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UC Riverside Undergraduate Research Journal

Title

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Journal

UC Riverside Undergraduate Research Journal, 20(1)

Author

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Publication Date

2026-10-10

DOI

10.5070/RJ5.64252

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Evaluating Acid Activation Parameters of Biochar for Ammonia Adsorption

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ABSTRACT

Ammonia emissions from agricultural systems are an ongoing environmental challenge, and gas adsorption is a common treatment approach. Biochar is charred organic material, usually made from wood or agricultural straw, that has proven to be a low-cost and effective adsorbent for ammonia removal. However, its performance often depends on production modifications such as acid activation. Although acid activation is known to enhance adsorption capacity, the influence of its preparation parameters remains insufficiently understood. This study investigates the effect of particle size (ground and unground), phosphoric acid concentration (15%, 30%, and 45%), and rinsing method (two rinses, five rinses, and a 1-hour soak) on biochar produced from cherry wood chips pyrolyzed at 500°C for 15 minutes. A total of 18 treatment combinations were evaluated in duplicate. The pH was measured before and after activation and used as an indirect indicator of ammonia adsorption potential, as increased surface acidity is associated with enhanced ammonia binding. Post-activation pH values ranged from 2.2 to 3.3, compared to initial values between 7.87 and 9.78. Unground biochar consistently exhibited lower pH values than ground samples, suggesting greater acid retention due to differences in particle structure. Higher acid concentrations produced lower pH values, while more extensive rinsing increased pH due to the removal of residual acid. These results demonstrate that preparation parameters influence biochar surface chemistry and should be optimized to improve ammonia adsorption performance.

KEYWORDS: Biochar, Ammonia, Adsorption, Acid Activation, Surface Functional Groups, Phosphoric acid, pH

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Melina Caraballo is a fourth year Environmental Engineering major. She conducts research under Dr. Amanda Rupiper, investigating the ammonia adsorption performance of various biochar strains made from agricultural feedstock. She is passionate about sustainability and circular systems and plans to pursue a career in environmental consulting.

Evaluating Acid Activation Parameters of Biochar for Ammonia Adsorption

INTRODUCTION AND BACKGROUND

Ammonia emissions from agricultural activities remain an environmental concern, and biochar is one of the many mitigation strategies available. However, raw biochar often exhibits a relatively limited adsorption capacity. Previous studies have determined that modified biochar can adsorb greater amounts of ammonium in liquid solutions compared to unmodified biochar (Zhang et al., 2020). Despite this, the parameters for acid activation are not well documented, and how different methods affect the adsorption potential remains unclear. Therefore, the objective of this study is to evaluate how variations in acid activation influence the properties of biochar.

Ammonia is a colorless gas that indirectly contributes to climate change by breaking down in the atmosphere and forming nitrous oxide, a greenhouse gas. In the United States, approximately 90% of ammonia emissions originate from agricultural activities such as livestock activity and the use and production of fertilizers (Ro et al., 2015). In addition to environmental impacts, ammonia emissions also affect air and water quality. Ammonia can react in the atmosphere and form fine particulate matter (PM_{2.5}), which is associated with respiratory issues and premature mortality (Wyer et al., 2022). These impacts highlight the need to capture and remove ammonia emissions to protect both environmental and human health.

Biochar is a carbon-rich material that is made from organic biomass such as rice husks, wood chips, poultry litter, coconut shavings, corn husks, etc. It is widely used as an adsorbent, similar to activated carbon. Biochar is formed through pyrolysis, a process in which biomass is heated in a low-oxygen environment ranging from 300 to 600°C for 15 to 60 minutes, depending on the desired outcome. Biochar has several advantages, including ease of production, low cost, environmental friendliness, and sustainability (Tang et al., 2025). Due to its porous structure and surface chemistry, biochar has emerged as a promising approach for pollutant control.

