing constraints. Even in the worst-case scenario of 25% of the original adsorption capacity, the process has an ROI of 80%.

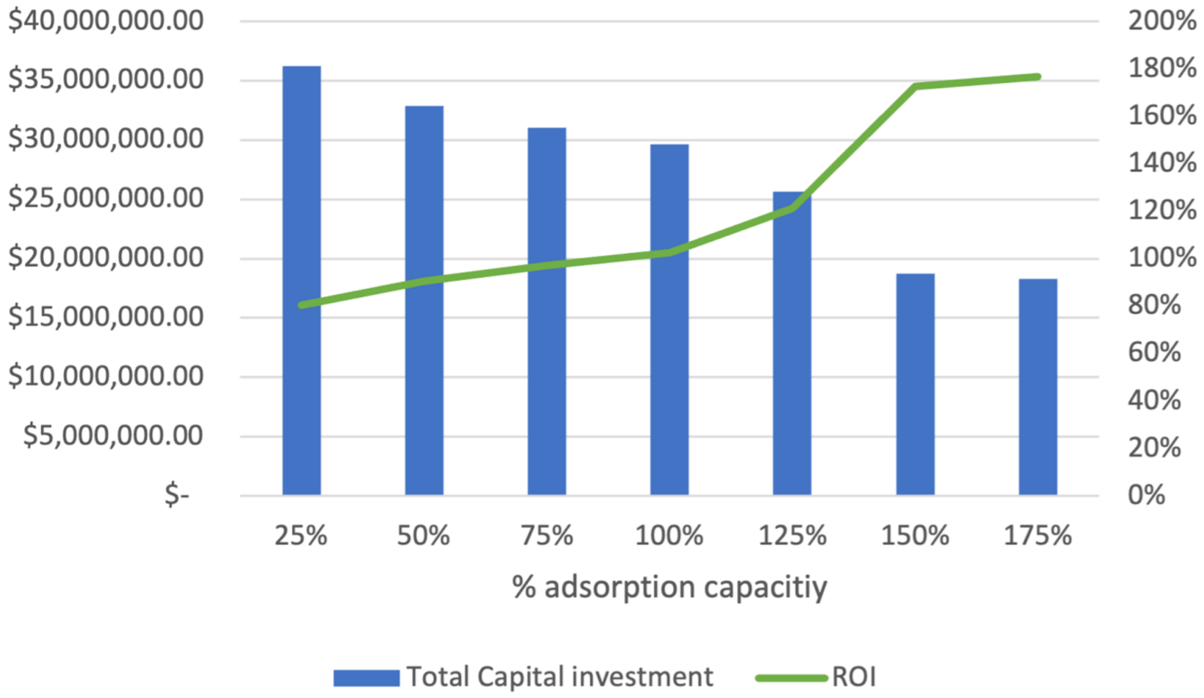

Figure 24.2.1: Sensitivity analysis on the % adsorption capacity of the biofilm-supported coconut coir. The total capital investment required and ROI as a percentage are displayed at varying levels of the base case adsorption capacities from 25% to 175%.

Figure 24.2.2 displays the % adsorption capacity results along with the cost in USD to treat a pound of wastewater. Importantly, there is a linear relationship between the adsorption capacity and the cost to treat the wastewater with a variance of 0.98.

