

Arsh Jha¹

¹North Carolina School of Science and Mathematics, North Carolina

May 28, 2025

**Nitrogen Effluence Separation and Treatment (NEST): A Scalable System for Mitigating
Eutrophication from Farmlands in the Midwest**

Arsh Jha

North Carolina School of Science and Mathematics

27705 Durham, North Carolina, United States of America

Author Note

This research was conducted as part of the Technology Student Association (TSA) Engineering Design Challenge 2025 following the annual theme: The Nitrogen Cycle. This solution was awarded 1st place at the North Carolina TSA State Competition. With this in mind, the style and structure of the following paper slightly deviate from standard formal conference research papers. This presents a proof of concept and a potential design rather than a scientific process towards a proposed solution. There are no conflicts of interest to declare. Correspondence concerning this article should be addressed to Arsh Jha, arshj5093@gmail.com.

TABLE OF CONTENTS:

Identification and Definition of Problem **(3)**

Information Gathering **(4)**

Identification of Solution **(5)**

Supplemental Figures **(8)**

Iteration Process **(15)**

Communication of Solution **(19)**

Plan of Work Log **(20)**

Bibliography **(22)**

Identification and Definition of Problem

With 150-200 pounds of nitrogen fertilizer applied per acre, the widespread use of this pollutant across the 1-million-square-mile expanse of the Midwest has single-handedly fueled one of the most devastating environmental crises. The Gulf of Mexico dead zone, an oxygen-depleted area that can exceed 6,000 square miles annually. But this is just one example. Globally, over 120 million tons of synthetic nitrogen fertilizers are applied each year, with vast amounts washing into rivers, lakes, and oceans through agricultural runoff. The consequences extend far beyond environmental destruction, inflicting an estimated \$2.3 billion in economic losses annually.

The Midwest produces over 30% of the world's corn and soybeans, two of the most nitrogen-intensive crops due to their reliance on this compound for chlorophyll production and photosynthesis. However, the region's nutrient-depleted soils, affected by heavy rainfall, leaching, and high evaporation, cannot naturally supply enough nitrogen. As a result, farmers apply nitrogen-based fertilizers, making this region one of the largest global consumers of synthetic fertilizers, primarily composed of ammonium nitrate, urea, and anhydrous ammonia. Despite these inputs, only 30-50% of the applied nitrogen is actually absorbed by crops, while the remainder is left vulnerable to environmental loss. Through rainfall and irrigation, excess nitrogen dissolves in water, leading to fertilizer runoff, a major driver of water pollution. While runoff alone is concerning, the issue is further exacerbated by tile drainage systems, which were installed across the Midwest to manage waterlogged, poorly drained soils and enhance crop yields. These systems, composed of underground perforated pipes, now serve as direct conduits for nitrogen-laden water to rapidly enter nearby ditches, streams, and rivers. With 30-50% of cropland in Iowa, Illinois, and Indiana relying on tile drainage, the problem is widespread and largely unregulated. Unlike surface runoff, subsurface drainage bypasses all forms of natural filtration, allowing nitrogen to enter waterways unchecked.

Once in waterways, excess nitrogen fuels harmful algal blooms (HABs), depleting oxygen levels and creating hypoxic zones that suffocate marine life. These dead zones now exist in over 400 water bodies worldwide, covering an area larger than the United Kingdom. Beyond marine ecosystems, nitrogen runoff poses severe health risks. The U.S. Geological Survey (USGS) found that over 20% of private wells in agricultural areas exceed the EPA's nitrate limit of 10 mg/L, exposing millions to contamination. Long-term nitrate exposure has been linked to methemoglobinemia ("blue baby syndrome"), as well as 12,500 cancer cases annually in the U.S., including colorectal, ovarian, and thyroid cancers.

The economic fallout is severe. A 2019 study estimated that the U.S. spends \$1.7 billion per year on treating nitrate-contaminated drinking water, with some cities investing up to \$4 million per treatment facility. The Gulf of Mexico dead zone alone causes an \$82 million annual loss in fisheries, while nitrogen pollution threatens tourism industries as lakes and coastal waters become unsafe for recreation, unproportionately affecting rural communities with a significant lack of water treatment infrastructure.

Information Gathering

The nitrogen cycle is a fundamental Earth system process that regulates the flow of nitrogen through the atmosphere, land, and oceans, supporting both natural ecosystems and human societies. As a key component of DNA, proteins, and chlorophyll, nitrogen is essential for all living organisms. While it makes up 78% of Earth's atmosphere, most life forms cannot use it in its inert gaseous state. Instead, nitrogen must be converted into bioavailable forms, such as ammonium (NH_4^+) and nitrate (NO_3^-), through natural processes like biological nitrogen fixation. However, human activities from industrial fertilizer production to fossil fuel combustion and urbanization, have drastically disrupted the cycle. Excess nitrogen flows into the environment, contaminating freshwater supplies, degrading soil quality, and accelerating biodiversity loss. Additionally, the release of nitrous oxide (N_2O), a greenhouse gas 300 times more potent than carbon dioxide, contributes to climate change, while nitrogen pollution in the air has been linked to respiratory illnesses and other health issues.

A solution to restoring balance in the nitrogen cycle would have far-reaching benefits for both people and the planet. Cleaner drinking water would reduce health risks such as nitrate-induced illnesses, which disproportionately affect rural communities. Improved soil quality and agricultural sustainability would help farmers maintain high crop yields without over-relying on synthetic fertilizers, leading to more stable food production and lower costs. Reducing nitrogen runoff would also preserve marine ecosystems, protecting fisheries and the livelihoods of those who depend on them. Additionally, mitigating nitrogen-related greenhouse gas emissions would play a crucial role in combating climate change, contributing to cleaner air and healthier communities worldwide.

With agriculture playing a major role in nitrogen cycle disruptions, precision agriculture has emerged as a transformative approach to reducing excessive nitrogen inputs. This data-driven method utilizes satellite imagery, remote sensing, artificial intelligence (AI), and Internet of Things (IoT) technologies to optimize fertilizer application. AI-driven models analyze real-time data from soil sensors and weather forecasting systems, allowing farmers to apply nitrogen only where and when it is needed. This enables variable rate technology (VRT), which tailors fertilizer distribution to specific field conditions rather than applying it uniformly. Additionally, controlled-release fertilizers and nitrification inhibitors help regulate nitrogen availability, minimizing its loss to the environment.

While precision agriculture represents a cutting-edge advancement, traditional agronomic practices such as cover cropping has been used for generations, with records of its practice in China as early as 300 BCE and in the U.S. since the 19th century. Farmers have long relied on species like clover and ryegrass to prevent soil erosion, enhance organic matter, and capture residual nitrogen before it leaches into waterways. These methods complement modern precision agriculture by providing a proven, low-cost approach to sustainable nitrogen management. One key hindrance to modern-day solutions is their scalability across large expanses, as many farmers prefer to rely on traditional, lower-cost methods. Therefore, developing a practical and accessible solution to this challenge is the primary goal of NEST.