Biochar can be modified through various physical and chemical activation methods, such as thermal treatment, steam activation, and chemical modification. Among these, phosphoric acid activation has been shown to improve

ammonia adsorption by increasing the number of acidic surface functional groups, which play an important role in ammonia binding (Ro et al., 2015). As a result, acid-activated biochar has been reported to achieve greater reductions in ammonia emissions compared to non-activated biochar, which highlights its effectiveness for ammonia removal (Baral et al., 2023).

Acid activation modifies biochar by treating it with an acid solution, typically phosphoric or nitric acid, for a set period of time. During this process, the acid diffuses across the surface and into the pores of the biochar. In doing so, it alters the surface chemistry and internal pore structure. These changes increase the number of available adsorption sites and enhance the interactions between the acidic biochar surface and the basic ammonia gas. In other words, acid activation of biochar after pyrolysis promotes acid-base interactions between the biochar surface and ammonia gas (NH₃), which improves overall adsorption capacity.

When the surface chemistry of biochar is altered during acid activation, new functional groups are formed on the material's surface. These newly formed functional groups increase the acidity of the biochar and become chemically bound to the carbon structure. Furthermore, studies have reported a linear correlation between the breakthrough capacity of ammonia and the number of surface functional groups present on the biochar (Huang et al., 2008). The presence of these groups increases the overall surface acidity of the biochar and provides additional active sites for ammonia adsorption. Acid modification has been shown to improve ammonium adsorption by increasing the concentration of oxygen-containing functional groups, such as carboxylic and lactonic groups (Vu et al., 2017). These groups enhance adsorption by allowing the biochar surface to retain ammonia molecules more effectively. Therefore, understanding how different acid activation parameters influence biochar surface chemistry is important for improving ammonia adsorption performance.

Previous work from this laboratory reported a pH of 8.94 for non-acid-activated biochar (Howlett et al.), which confirms the neutral or alkaline nature of untreated materials and the necessity of acid activation to enhance ammonia adsorption yield. As the effectiveness of acid activation has

Evaluating Acid Activation Parameters of Biochar for Ammonia Adsorption

been well established in the literature, this study does not seek to re-evaluate its benefit over untreated biochar. Instead, this study builds upon these findings to address a gap in the literature regarding how specific preparation parameters, such as particle size, acid concentration, and rinsing method, influence the pH of the biochar. By varying these conditions, this study aims to identify an optimal acid activation procedure for improving ammonia adsorption capacity.

METHODS

Experimental Design

This experiment was designed to evaluate the effects of particle size, phosphoric acid concentration, and post-treatment rinsing method on biochar pH. The variables included two particle sizes (ground and unground), three phosphoric acid concentrations (15%, 30%, and 45%), and three rinsing treatments (two rinses, five rinses, and a 1-hour soak), which resulted in 18 unique treatment combinations. A baseline condition representing standard activation practice for woodchip biochar was defined as a ground sample treated with 30% phosphoric acid and subjected to five rinses. This condition served as a reference point for comparison, with other treatment combinations representing deviations from this baseline. Each condition was prepared using 1 gram of biochar and conducted in duplicate, yielding a total of 36 experimental samples. Initial pre-activation pH values were measured for the samples and used as a baseline for comparison with post-activation measurements.

Biochar Production

The biochar used in this experiment was produced from cherry woodchip shavings and was pyrolyzed at 500°C for 15 minutes using a muffle furnace. Production was conducted between January 16 and January 27, 2026, in which over 60 grams of biochar were produced. Excess biochar was produced to allow for duplicate testing. One of the parameters tested was particle size. For the unground biochar, the woodchips were simply used as received, and for the ground biochar, the woodchips were reduced to a smaller and more uniform size using a mortar and pestle prior to pyrolysis. Samples were placed in crucibles, covered with aluminum foil, and sealed with a lid in order to achieve the low oxygen conditions required for pyrolysis. After 15

minutes, the crucibles were removed from the muffle furnace and left to cool before weighing and packaging.

