Circular Bionutrient Economy: Fertilizer Derived from Human Waste

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Abstract

Of the world's most pressing issues, food security and sanitation are situated at the top. Our existing agricultural systems, which are already under severe pressure, will be unable to feed the world's growing populations in the wake of climate change. In many developing countries there is a lack of infrastructure to properly contain human waste, which poses massive health and environmental concerns. In countries with extensive waste management systems, these processes are often energy intensive, and still do not always deal with excess nutrients properly. When excess phosphorus and nitrogen contaminate waterways, this causes remarkable decline in ecosystem health.

The Circular Bionutrient Economy (CBE) is a way of rethinking these broken systems. Waste, rather than being a problem that needs to be disposed of, can be used as a valuable resource. There are countless innovative ways to "close the loop" between waste streams and resources necessary to human survival. This paper explores one such way that nitrogen, phosphorus, and potassium from human waste can be turned into agricultural fertilizer.

Problem Statement

Using human excreta as agricultural fertilizer is not a novel or untested strategy (Martin et al. 2022). However, depending on scale and location, there are a few logistical concerns with the direct application of human waste on agricultural lands. Urine is mostly water and thus transporting it over long distances is costly and energy intensive. Furthermore, the pH and salinity of urine is above what plants typically need to thrive (Martin et al. 2020). Depending on location, human waste can contain higher levels of PFAS and pharmaceuticals than what is recommended to apply to agricultural lands. Certified organic agriculture also prohibits the application of sewage sludge due to possible contaminants in the substance (McEvoy 2011). Finally, massive stigma exists around human excreta. People immediately assume that any application of human excreta applied in agricultural contexts poses a massive threat to human health.

To address these issues, we built a reactor to capture nitrogen, phosphorus, and potassium (NPK) from human urine and store it on clean biochar. Biochar is a carbon rich soil amendment made through the process of burning organic matter in the presence of low or no oxygen, known as pyrolization. The result is an extremely porous material that can absorb nutrients and act as a slow release fertilizer (Wang 2022). While biochar can be made from any number of substances, we specifically favor using biochar from human biosolids (i.e solids from a wastewater treatment plant) and dairy manure solids to further the prospects of turning waste into valuable resources.

Methods

Before setting up our reactor design, we first aimed to determine the chemical effects of biochar on urine and other nitrogen containing solutions. For our experiments we used a 1.5 g Nitrogen per liter NH_4OH solution. The NH_4OH solution provided us with consistent levels of nitrogen in our experiments. In addition, when air is bubbled through urine, it creates a massive amount of foam that is hard to work with and messy to clean up. Using a 1:15 biochar to liquid ratio, we set up a batch bubbling experiment that tested the impact of different types of biochar on the pH of NH4OH as air was bubbled through the samples at 10 L/minute for 2.5 hours. There were five bubbling solutions set up simultaneously: two naturally high pH biochars (raw manure and digested manure solids), two lower pH biochars (food waste and paper waste), and a no biochar control.

The goal was to create a reactor, or chain of reactors, that could capture nitrogen through ammonia volatilization and phosphorus and potassium through struvite precipitation. To induce ammonia volatilization, we used an air stripping tower design where a material, in our case biochar, was packed into a reactor column and air and liquid were pumped through in opposite directions. The escaping air from the top contains the volatilized ammonia that can be stored on biochar or captured in an acid trap for analysis. To create a phosphorus precipitation reactor, we chose a fluidized bed reactor where biochar and liquid are in constant motion and in contact with each other. For the purposes of this paper, I will primarily discuss the ammonia volatilization reactor.