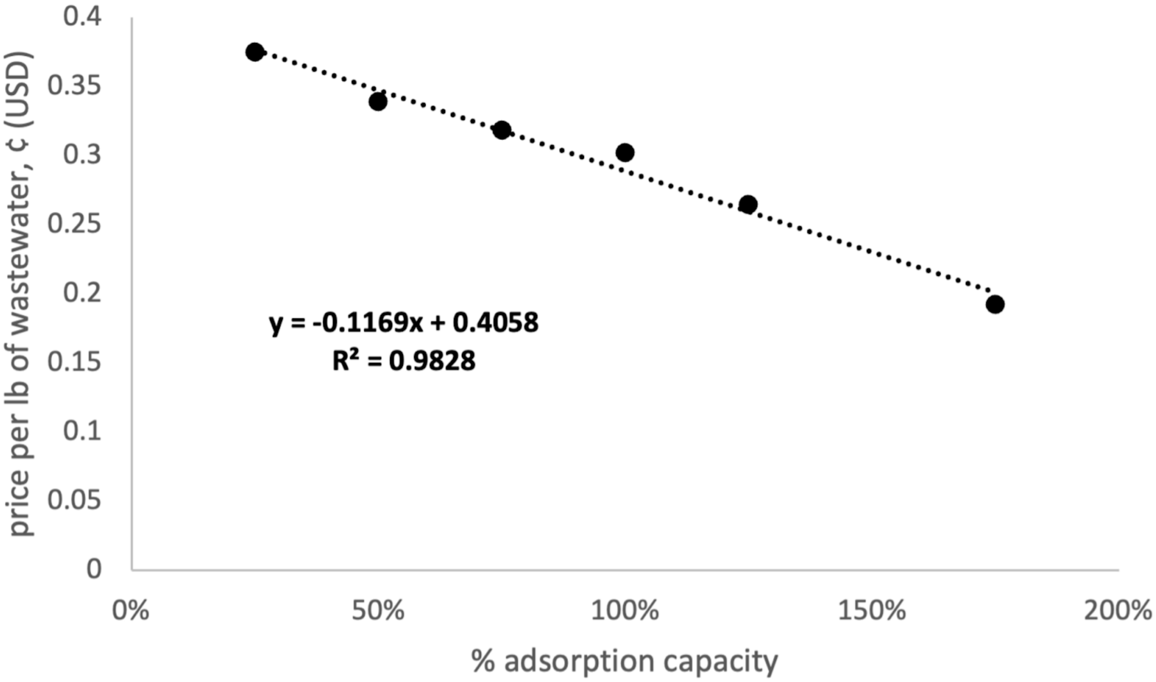

Figure 24.2.2: Sensitivity analysis on the % adsorption capacity of the biofilm-supported coconut coir. The price per pound of wastewater treated in cents is displayed at varying levels of the base case adsorption capacities from 25% to 175%. The R^2 is 0.98 with a linear regression slope of -0.12 cents/% adsorption and intercept of 0.41 cents.

Due to the significance of this data and the adsorption capacity serving as a key driver for all other costs, this model could be used to compare the feasibility of other lignocellulosic materials and estimate the cost to treat a pound of wastewater using a similar design to our process. For example, wheat straw's adsorption capacity is approximately 40% that of coconut coir. Interpolating this using our financial model, the cost of a wheat-based treatment facility would be 0.359 ¢ per pound of wastewater treated. While this interpolation includes a variety of assumptions, namely that the wheat has similar compatibility with the *P. putida* biofilm among other important process considerations, it could serve as a rough estimate to approximate other biomaterials compatible with our design.

It was hypothesized that the raw material cost of the coconut coir would be another key driver of the overall plant costs. However, after performing a sensitivity analysis scaling and optimizing the cost of the coconut coir from 0% to 175% of the base-case cost from the supplier, the cost of the coconut coir had a marginal impact on the profitability metrics. **Figure 24.2.3** exhibits the results of the sensitivity analysis on the coconut raw material cost and its effect on the ROI and price per pound of wastewater. The price varies between 0.27 cents and 0.32 cents per pound and the ROI only fluctuates between 100 and 107 percent. As a result, the cost of the coconut coir imparts a reduced impact on subsequent decision making that pertains to the plant location and feasibility.