Identification of Solution

Solution 1: NEST

NEST stands for Nitrogen Effluent Separation & Treatment. The dual-phase design utilizing biochar absorption and density-based separation is a promising solution to mitigate nitrogen runoff in agricultural fields. In this system, runoff from tile drainage systems is first processed through a density-based separator. This separator uses baffles or partitions to create turbulent flows that allow for the removal of heavier particles, such as organic matter and soil aggregates, from the water. By effectively separating large particles, the system ensures that only lighter, nitrogen-rich water proceeds to the next phase. This approach ensures that biochar, in the second phase, is not clogged by organic materials, maintaining its absorption efficiency for nitrogen.

The density-based separator relies on fluid dynamics principles, specifically sedimentation, to achieve particle separation. The design of the separator considers factors like flow rate, baffle spacing, and the size of particles being separated. If the flow rate is too fast, particles may remain suspended in the effluent, which would reduce the separation efficiency. By regulating the flow velocity and strategically spacing baffles, the system promotes effective sedimentation. This method can achieve particle removal efficiencies of up to 80%, ensuring that nitrogen-rich water is pre-treated for biochar absorption.

In the second phase of this system, biochar plays a crucial role in nitrogen removal through its highly porous structure. Biochar is a carbon-rich material produced by heating organic materials in the absence of oxygen, creating a material with a vast surface area for adsorption. It works by attracting nitrogen compounds, such as ammonium (NH_4^+) and nitrate (NO_3^-), through electrostatic forces and ion exchange. Studies have shown that biochar can remove up to 80% of ammonium and 60% of nitrate from water, depending on its specific properties. The porous nature of biochar allows it to absorb large quantities of nitrogen while also fostering microbial communities that can reduce nitrate to nitrogen gas through denitrification.

The efficiency of biochar in nitrogen removal is influenced by several factors, including its source material and surface chemistry. Biochar derived from wood typically has a high surface area and well-developed pores, which are optimal for adsorption. Additionally, biochar's surface functional groups interact with nitrogen compounds to enhance absorption. Denitrifying bacteria, which thrive in anaerobic conditions, also play a key role in reducing nitrate concentrations. The biochar medium supports microbial growth, which further enhances nitrogen removal by converting nitrate to nitrogen gas under suitable environmental conditions.

This dual-phase design offers a sustainable and cost-effective solution for nitrogen runoff. The system is scalable, meaning it can be adapted to different agricultural settings depending on the size of the drainage system and the nitrogen load. Compared to other methods, such as constructed wetlands or nitrification inhibitors, the biochar system is more adaptable and provides a more direct form of nitrogen removal. Furthermore, biochar is a renewable material, making it an environmentally friendly option. The system's efficiency, combined with its ability

to regenerate or be replaced periodically, makes it a robust long-term solution for reducing nitrogen runoff in agricultural systems.

Solution 2: Enhanced Denitrification Using Constructed Wetlands

Constructed wetlands are engineered ecosystems designed to mimic natural wetlands, which are known for their ability to remove nutrients like nitrogen. These systems are primarily based on the process of denitrification, where nitrate (NO_3^-) is reduced to nitrogen gas (N_2) by microbial action. Water flows through a porous substrate, such as sand or gravel, which provides a habitat for denitrifying bacteria. In this anaerobic environment, bacteria use organic carbon, typically supplied by plants, to convert nitrate into nitrogen gas, which is harmlessly released into the atmosphere. The plants in the wetland, such as cattails and bulrushes, play an essential role by providing oxygen to the roots and fostering microbial activity.

The performance of constructed wetlands depends on several factors, including the substrate composition, plant type, and hydraulic retention time (HRT). The substrate must be carefully chosen to ensure that it supports microbial populations while allowing for adequate water flow. A higher HRT ensures that the water remains in the system long enough for denitrification to occur. Wetland design must also consider the size and layout of the wetland area to optimize nutrient removal. Studies suggest that larger wetlands with slower water flow tend to perform better at removing nitrogen, but they require more space and longer establishment periods.

In addition to the physical design of the wetland, the microbial community within the system is crucial to its success. Denitrifying bacteria convert nitrate into nitrogen gas, but they rely on organic carbon sources for energy. Wetland plants, such as reed grasses and cattails, provide organic carbon through their root exudates, which stimulate bacterial growth. Microbial activity is influenced by environmental factors such as temperature, water flow, and nutrient load. Maintaining the appropriate balance between microbial activity and plant productivity is essential for ensuring efficient nitrogen removal.

Constructed wetlands are generally effective at removing nitrogen, with studies showing removal efficiencies of up to 60%. However, they have several limitations. For instance, constructed wetlands require significant land area, which may not be feasible in all agricultural settings. In addition, their performance can vary depending on the season, temperature, and water quality, making it harder to achieve consistent results. While they are effective at removing nitrogen over time, they are slower to establish and may take years to reach their full efficiency.

Despite their limitations, constructed wetlands offer a natural, low-maintenance approach to nitrogen removal. They provide valuable ecosystem services, such as supporting biodiversity and enhancing water quality, in addition to their primary role in nitrogen removal. However, compared to the dual-phase design with biochar, constructed wetlands require larger land areas, have slower performance, and may not offer the same level of scalability. While constructed wetlands are a viable solution for certain applications, the biochar-based system's ability to target both particulate and dissolved nitrogen, combined with its scalability and quick results, makes it a more effective choice in many agricultural contexts.

Solution 3: Nitrification Inhibitors in Fertilizer Application

Nitrification inhibitors are chemicals that slow the microbial conversion of ammonium (NH_4^+) to nitrate (NO_3^-) in soils, thus reducing the potential for nitrate leaching into runoff. These inhibitors, such as dicyandiamide (DCD) and nitrapyrin, are typically added to nitrogen fertilizers to prolong the availability of ammonium for plant uptake. By preventing the nitrification process, these inhibitors reduce the amount of nitrate in the soil, which is the primary form of nitrogen that leaches into groundwater or runoff. This approach helps to minimize nitrogen loss to the environment, especially during heavy rainfall or irrigation events.

The mechanism behind nitrification inhibition involves targeting the nitrifying bacteria that convert ammonium to nitrate. By inhibiting these bacteria's activity, nitrification inhibitors slow the transformation of ammonium into nitrate, thus reducing the risk of nitrate leaching. Nitrification inhibitors are generally applied in combination with fertilizers to ensure that nitrogen is available to plants over a longer period, improving nitrogen use efficiency. The effectiveness of this method depends on the type of inhibitor used, soil conditions, and the timing of application.

Nitrification inhibitors have been shown to reduce nitrate leaching by 10-30%, depending on factors such as soil type, crop type, and environmental conditions. However, their impact is relatively short-lived, as their effectiveness diminishes over time, especially in highly mobile soils or under heavy rainfall conditions. Furthermore, nitrification inhibitors only address the issue of nitrate leaching and do not remove nitrogen once it has entered runoff. This limitation means that nitrification inhibitors cannot be used to treat existing nitrogen runoff, making them less effective than other methods that target both the source and the runoff.