Acid Activation Procedure and Storage

Three phosphoric acid solutions were prepared at 15%, 30%, and 45% dilution; 100 mL of each solution was prepared. For each treatment condition, 1 gram of biochar was placed into a 50 mL beaker, and 3 mL of phosphoric acid was added. This volume was selected to ensure complete wetting and coating of the biochar surface and was kept consistent across all samples. Samples were thoroughly mixed to promote uniform contact between the acid and biochar. Beakers were then sealed with Parafilm and stored in a dark cabinet overnight for approximately 15 hours to allow for sufficient interaction time while preventing the acid from volatilizing and the mixture from drying out.

Rinsing method and post-treatment

After being left undisturbed overnight, the biochar was removed from the 50 mL beakers and underwent a rinsing treatment to remove the acid. For the rinsing treatment, the biochar was transferred to funnels that were lined with filter paper and placed over graduated cylinders. The filter paper was pre-wetted with water before the biochar was added. For the 1-hour soak treatment, a layer of Parafilm was placed beneath the filter paper to ensure the water stayed in place. A 20 mL volume of DI water was used for the soak, which allowed all the biochar to be submerged during the treatment, and in order to keep conditions consistent, 20 mL was used for the rinses as well. Each rinse was timed, averaging from 1 to 1.5 minutes per rinse. Afterward, the filter papers were placed on brick plates, and the biochar was evenly spread out into a thin layer before being placed in a drying oven at 100°C for 1 hour to remove residual moisture while avoiding burning the filter paper.

Final pH Measurements

After drying, the biochar was gently brushed off the filter paper and transferred to a weigh boat to obtain the post-activation weight before being placed into a 50 mL beaker. A 30 mL volume of DI water was added to each beaker and stirred thoroughly before measuring the final post-activation pH. In order to maintain consistency, the pH meter was calibrated every two weeks and before each use.

Evaluating Acid Activation Parameters of Biochar for Ammonia Adsorption

Two measurements were taken per trial and then averaged to obtain a more accurate reading.

DISCUSSION

Biochar Sample Identification and pH Measurements

Tables 1 and 2 summarize the identification system used for each sample, along with its pre- and post-activation pH measurements. The naming convention goes as follows: letter–particle size–acid concentration–rinsing method. (e.g. A-UG-15%-2x). The pre- and post-activation weights of the samples were recorded in order to verify consistency and detect mass loss during processing. Some samples had slightly higher final weights than their initial weights, which is likely attributable to filter paper residue that transferred over after the drying process. Only minor changes in mass were observed, which suggests that the activation and rinsing procedures did not substantially alter the amount of biochar used in the final pH measurements. The final pH values

measured for each biochar sample following activation and rinsing are summarized below.

Trends in Final pH Measurements

Trial 1 was conducted on January 30–31, 2026, and trial 2 was conducted on February 14 to 15, 2026. The initial pH for trial 1 was measured on January 29 and showed an unground pH of 8.82 and a ground pH of 9.78. The initial pH for trial 2 was measured on February 14 and showed an unground pH of 7.87 and a ground pH of 8.92. This variation may be attributed to the storage period between trials. Trial 2 was conducted approximately two weeks after the first trial, during which the stored biochar samples could have adsorbed atmospheric compounds present in the laboratory environment.

A similar trend can be observed in the final pH measurements, as shown in Figure 1, where the final pH measurements for trial 2 were generally slightly higher than those from trial 1. Trial 1 had pH ranges as low as 2.29 and

Sample ID	Trial 1 Final pH Average	Trial 2 Final pH Average
A-UG-15%-2x	2.64	2.695
B-UG-30%-2x	2.55	2.605
C-UG-45%-2x	2.32	2.395
D-UG-15%-5x	3.005	3.195
E-UG-30%-5x	2.9	3.035
F-UG-45%-5x	2.835	2.86
G-UG-15%-1hr	2.83	2.88
H-UG-30%-1hr	2.415	2.545
I-UG-45%-1hr	2.295	2.375

Table 1: Final pH measurements for Unground Biochar following acid activation with an initial UG pH of 8.82 for trial 1 and 7.87 for trial 2.