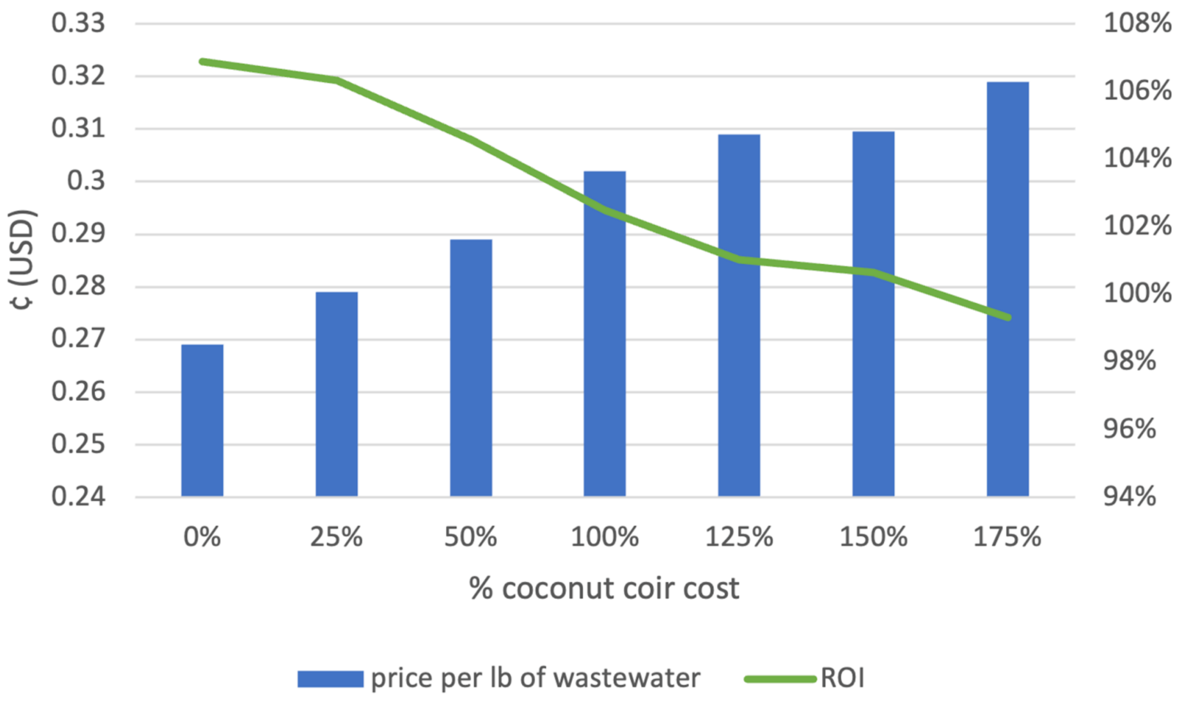

Figure 24.2.3: Sensitivity analysis on the % coconut coir raw material cost. The price in cents to treat one pound of wastewater and ROI as a percentage are displayed at varying levels of the base case raw material coconut coir costs from 0% to 175%.

The plant location in the United States is another important consideration for sensitivity analysis. Four potential locations were chosen for varying rationales as expanded upon in Section 23.4. The profitability analysis and optimization formula considered the site factors of different locations based on the cost of manufacturing in addition to the average ambient temperatures and its effect on the heat duty required to operate the plants. The results of this sensitivity analysis are displayed in **Figure 24.2.4.**