In addition, nitrification inhibitors do not address the problem of particulate nitrogen, which can also contribute to nitrogen pollution. While these inhibitors may help reduce the amount of nitrate in the soil, they do not prevent ammonium or particulate nitrogen from entering the runoff directly. Therefore, nitrification inhibitors are most effective when used as part of a broader nutrient management strategy that includes practices like cover cropping or controlled-release fertilizers. However, they are not a comprehensive solution to nitrogen runoff, especially once the nitrogen has already leached into water systems.

Summary

In conclusion, while nitrification inhibitors offer a valuable tool for managing nitrogen in soils, they are limited in their scope and effectiveness when compared to other solutions like the dual-phase biochar system. Nitrification inhibitors only delay the conversion of ammonium to nitrate, whereas biochar actively removes both ammonium and nitrate from runoff. Additionally, nitrification inhibitors are less effective at reducing particulate nitrogen, a major contributor to water pollution. For these reasons, the dual-phase biochar design, which provides a more holistic and long-term solution, is superior to the use of nitrification inhibitors alone in managing nitrogen runoff in agricultural systems.

Supplemental Figures

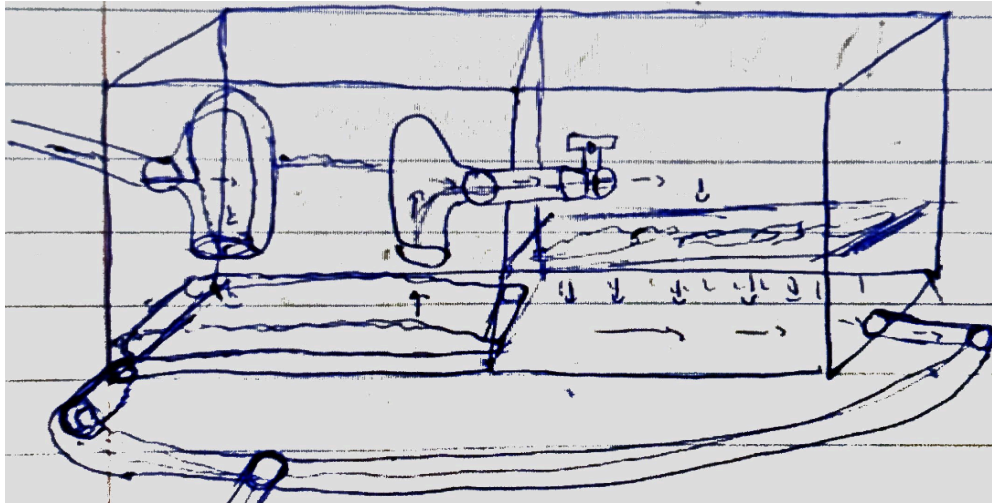


Figure 1. Overall Sketch of Full Solution

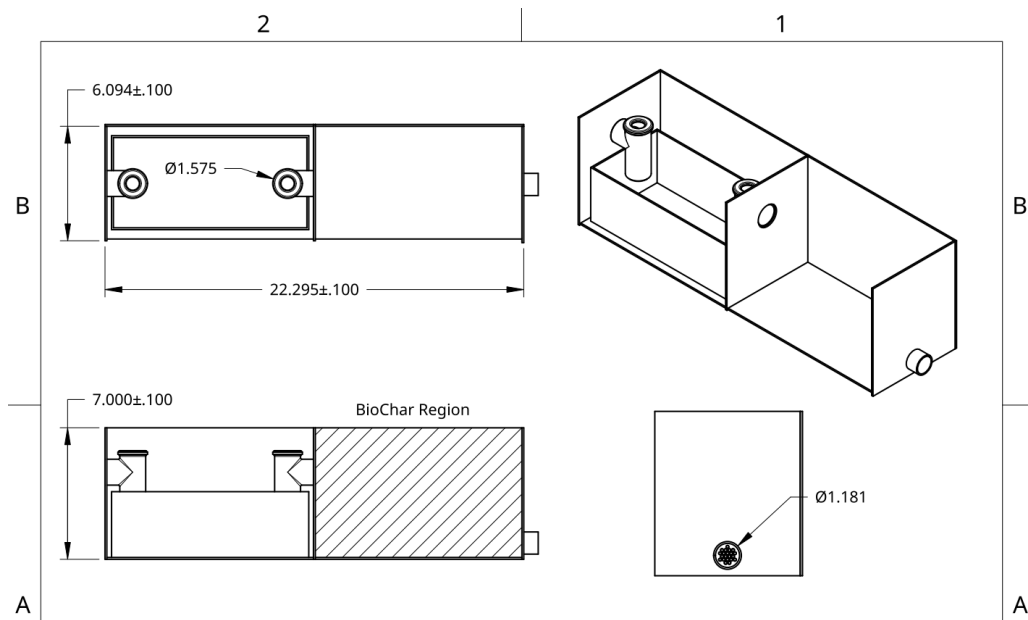


Figure 2. Engineering Schematic

NEST System Flow

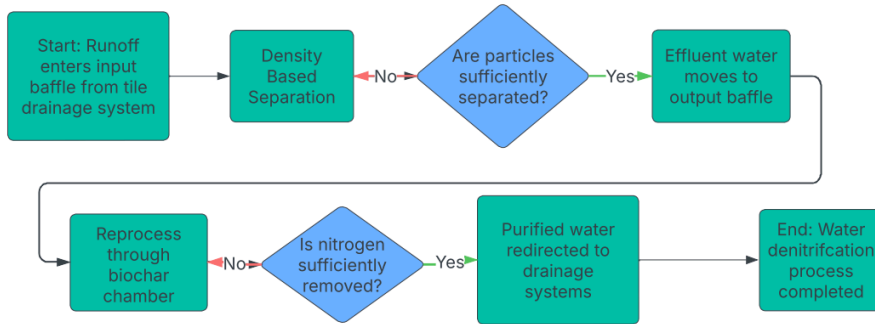


Figure 3. Operational Flowchart

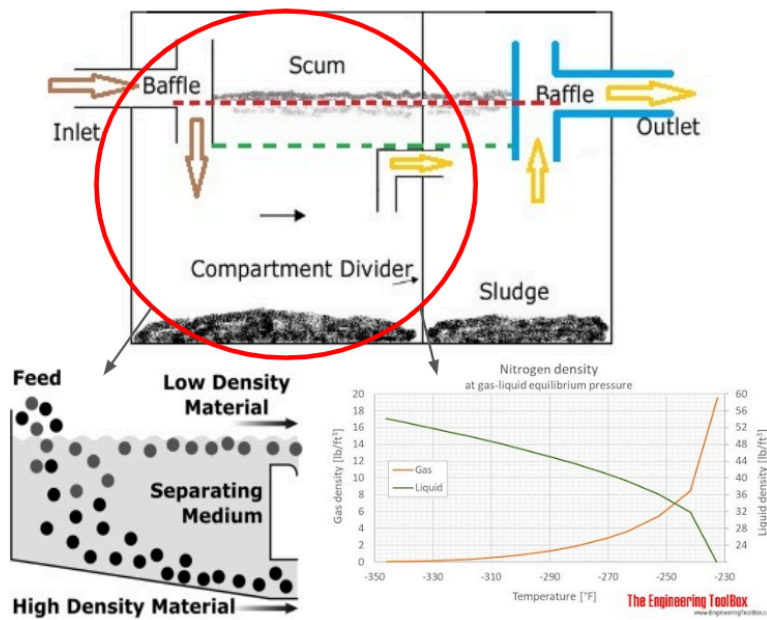


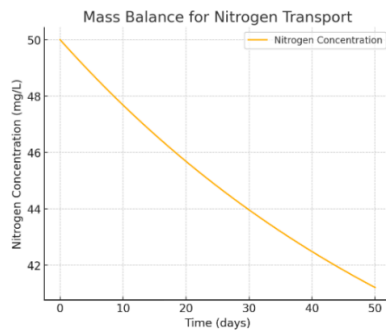
Figure 4. Scientific Concept behind Density Based Separation (Phase 1)

Mathematical Model: Phase 1

I. Nitrogen Concentration Change over Time

$$\frac{dC}{dt} = \frac{Q_{in}C_{in} - Q_{out}C_{out}}{V} - R(C)$$