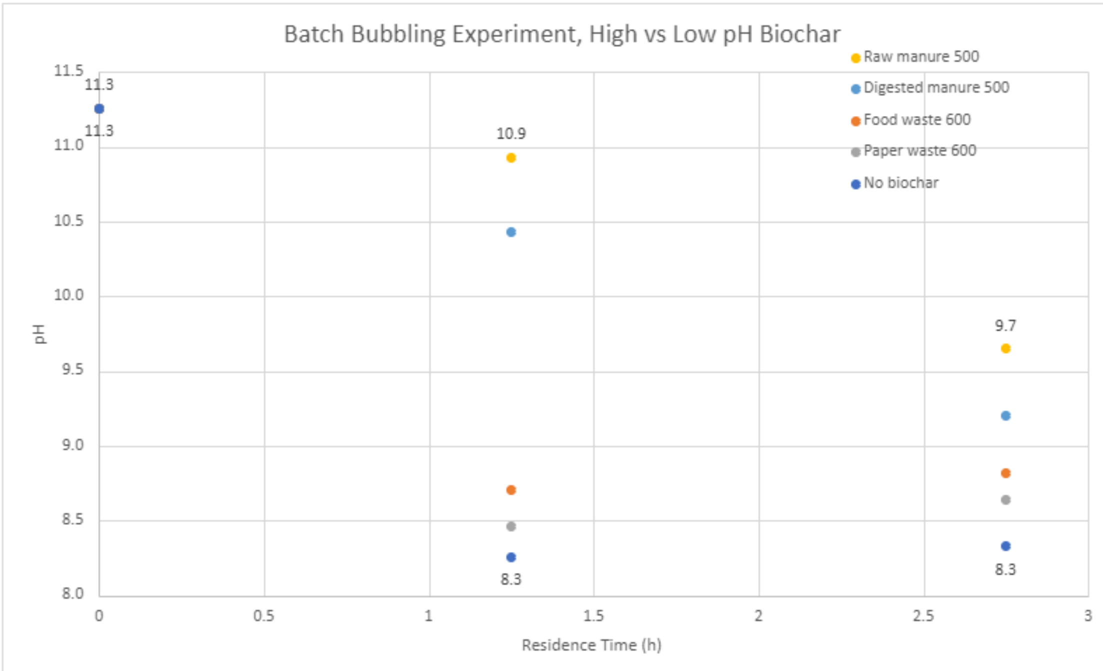
The ammonia volatilization reactor was built using PVC pipes, tubing, a peristaltic pump, air valve, 1.5 g NH4OH solution, and an H2SO4 acid trap. We used a packed bed reactor design with downward water flow and upward airflow. The material inside the reactor was biosolids-based biochar in 2-4 mm pieces. While running our experiments, the peristaltic pump was set to 2 (approximately 100 mL/min) and the air valve was set to 10 L/min. While it was typically our intention to leave the reactor running for 24 hours, we encountered significant issues with our reactor leaking. We tried to remedy this with sealing tape, but sometimes the leaking became too intense and we had to stop the experiment early. Experiments ultimately lasted 3.5-45 hours dependent on reactor design and leaking dilemmas.

To analyze nitrogen levels of our samples, we used photospectroscopy. All samples were acidified or made basic to be in the range 4-7 pH using H_2SO_4 or NaOH. The samples were then diluted using hypothesized ranges of nitrogen levels. In this method, sodium salicylate was the primary reagent that was used to cause the color reaction with ammonium. Samples were compared to an ammonium stock solution made from NH_4Cl with standard amounts of Nitrogen.

In our first experiment we used non pH adjusted biochar as the packing material for this reactor. The pH of this biosolids based biochar was 7.6. For the next experiment, we adjusted the pH of the biochar to 10.89. For the final experiment, we used pH adjusted biochar and added NaOH to the NH_4OH solution every hour to stabilize the pH through the experiment. The process of nitrogen volatilization naturally lowered the pH of the solution. For future reactor runs we are looking to add a pH probe to our solution tank and an arduino controlled pH adjustment system to continually add NaOH.

Findings

Through the batch scale bubbling experiment, we determined that high pH manure-based biochar did a better job at buffering in the solution and kept the pH of the NH_4OH solution higher for longer. The lower pH biochars also had a positive effect on the pH as compared to the no-biochar control.



We found that pH-adjusted biochar with continuous, manual pH adjustment resulted in 93% nitrogen removal over 3.5 hours. This is an improvement from previous experiments without any biochar adjustment that only resulted in 85% removal over 45 hours, or only biochar pH adjustment that resulted in 85% removal over 5 hours.

Biochar pH	Continual pH adjustment?	% Nitrogen Removal
Non-adjusted	No	85% in 45 hours
Adjusted to 10.89	No	85% in 5 hours
Adjusted to 11.64	Yes (manually)	93% in 3.5 hours

However, after running mass balance analysis on our data, it was found that between reactor run experiments, the biochar was holding onto some amount of Nitrogen and releasing it during the next experiment.