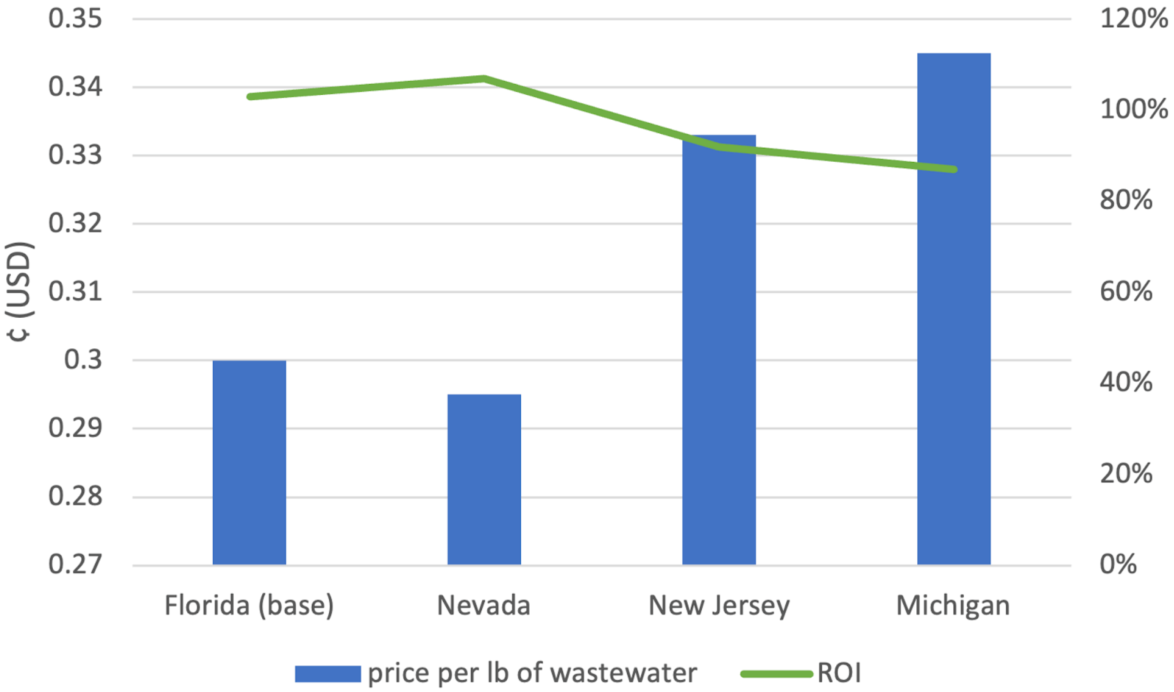

Figure 24.2.4: Sensitivity analysis on the site location for the bioremediation plant. The price in cents to treat one pound of wastewater and ROI as a percentage are displayed in Florida (base case), Nevada, New Jersey, and Michigan. The four locations have average ambient temperatures that were factored into the optimization of 70, 69, 53, and 48°F respectively for Florida, Nevada, New Jersey, and Michigan.

Flint, Michigan financially is the most expensive location for operation at 0.34 cents per pound of wastewater treated and an ROI of 87%. This is largely due to a combination of expensive site factors increasing the bare module costs of installation of equipment coupled with the average ambient temperature of 48°F. In this analysis, it was revealed that Nevada is slightly more profitable than the base case in Florida in terms of the site factor and ambient temperature of 69°F. The ROI in Nevada is 107% compared to the base case 103% in Florida. However, as is discussed in Section 24.3, other important factors beyond the site factor are included in the selection of the best-case plant location scenario, combining the results of multiple sensitivity analyses.

One final consideration for the sensitivity analysis and subsequent optimization is the qualification for the IRA tax credit on 30% of the equipment costs. The tax credit, as explained in Section 23.6, can tremendously reduce the overall costs as the equipment and capital costs are the main driver of plant expenses. While it is divisive as to whether a municipal wastewater treatment plant would qualify for the credit, there exists enough evidence to include the reduction in equipment costs by 30% in the best-case economic scenario.

Best and Worst Case Profitability Scenario

After completing the sensitivity analyses, different scenarios were constructed to create a best case and worst case for the plant economic outlook. **Table 24.3.1** tabulates the criteria used to calculate the profitability of each of these three cases. The worst case scenario does not include the sale of excess steam, operates with 75% the original adsorption capacity, pays for hazardous disposal costs, purchases the coir at 150% of the base cost and is located in Flint, Michigan with cool ambient temperatures for operation. The best case scenario includes the sale of excess steam, qualifies for the IRA tax credit, and forgoes both the raw material cost of coconut coir as a result of being located in Florida with free coconut coir waste and the disposal costs for hazardous waste. The spent coir is assumed to be taken at cost for the production of bricks.

Table 24.3.1: Criteria for worst, base, and best case scenarios.

Criteria	**Worst Case**	**Base Case**	**Best Case**
Selling Excess Steam	No	Yes	Yes

IRA Tax Credit	No	No	Yes
Adsorption Capacity	75%	100%	100%
Disposal Costs	Yes	Yes	No (Bricks used)
Coconut Coir Cost	150%	100%	0%
Location	Michigan	Florida	Florida

Table 24.3.2 contains the results of the important outputs of the profitability spreadsheet for each of these three scenarios. The robust sensitivity analysis code was used in generating these results so that equipment sizes and costs could vary under the fluctuating inputs as determined by the sensitivity analysis. The NPV of the worst case, base case, and best case are $136, $146, and $157 million USD respectively. The ROI for the worst case is 80.3%, the base case 102.5%, and the best case 141.1%. The NPV and ROI of these cases are plotted in **Figure 24.3.1**.