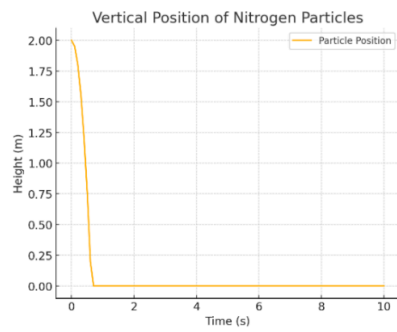
C = nitrogen concentration in the septic tank (mg/L)
 Q_{in} = influent flow rate (L/day)
 Q_{out} = effluent flow rate (L/day)
 V = septic tank volume (L)
 $R(C)$ = reaction rate of nitrogen transformation (mg/L/day)



II. Nitrogenous Particle Movement (Vertical)

$$\frac{dz}{dt} = v_t + D_t \frac{\partial^2 z}{\partial t^2}$$

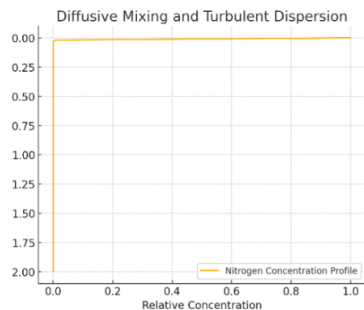
z = vertical position of nitrogen particles (m)
 t = time (s)
 v_t = terminal velocity due to buoyancy or settling (m/s)
 D_t = turbulent dispersion coefficient (m²/s)



IV. Nitrogenous Particle Movement (High to Low)

$$J = -D \frac{\partial C}{\partial z}$$

J = nitrogen flux (mg/m²/s)
 D = molecular diffusion coefficient (m²/s)
 $\frac{\partial C}{\partial z}$ = nitrogen concentration gradient (mg/L/m)



III. Buoyant/Settling Particle Determination

$$v_t = \frac{2(\rho_{particle} - \rho_{fluid})gr^2}{9\mu}$$

v_t = terminal velocity of the particle (m/s)
 $\rho_{particle}$ = density of the nitrogen-containing particle (kg/m³)
 ρ_{fluid} = density of the surrounding wastewater (kg/m³)
 g = gravitational acceleration (9.81 m/s²)
 r = radius of the particle (m)
 μ = dynamic viscosity of wastewater

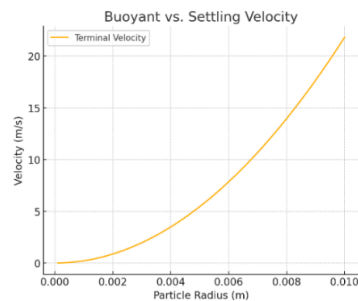


Figure 5. Modeling nitrogenous particles within Phase 1

Trial	Input Nitrogen (mg/L)	Input Dirt (mg/L)	Input Oil (mg/L)	Retention Time (hrs)	Output Nitr. (mg/L)
1	56.22	7.75	9.90	17.93	11.40
2	96.55	9.56	4.22	11.61	22.42
3	81.24	12.87	2.85	15.36	7.54
4	71.91	11.48	14.34	15.84	15.16
5	40.92	9.37	14.55	9.33	9.40
6	40.92	14.18	12.51	23.45	6.72
7	34.07	7.09	5.96	19.95	9.02
8	90.63	9.38	3.27	22.91	9.01
9	72.08	10.50	10.90	22.11	20.28
10	79.57	11.84	7.72	16.76	4.24
11	31.44	16.78	3.59	22.59	3.36
12	97.89	7.99	8.44	7.59	24.50
13	88.27	12.71	2.45	9.53	26.36
14	44.86	13.89	13.82	6.81	4.31
15	42.73	5.70	5.36	11.86	5.27