Sample ID	Trial 1 Final pH Average	Trial 2 final pH Average
J-G-15%-2x	2.885	2.94
K-G-30%-2x	2.54	2.595
L-G-45%-2x	2.485	2.46
M-G-15%-5x	3.27	3.325
N-G-30%-5x	3.08	2.985
O-G-45%-5x	2.995	2.915
P-G-15%-1hr	2.74	2.73
Q-G-30%-1hr	2.465	2.515
R-G-45%-1hr	2.3	2.365

Table 2: Final pH Measurements for Ground Biochar following acid activation with an initial G pH of 9.78 for trial 1 and 8.92 for trial 2.

Evaluating Acid Activation Parameters of Biochar for Ammonia Adsorption

as high as 3.27, whereas trial 2 had a range from 2.36 to 3.33. Despite this difference, the overall trends in the data remain consistent. Ground samples had higher pH values than their unground counterparts. Additionally, pH decreased with increasing acid concentration, and samples rinsed five times had higher pH values compared to those rinsed twice. The standard error was calculated for each data point, with values ranging from 0.005 to 0.095, indicating minimal variation between the replicate trials. A one-way ANOVA test confirmed that differences in pH across the 15%, 30%, and 45% acid concentrations were statistically significant ($p=0.0025$), supporting the observed trend of decreasing pH with increasing acid concentration.

Effect of Activation Parameters on Final pH

The difference in particle size is illustrated in Figure 2, where sample C represents the unground and sample Q represents the ground. Unground samples consistently exhibited lower final pH values than did ground samples. One possible explanation is that larger particles retain more acid in their pore structure, which limits acid removal during rinsing. Residual acid trapped within these pores may contribute to lower measured pH values. In contrast, the smaller and more uniform structure of the ground samples may facilitate more effective rinsing, resulting in higher final pH values. However, this mechanism was not directly tested and would require further characterization to confirm.

The influence of acid concentration on final pH was also evident. Lower pH values in the 45% phosphoric acid-treated biochars indicate that the stronger acid concentration had a more significant effect on the biochar's final pH. Similarly, the 15% acid-treated strains had higher final pH values, suggesting that higher acid concentrations result in greater surface acidity after activation. This trend is also seen in Figure 1, where the final pH values for unground samples, rinsed twice, linearly decreased as the acid concentration increased.

The rinsing method had a distinct effect for the two and five-time rinse treatments; however, the 1-hour soak was inconsistent. Samples that underwent 5 rinses generally showed higher final pH values than samples rinsed only twice, suggesting that additional rinsing removed residual acid from the biochar surface. The 1-hour soak treatments produced more variable pH values, which suggests that this method might not be consistent in removing residual phosphoric acid.

RESULTS

The overall trends in the data indicate that unground biochar treated with 45% phosphoric acid produced the lowest final pH values across the tested conditions. Additionally, the samples subjected to five rinses consistently exhibited higher final pH values than those rinsed only twice, suggesting a