Table 24.3.2: Profitability Metrics for Worst, Base, and Best Case Scenarios.

Metric	Worst Case	Base Case	Best Case
IRR	78.3%	96.34%	130%
NPV	$136M	$146M	$157M
Annual Sales	$52M	$52M	$52.5M
Annual Costs	($12M)	($11M)	($10M)
Depreciation	($2.4M)	($1.9M)	($1.4M)
Income Tax	($8.6M)	($9M)	($9.4M)
Net Earnings	$29M	$30M	$31M
Total Capital Investment	$36M	$29.6M	$22M
ROI	80.3%	102.5%	141.1%

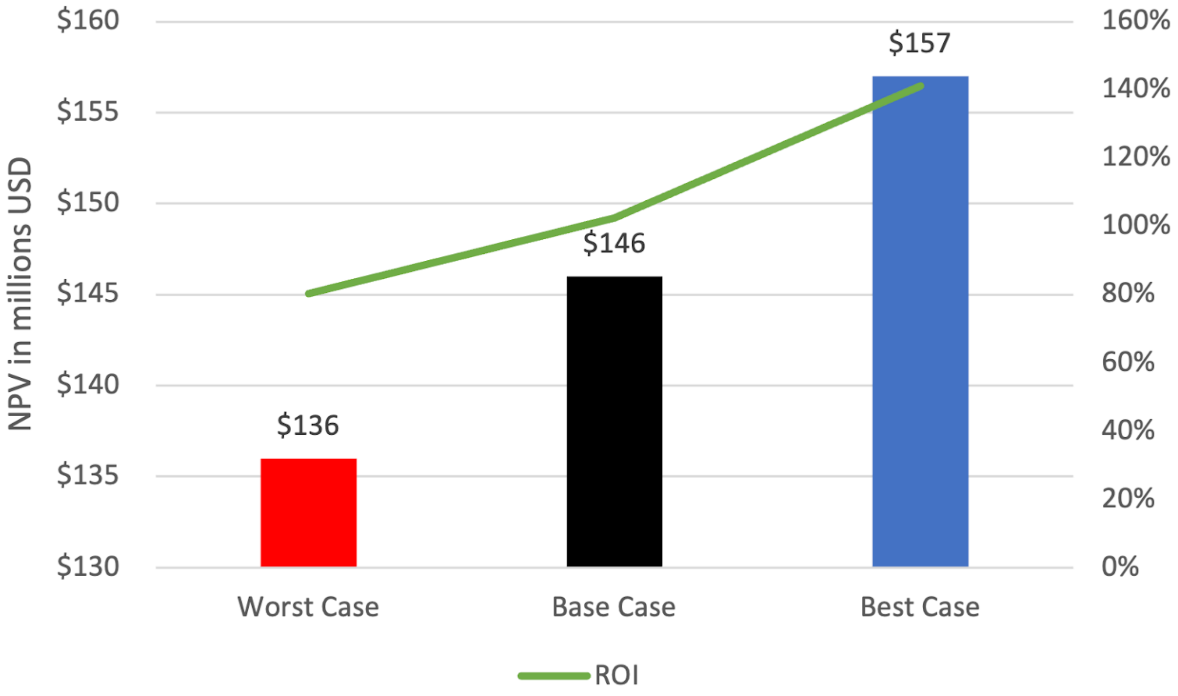

Figure 24.3.1: Worst (red), base (black), and best (blue) case profitability scenario. The NPV in millions of USD is plotted on the left y-axis and labeled above the bar plots. The ROI as a percentage is plotted on the right y-axis and displayed as a green line on the same plot.