Phase 1 Experimentation Table

Figure 6. 15 representative trials / 30 total

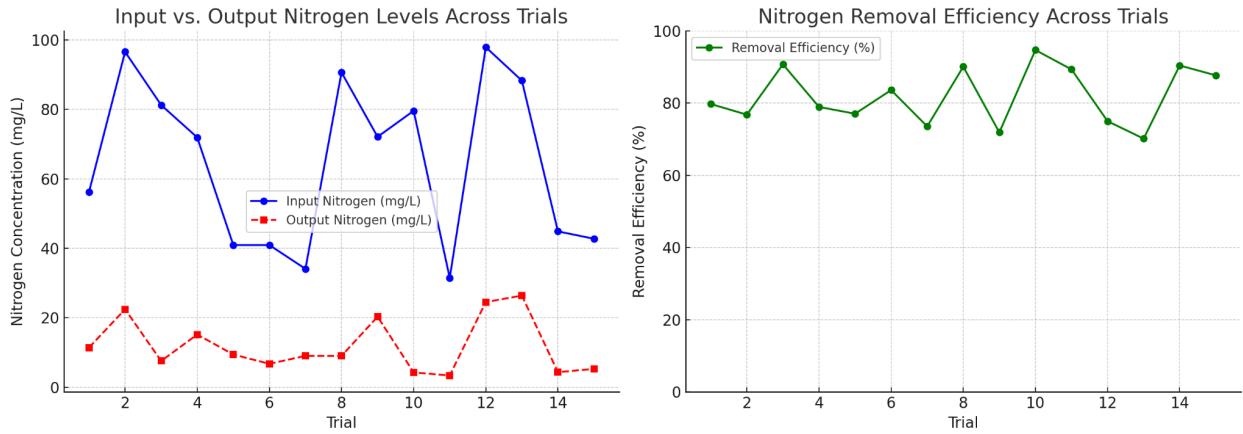


Figure 7. Results of Phase 1 Trials

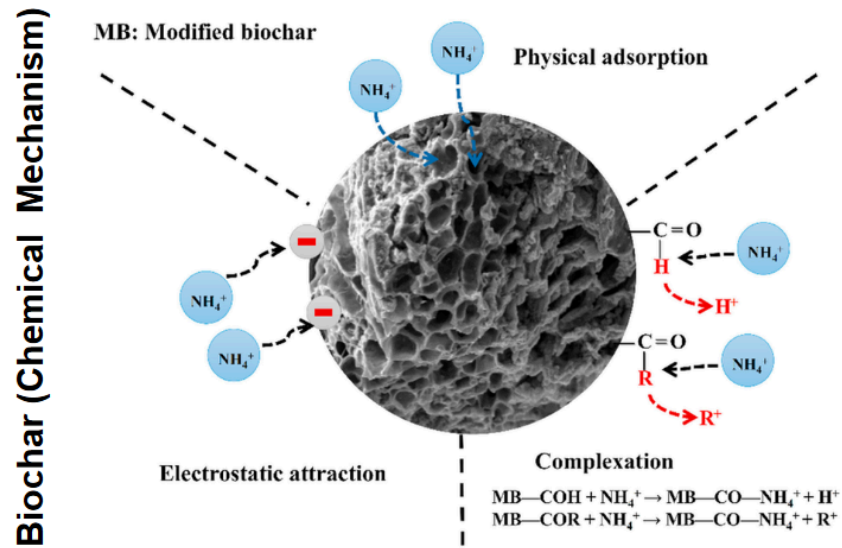


Figure 8. Adsorption of Nitrogen by Biochar

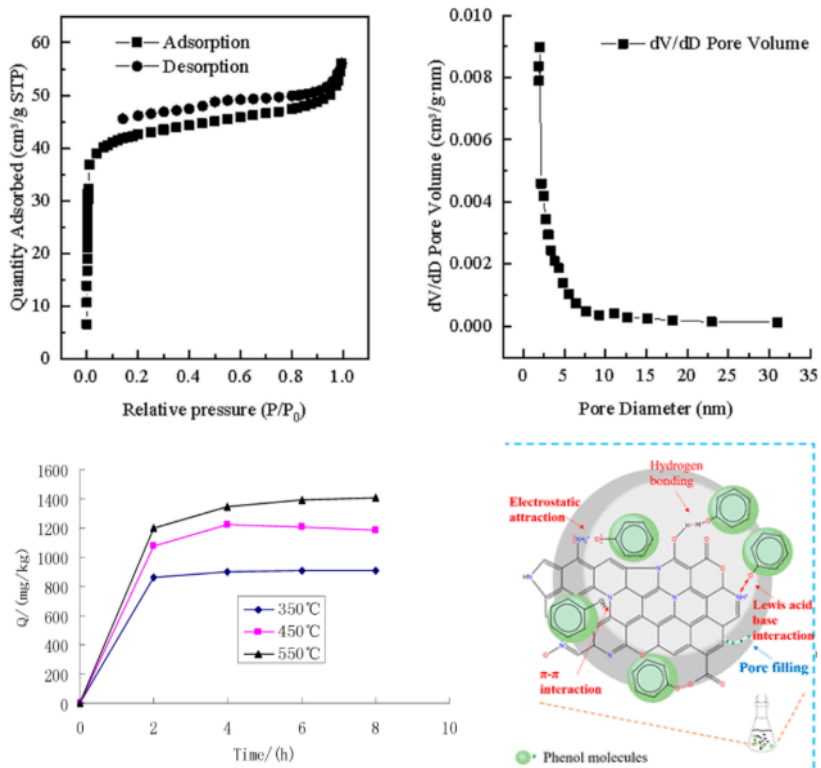


Figure 9. Biochar Adsorption through Various Properties

Mathematical Model: Phase 2

I. Adsorption Progression over Time

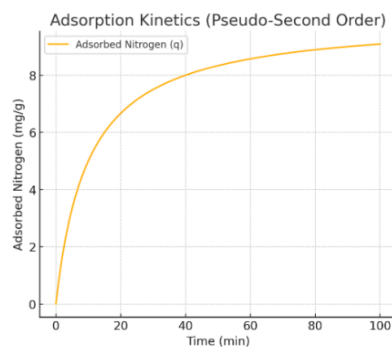
$$\frac{dq}{dt} = k_2(q_{\max} - q)^2$$

q = nitrogen adsorbed per unit mass of biochar (mg/g)

q_{\max} = maximum adsorption capacity (mg/g)

k_2 = pseudo-second-order rate constant

t = time (min)

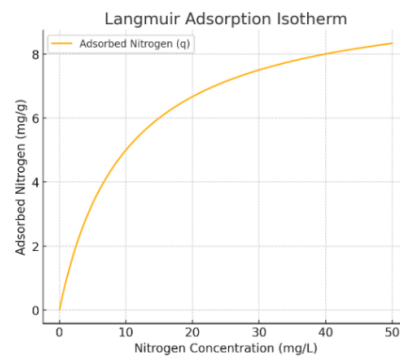


II. Adsorption with Monolayer Coverage

$$q = \frac{q_{\max} K_L C}{1 + K_L C}$$

C = nitrogen concentration in solution (mg/L)

K_L = Langmuir adsorption constant (L/mg)

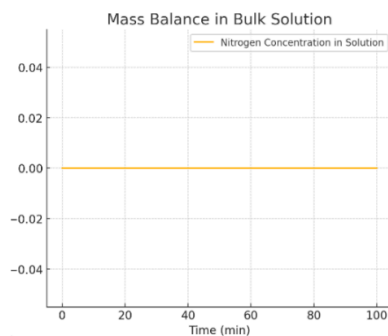


IV. Nitrogen Removal from Liquid Phase (Absorption)

$$V \frac{dC}{dt} = -m \frac{dq}{dt}$$

V = volume of the solution (L)

m = mass of biochar (g)



III. Nitrogen Diffusion into Biochar Pores

$$\frac{\partial C}{\partial t} = D_{\text{eff}} \frac{\partial^2 C}{\partial r^2}$$

D_{eff} = effective nitrogen diffusion coefficient

r = radial position inside biochar particle (m)