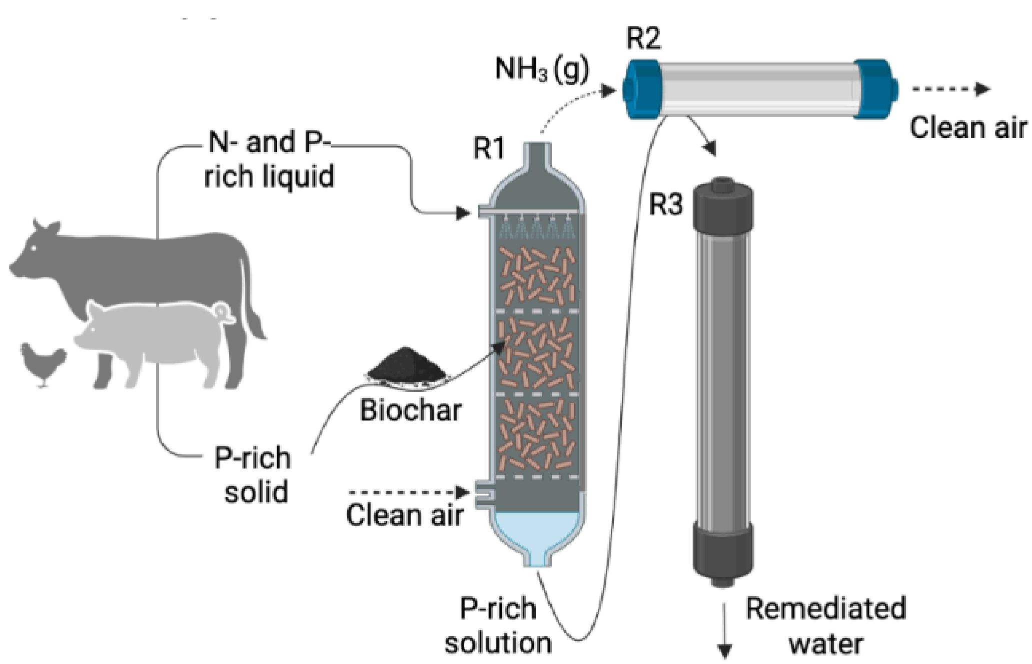
Mass balance for pH adjusted BC & Continual pH adjustment				
Time	NH4OH N removed	H2SO4 N accumulated	% removed	% accumulated of removed
0-30mins	776.0	1927.3	23%	248%
30-60mins	799.3	3036.8	46%	380%
60mins-2h	1126.9	2047.8	79%	182%
2h-3.5h	500.8	1907.5	93%	381%
Total	3203.0	8919.4	93%	278%

Discussion

At pH of 9.25 the proportion of ammonia (NH3) to ammonium (NH4) is roughly 1:1, but at pH >11, almost all of the ammonium will volatilize into ammonia. Thus, as it would follow, the higher the pH of the solution, the higher the efficiency in ammonia volatilization (Başakçılardan-Kabakcı 2007). There are two ways that biochar can improve the ammonia volatilization efficiency: through chemical buffering capacity or mechanical properties. While we established the biochar assists the NH4OH solution in retaining a high pH, even as ammonia volatilized and naturally lowered the pH, we still need to run more batch bubbling experiments to determine if the same buffering capacities apply to solutions of synthetic urine and real human urine.

From a fluid dynamics point of view, using biochar as a packing material in our reactor can also help increase volatilization efficiency. The biochar increases surface area, thus enabling a higher air to liquid contact ratio. To further test the mechanical impacts of biochar on this reactor, we will set up an experiment with no biochar or packing material whatsoever.

Moving forward with this project, we are aiming to create a continuous chain of reactors that can remove both phosphorus and nitrogen from urine and load it onto a "clean" biochar.



Full reactor set up in a dairy farm application. In place of animal manure, human waste from a wastewater treatment plant can also be used as it is similarly high in N and P.

Impacts

At the crux of the Circular Bionutrient Economy is the understanding that no individual solution will work for every type of location. The direct application of diluted urine as a fertilizer might work best in a situation where a family can collect their own urine and apply it to their own small fields. In addition, in places where average temperature is quite high, urine would not need to sit for as long a time period before it is considered safe to apply to soil. In places where there is not existing sanitation infrastructure (e.g. peri-urban regions in Kenya, a community garden, etc.) building a simple urine collecting toilet is a cost-effective way to rescue resources and work towards sustainable sanitation practices.

On the flipside, with the uneven distribution of agriculture and population density across the US, single-family urine collection is not a widely viable solution. Instead, a reactor like the one outlined in this paper could become a part of local wastewater treatment facilities. As another example, as an alternative to traditional porta potties, a company could install source-separating temporary toilets, then use this type of reactor and a biochar kiln to turn human excreta collected at concerts and events into a marketable agricultural soil amendment.

In the early 20th century with the Green Revolution, agricultural practices changed dramatically. Farms grew in size, shifted towards only growing one type of crop, and increased their dependence on synthetic fertilizers (Pingali 2012). The results were outstanding! At a time when it was unclear how agriculture was going to keep up with a rapidly increasing global population, the Green Revolution solidified global food security. Similarly, the toilet and modern sanitation infrastructure is considered one of the greatest inventions of all time, saving lives through the prevention of the spread of disease. There is no debate that these inventions changed the course of history for the better.

However, these same inventions that saved countless lives are now impeding our planet's ability to thrive into the future. The Haber-Boche process, which allows for ammonia (nitrogen in a plant-available form) to be synthesized from nitrogen in the atmosphere, currently accounts for around 1% of global energy consumption and 1.4% of global CO2 emissions (Capdevila-Cortada 2019). It is imperative that we work towards fundamentally shifting sanitation and food production systems away from practices that exacerbate ecological distress and towards ecological resilience.

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