These three economic analyses demonstrate that the profitability of this plant operation is extremely high even in the worst economic and engineering outlook. A worst possible ROI of 80% is staggering, and is a result of the high price the plant is charging for wastewater treatment aligned with competitors at $0.02 per pound. A much more reasonable scenario for a target of 15% ROI would reduce the price per pound until that figure is met. The ultimate goal of this project is to reduce costs for industry to be incentivized to remove heavy metals from the water supply, especially in underfunded municipal districts. Thus, charging such a high product price is not realistic. However, for the sake of meeting the design criteria, the profitability analysis supports that the plant design is not only feasible financially but is an immensely profitable low-cost alternative compared to competitors in ion-exchange and membrane separation.

Conclusions and Recommendations

Heavy metal pollution is a worldwide environmental concern, with waste dumpsites posing a severe risk to public health, and the ecosystem nearby. Conventional methods for heavy metal removal such as ion-exchange resins and membrane separation, while effective, are prohibitively expensive and dissuade corporations from treating waste contaminated with toxic metals. This project had the goal of evaluating the feasibility of using waste lignocellulosic biomass for heavy metal removal on an industrial scale, a low-cost alternative that gained attention in the last decades. In particular, the project sought to design a treatment process to remove arsenic, lead, and cadmium using coconut coir coated with *P. putida* biofilm. Coconut is one of the most effective lignocellulosic materials in water treatment, and the biofilm enhances its adsorption capacities. The project designed a wastewater treatment process that treats 1 MGD (millions of gallons per day) of wastewater containing 0.5 mg/L of arsenic (III), 0.25 mg/L of lead, and 0.012 mg/L of cadmium.

Using a hybrid batch and continuous process, biofilm-coated coconut coir was packed in 5 adsorption beds in series, being able to remove metals from the feed wastewater to below EPA limit values for 19.16 days. Intercalating with backup adsorption beds allows the treatment process to run continuously. When saturated, the coconut is then combusted in a biomass boiler on-site, generating steam that with heat integration leads the process to have a low utility requirement of 2020 kWh of electricity per day. Heavy metal-rich Ash is the byproduct of the process, and can either be safely disposed of in a hazardous waste landfill or used in the production of bricks that trap the metals inside.

The cost of this process was mainly compared to a competitor's price of $0.02/lb of wastewater treated for ion-exchange processes. The proposed bioremediation process costs are estimated to cost $0.00304/lb of wastewater treated, 15.2% of the cost of ion exchange, being economically advantageous. For profitability measures, wastewater treated was considered to be sold at the same price of ion exchange along with excess team generated by the biomass boiler from coconut coir combustion. In that case, the process has an NPV of $146M, an ROI of 103%, and an IRR of 96% over the 17-year project in the base case scenario. In addition, selling excess steam from the boiler reduces utility requirements for methane combustion, thus leading the process to have a net-negative carbon footprint, possibly eligible for tax credits. This project is an economically viable and sustainable alternative, not only reducing heavy metal waste but also encouraging the reuse of agricultural residues in a carbon-negative process with net emissions of -1227 kg CO2e per million liters of water treated. Therefore, we recommend the advance of the use of lignocellulosic materials and especially coconut coir for heavy metal removal.

While this process is recommended as a viable mechanism for removing heavy metals from wastewater, there are important considerations to note when further developing the project. First, this project only considered coconut coir as the lignocellulosic material for the development of the biofilm and adsorption of heavy metals. Future processes can importantly consider alternative lignocellulosic biomass and mixtures for heavy metal adsorption such as rice husk, corn husk, and sugarcane bagasse. Additionally, one of the challenges with this process is the introduction of solids handling system that can effectively transport fibrous, lignocellulosic material.

Exploration, experimental testing, and design of specialized equipment for use of lignocellulosic fibers have the potential to shrink costs and simplify the wastewater treatment process. Overall, lignocellulosic biomass is an economical method for which industry can pursue large-scale wastewater treatment processes for the removal of heavy metals. Furthermore, these materials are known to adsorb a variety of hazardous pollutants, thus this project can serve as a framework for the development and implementation of diverse processes that are environmentally friendly and that improve climate resilience.

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