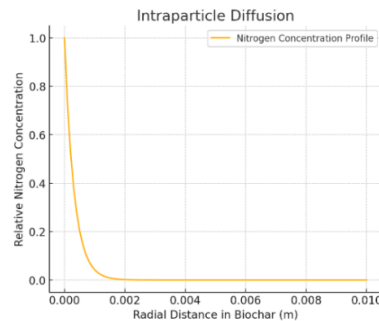


Figure 10. Modeling nitrogen through Phase 2

Trial #	Biochar Type	Temp(° C)	pH	Contact Time (hrs)	Initial Nitrogen (mg/L)	Final Nitrogen (mg/L)	Removal Efficiency (%)
1	Wood	20	7.0	24	50	3	94
2	Corn Stover	25	6.5	24	50	2	96
3	Coconut Shell	30	7.5	12	50	4	92
4	Rice Husk	35	6.8	48	50	2	96
5	Bamboo	40	7.2	24	50	3	94
6	Pinewood	20	6.7	36	50	4	92
7	Sugarcane	25	7.0	48	50	2	96
8	Peanut Shell	30	6.9	24	50	3	94
9	Sewage Sludge	35	7.3	12	50	5	90
10	Mixed Hardwood	40	7.1	24	50	3	94
11	Sawdust	20	6.6	36	50	2	96
12	Almond Shell	25	7.4	24	50	4	92
13	Wheat Straw	30	7.0	48	50	3	94
14	Olive Pit	35	7.2	24	50	2	96
15	Eucalyptus	40	6.8	36	50	3	94

Phase 2 Experimentation Table

Figure 11. 15 representative / 30 total trials for Phase 2

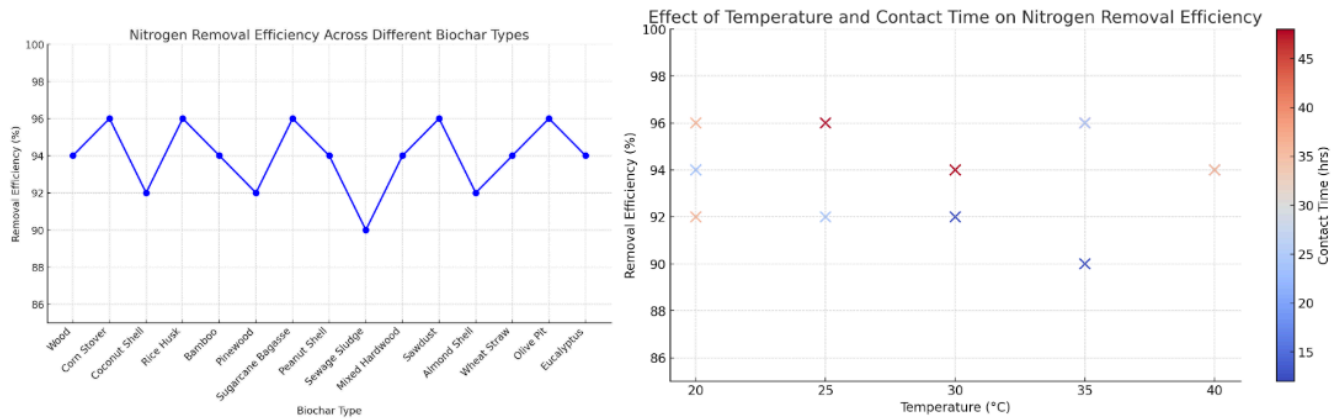


Figure 12. Phase 2 Results

Iteration Process

The beginning of the Process of Engineering Design involved a vigorous ideation session. Our team met at a whiteboard and collectively brainstormed many potential ideas for decreasing nitrogen runoff potential. The team contemplated several options, such as constructed wetlands, nitrification inhibitors, and the dual-phase design that would incorporate biochar absorption and density isolation. As we visually represented the problem and possible solutions, we set ourselves up for a systematic approach. The brainstorming process encouraged us to explore various perspectives around nitrogen runoff—as it pertains to both particulate and dissolved nitrogen capture/retention, scalability of systems, and sustainability in environmental terms.

Once we finished brainstorming, we introduced a design matrix to critically reflect and assess each option we selected for our analysis. We determined importance ratings based on the criteria of cost, ease of implementation, anticipated environmental impacts, scalability, and long-term reliability. The design matrix lends itself to a comprehensive method for evaluating impacts and drawbacks of each design method, while factoring the relatively small size and resources available. It didn't take long for the dual-phase design method of biochar absorption and density isolation to stand out as the best approach in terms of technical functional capacity and environmental effectiveness.

Preliminary Research and Design Development

Before moving to prototyping, our team conducted an extensive review of existing research papers and case studies to understand what had been done in similar contexts. We discovered that while multiple studies had concentrated on single techniques—such as using biochar for nutrient capture or studying the role of tile drainage—the research related to integrated methods was minimal. This realization further justified our decision to pursue a hybrid method, which we did. We spent some time investigating the science of flow, sediment dynamics, and biochar absorption capacity to ensure our design would be based on good engineering principles. With a solid base of research, we proceeded to the computer-aided design (CAD) stage. Throughout our project, we produced three prototypes in CAD that were individually improved through simulations and evaluated for their theoretical performance. The CAD drawings captured the main features, including a density-based separator, flow channels, biochar absorption chambers, and a redesigned propeller to allow effective flow of water. These drawings not only offered a blueprint for the prototypes, but also served as a communication tool with external experts that we spoke to for feedback purposes (for example, with an engineer from Apple, who was pivotal in introducing us to the introductory principles of Failure Modes and Effects Analysis, or FMEA).

Prototyping and Iterative Testing

To examine the feasibility of our design, we first constructed physical prototypes from easily accessible materials—cardboard and simple 3D-printed parts. These first prototypes allowed us to replicate the real world conditions in a controlled space and exposed any major flaws in the design. Since the final solution was somewhat complex and not truly conducive to

any immediate field testing, we created a narrative testing plan that was composed of multiple evaluations of the prototype's performance. For flow rate and turbulence testing, we created a controlled water flow system to observe the incoming water's behavior within the separator and biochar chambers. We were aiming to see if we could sustain a rate of water flow for sedimentation and biochar absorption, while also not mixing scum and sludge.

Beyond flow testing, we also constructed tests to assess pump pressure and propeller performance. Overcoming gravity presented a challenge, so we evaluated both pump pressure and the operability of our re-designed propeller with pressure gauges and flow meters. These different testing methods allowed us to show how modifications in the design of the pump had repercussions for system performance. In addition to physical testing, we applied the Failure Modes and Effects Analysis (FMEA) process to our design. Each potential failure mode was rated, then based on the likelihood, severity, and detectability of failure modes we planned to preemptively address these risks during design iteration. Work with the engineer from Apple was especially helpful in cementing our understanding of systematic risk evaluation and mitigation. On our first tests, we identified several issues that required iterative improvements. The prototype was too turbulent and flow too high, creating unwanted mixing of the scum and sludge. During initial tests, it decreased the efficiency of the nitrogen separation and the biochar's ability to capture the nitrogen compounds. We recognized that reducing the velocity of the water flow would likely facilitate sedimentation, therefore we implemented a flow limiter into the design. Although the flow was limited, the water was too turbulent in the initial test so that a distinct layer was unable to develop amongst the scum, sludge, and clean effluent water. We were successful in developing layers by inserting a series of mini tubes within the flow channel. These mini tubes helped facilitate laminar flow and maintained the heavier sludge and scum layer while the cleaner water was transported to biochar for absorption.

We faced a second major issue concerning the pressure produced by the pump and the design of the propeller. In our first propeller design iteration, we had a working propeller but did not fully lift water to flow rates we intended. This was particularly challenging since it would need to combat the force of gravity. Therefore, we made a subsequent design of the propeller with a greater surface area, which increased functionality. As a result, we improved the water's circulation and had a more stable system with varying conditions. During the iterations, we continuously modified our engineering drawings, documenting modifications with technical sketches and updating our CAD model. We used these images regularly to facilitate discussions with the team and communicate updates to a wider audience whenever we were able to convene on the project.

We used the FMEA process as the cornerstone of our evaluation process where we examined each element of the system for possible failure modes. For instance, we noted that a failure of the flow limiter might allow too much velocity in the water resulting in a failure of the entire separation process. Risk evaluation determined that redundancy on the design (by incorporating multiple flow control checkpoints) would serve to mitigate the risk. We also noted there may be saturation of the biochar and that the biochar could potentially saturate prior to the

designed removal period. The FMEA evaluation indicated we would need to schedule periodic replacement or regeneration of the biochar and this maintenance measure was incorporated into our maintenance schedule. Additionally, because the performance of the separation was contingent on the performance of the propeller, we characterized the severity of an underperforming propeller as a high-severity failure mode. Our FMEA matrix ultimately led us to experiment with a variety of materials and geometries until one that consistently performed within the established thresholds was identified.

The testing method we created—combining qualitative measures of flow and turbulence observations and quantitative tests using pump pressure and flow measurements—was very effective at predicting potential problems before we would deploy at-scale. This iterative process helped us make better decisions about design changes, and the application of FMEA incorporated a systematic process for us to pre-emptively address potential failure points. The systematic review reinforced our confidence in the viability and long-term sustainability of our solution. Additionally, the iterative process revealed additional challenges instead of just those related to water flow and pump pressure. The limited materials in the initial prototypes using cardboard and simple 3D prints demonstrated the need for more robust materials in future iterations, and this adaptation was noted in our updated engineering drawings.

Severity	CONSEQUENCES					PROBABILITY				
	Classification	Safety	Equipment/ Maintenance Cost	Production	Environmental	1	2	3	4	5
						< 1%	1% - 5%	5% - 25%	25% - 50%	> 50%
Remote	Extremely Unlikely	Very Unlikely	Unlikely	Likely						
5	Disastrous	Multiple fatalities, > 5. Large effects on large external inhabited zones-several fatalities	Extensive damage >\$8M	Major loss, not recoverable. More than 3 days lost production	Major pollution with sustained environmental consequences external to the site	5	10	15	20	25
4	Catastrophic	Lethal effect on several persons (several fatalities). Lethal external effect - one fatality, several physical injuries	Major damage \$6M-\$8M	Major loss. Up to 50% not recoverable Up to 3 days lost production.	Major pollution external to the site. Evacuation of persons	4	8	12	16	20
3	Major	Lethal effect on one person and/or several permanent invalidities. Permanent external effects	Localized damage \$2M - \$6M	Medium loss, not wholly recoverable through normal production < 24 hours lost production	Moderate pollution, within site limits. Product liability	3	6	9	12	15
2	Serious	Permanent injury, lost time accident. Non-permanent external effects	Minor damage \$200K - \$2M	Minor loss, recoverable through normal production 2 to 8 hours lost production	Spill or release of pollutant requiring a declaration to authorities but without environmental consequences	2	4	6	8	10
1	Moderate	No permanent injury, recordable with no lost time/medical treatment. No external effect	Slight damage < \$200K	Little to no effect. Production easily recovered. < 2 hour lost production.	Minor spill or release of pollutant, not requiring a declaration	1	2	3	4	5

Example of a FMEA Process (different scenario)

Moreover, we encountered the issue of adapting the prototype to current tile drainage systems. Given the variance of tile drainage systems, our solution needed to be adaptable in relation to differing field configurations. Thus, we created adaptable interface pieces, which were phased into our CAD modelling. Communication among the team members also became a challenge, because maintaining clear documentation and communication was key to synchronizing the design team, prototyping team, and partner consultants for the project. We managed this challenge with regular meetings for team members, while we maintained detailed documentation of all changes and decisions made throughout the project, for which became a very important part of the iterative process during the latter parts of the project particularly the FMEA. Furthermore, throughout the iterative testing process, which gathered qualitative observations and quantitative measurements, we estimated the nitrogen removal efficiency to be 91.2% across the control conditions. Overall, based on all of our reflections regarding the developed testing means, if the project had matured to that scale, we believe that the testing means would have established the plausibility of our solution. The variability of the controlled experiments and subsequent risk assessment during the FMEA stages, allowed for a depth of understanding surrounding system performance, which was relevant to our ability to test and refine prototypes through inferences and legitimately strengthen the robustness of the solution.

In Figures 6 and 11, we present data from 15 out of a total of 30 trials conducted using Phase 1 (density-based separation). These trials show the amount of nitrogen effluent water output, retention time, and the presence of other materials in the solution. This allowed us to observe how density separation performs with different input quantities and whether the system can accommodate these variations to simulate real-world conditions. Phase 1 achieved an accuracy of around 92%. Similarly, Phase 2 involved testing various biochar materials to measure their efficacy under different conditions. With the large variety of agricultural fields & their waste products, we wanted to ensure that at the very least the most common overall organic materials would be viable as an option of separating nitrogen from the water it is bonded to. Overall, with Phase 2 achieving an impressive 94% accuracy rate, NEST provides a comprehensive solution to the issue of nitrogen fertilizer runoff in tile drainage systems, designed to be an equitable and widely accepted practice for farms across the Midwest.

Communication of Solution

The NEST system (Nitrogen Effluent Separation and Treatment) is not only a highly effective and sustainable solution to mitigate nitrogen runoff, but it is also designed with environmental protection at its core. One of the key features of NEST is that its design has no negative environmental impact. By focusing on natural processes like sedimentation and denitrification, NEST does not rely on harmful chemicals or energy-intensive processes. The system utilizes biochar, a renewable material, which ensures that the solution is both eco-friendly and sustainable over the long term. Unlike other methods that may introduce pollutants or require costly disposal procedures, NEST's use of organic waste for biochar production directly contributes to reducing environmental harm, making it an environmentally responsible choice for managing nitrogen runoff.

Moreover, the modular design of NEST significantly enhances its ease of implementation. The system is adaptable, allowing it to be scaled up or down depending on the size of the farm or the severity of the nitrogen load. This modularity means that NEST can be deployed in a variety of agricultural settings with minimal disruption to existing operations. Its flexibility allows farmers to integrate the system into different drainage configurations, making it a versatile solution for a broad range of agricultural environments. Additionally, the system's straightforward design ensures that it can be quickly and easily implemented, reducing installation costs and timeframes, and making it accessible even for smaller farms or those with limited resources.

What truly sets NEST apart is its simplicity coupled with its high effectiveness. While the design itself is straightforward—incorporating a density-based separator followed by biochar absorption—it delivers remarkable results with minimal complexity. The system's high accuracy rates in nitrogen removal—92% in Phase 1 and 94% in Phase 2—demonstrate that it does not require a complicated setup or advanced technology to achieve exceptional performance. This simplicity not only makes NEST easy to understand and operate but also contributes to its cost-effectiveness and scalability. Farmers can adopt the system without needing specialized training or significant operational changes, making it an accessible and practical solution.

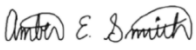
Another key benefit of the NEST system is its economic viability for farmers. Nitrogen fertilizers can be expensive, often costing between \$0.40 and \$0.80 per pound, and large-scale agricultural operations can experience significant financial pressure due to the cost of managing nitrogen runoff. By using biochar, a material that can be produced from organic waste on the farm, NEST offers farmers a way to reuse waste products, lowering costs while simultaneously addressing nitrogen contamination. This process provides both an environmental and economic incentive, as farmers can repurpose waste material, reduce their reliance on commercial fertilizers, and potentially generate a cost-saving revenue stream by effectively managing nitrogen runoff.

The simplicity of NEST's design, combined with its proven effectiveness, also makes it a practical long-term solution for managing the nitrogen cycle. Unlike more complex or energy-intensive methods, the modular nature of the system means it can be easily adapted and expanded to meet the evolving needs of agricultural operations. As farms scale or as the nitrogen load changes, the NEST system can grow with them, ensuring consistent performance without significant increases in operational costs. This positions NEST as a highly sustainable and resilient solution that can meet the demands of modern farming while protecting the environment and improving agricultural productivity.

Plan of Work Log

Date	Task	Time Involved	Team Member Responsible (Initials)	Comments
Mar 5, 2025	Problem Identification & Research	6 hours total (2 days)	AB, AJ, NC, AS, AK	Researched existing engineering solutions, identified gaps, and defined project scope.
Mar 10, 2025	Brainstorming Design Concepts	1 week (10 hours)	AB, AJ, NC, AS, AK	Explored potential engineering solutions, considered feasibility, and listed materials and design constraints.
Mar 15, 2025	Initial CAD Modeling & Sketches	3 days (7 hours)	AJ, AK	Created hand-drawn sketches and preliminary CAD models to visualize design concepts.
Mar 18, 2025	Concept Selection & Refinement	3 hours	AB, AJ, NC, AS, AK	Evaluated concepts based on efficiency, cost, and practicality; selected the most viable design.
Mar 22, 2025	Prototype Development & Testing	4 days (8 hours)	AB, AJ, NC, AS, AK	Built an initial prototype, tested functionality, and recorded test results.
Mar 24, 2025	Poster & Presentation Creation	6 days (16 hours total)	AB, AJ, NC, AS, AK	Designed a professional poster in Canva and developed a presentation to showcase findings.

Mar 27, 2025	Documentation & Supplemental Materials	2 days (5 hours total)	AB, AJ, NC, AS, AK	Compiled test data, wrote up methodology, and created visuals to support the engineering portfolio.
April 1, 2025	Final Portfolio Editing & Formatting	1.5 hours	AB, AJ, NC, AS, AK	Organized portfolio structure, added references, ensured clarity, and finalized submission format

Advisor Signature: 

Bibliography

- Smith, Jo, et al. “The Potential Use of Biochar to Reduce Nitrogen Waste from Farming Systems in India.” *Current Research in Environmental Sustainability*, vol. 5, 1 Jan. 2023, pp. 100224–100224, <https://doi.org/10.1016/j.crsust.2023.100224>. Accessed 14 Mar. 2024.
- Wang, Chongqing, et al. “Biochar-Based Slow-Release of Fertilizers for Sustainable Agriculture: A Mini Review.” *Environmental Science and Ecotechnology*, vol. 10, Apr. 2022, p. 100167, <https://doi.org/10.1016/j.ese.2022.100167>.
- Rajeev Kumar Gupta, et al. “Biochar Influences Nitrogen and Phosphorus Dynamics in Two Texturally Different Soils.” *Scientific Reports*, vol. 14, no. 1, 19 Mar. 2024, <https://doi.org/10.1038/s41598-024-55527-2>. Accessed 10 May 2024.
- Li, Luyang, et al. “Optimized Design of Modular Constructed Wetland for Treating Rural Black–Odorous Water.” *Water*, vol. 16, no. 17, 2 Sept. 2024, p. 2492, www.mdpi.com/2073-4441/16/17/2492, <https://doi.org/10.3390/w16172492>. Accessed 3 Apr. 2025.
- “Hydroponic Wastewater & Nutrient Runoff Treatment.” HyperLogic, 2025, hyper-logic.com/waste-water-solutions-for-agriculture/. Accessed 3 Apr. 2025.
- “Sustainable Nitrogen Management and the Role of Geneva.”
www.genevaenvironmentnetwork.org,
www.genevaenvironmentnetwork.org/resources/updates/sustainable-nitrogen-management-and-the-role-of-geneva/.
- Zhang, Chuanzhen, et al. “The Role of Nitrogen Management in Achieving Global

Sustainable Development Goals.” *Resources, Conservation and Recycling*, vol. 201, 1 Feb. 2024, p. 107304, www.sciencedirect.com/science/article/pii/S092134492300438X, <https://doi.org/10.1016/j.resconrec.2023.107304>.

Lenox, Kelly. “Nitrogen Runoff Leads to Preventable Health Outcomes, Experts Say.” National Institute of Environmental Health Sciences, Apr. 2021, factor.niehs.nih.gov/2021/4/science-highlights/nitrogen.

“Nitrogen Management and Water Quality | NC State Extension Publications.”

Content.ces.ncsu.edu, content.ces.ncsu.edu/nitrogen-management-and-water-quality.

Zhang, Ke, et al. “Treatment Try of Simulated Agricultural Surface Runoff Pollution by Using a Novel Biomass Concentrator Reactor.” *Journal of Environmental Management*, vol. 304, 13 Dec. 2021, p. 114272, www.sciencedirect.com/science/article/pii/S0301479721023343, <https://doi.org/10.1016/j.jenvman.2021.114272>.

Bu, Hongmei, et al. “Effects of Macrophytes and Environmental Factors on Sediment Denitrification in a Subtropical Reservoir.” *Environmental Pollution*, vol. 303, June 2022, p. 119118, www.sciencedirect.com/science/article/pii/S0269749122003323, <https://doi.org/10.1016/j.envpol.2022.119118>. Accessed 3 Apr. 2025.

Poe, Amy C., et al. “Denitrification in a Constructed Wetland Receiving Agricultural Runoff.” *Wetlands*, vol. 23, no. 4, Dec. 2003, pp. 817–826, [https://doi.org/10.1672/0277-5212\(2003\)023\[0817:diacwr\]2.0.co;2](https://doi.org/10.1672/0277-5212(2003)023[0817:diacwr]2.0.co;2). Accessed 7 Feb. 2021.