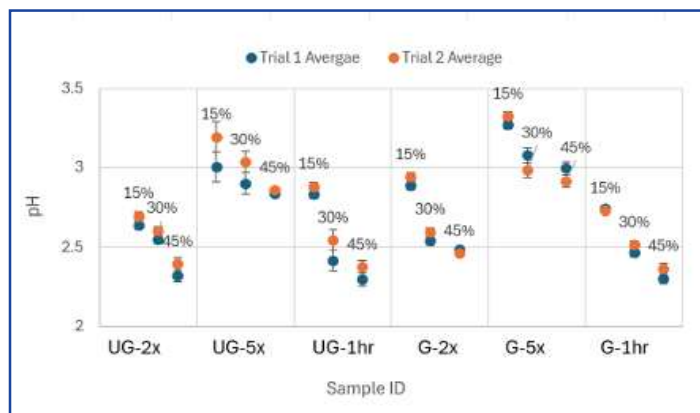


Figure 1: Average Final pH Values of Biochar Samples for Trials 1 and 2



Figure 2: Visual Comparison of Particle Size in Ground vs. Unground Samples

Evaluating Acid Activation Parameters of Biochar for Ammonia Adsorption

more effective removal of residual phosphoric acid. These results demonstrate that both feedstock preparation and acid activation play significant roles in influencing the surface acidity of acid-activated biochar.

EXPERIMENTAL LIMITATIONS

While the final pH of the biochar provides a useful indicator of surface acidity and potential adsorption, additional testing would be required to quantify the adsorption performance under each treatment. Additionally, it is important to consider that some rinsing procedures might not have fully removed residual activating acid from the biochar surface. Samples subjected to fewer rinses or soaking treatments may have retained trace amounts of acid, which could artificially lower pH measurements. This interpretation is also supported by qualitative observations, as a majority of samples treated with two rinses or the 1-hour soak retained a noticeable acidic odor after their rinse treatment. This further suggests that residual phosphoric acid may still have been present. Residual acid is important to consider as it may react with the ammonia differently than a biochar surface containing only bound acidic functional groups. Surface functional groups are chemically bound to the carbon structure of the biochar and promote the adsorption of ammonia gas. If residual phosphoric acid remained on the biochar, adsorption would be less likely to occur, and a direct acid-base reaction between phosphoric acid (H_3PO_4) and ammonia (NH_3) would occur instead.

FUTURE DIRECTIONS

While pH provides a useful indicator of surface acidity, it does not directly quantify ammonia adsorption capacity. Therefore, the next step in this research is to perform ammonia adsorption experiments in order to directly determine how these activation parameters influence adsorption performance. Future testing will focus on evaluating adsorption capacity and assessing whether the two-times rinse or 1-hour soak preparations artificially raise adsorption capacity.

In addition to adsorption testing, future work will include scanning electron microscopy (SEM) analysis to directly

examine biochar surface structure. SEM imaging will allow for visual characterization of differences in pore structure and surface texture resulting from different biochar samples and activation parameters. This analysis aims to provide a more complete picture of how the acid preparation process influences biochar surface chemistry. These future directions will bridge the gap between the pH-based findings of this study and direct measurements of surface properties and adsorption performance.

CONCLUSION

The goal of this study was a better understanding of the acid activation parameters of biochar used for ammonia adsorption. Parameters such as particle size, acid concentration, and rinsing method were tested to see how they affected the pH of the biochar after pyrolysis. The results suggest that activation conditions influence the pH and surface acidity of biochar, which is a valuable indicator of the potential ammonia adsorption yield. In general, treatments that result in a lower pH while still ensuring no residual acid remains to react with the ammonia may be favorable indicators of surface activity, and optimizing acid activation conditions is an effective strategy for improving the performance of biochar as a low-cost adsorbent for ammonia emissions.

Studies have shown that in agricultural systems, biochar can improve pH, porosity, and water availability in soils, which helps increase nutrient uptake by plants (Joseph et al., 2021). When biochar is used to reduce these emissions, the captured ammonia remains adsorbed onto the surface of the biochar. Once the biochar is saturated and is no longer able to capture ammonia, it can be applied to the soil and become an additional nutrient source for plants. The trends observed in this study suggest that acid-activated biochar may offer dual benefits by both capturing ammonia emissions and subsequently serving as a nutrient source when applied to soil. These findings emphasize the importance of controlling activation conditions when producing biochar in order to ensure that it is both effective for ammonia adsorption and suitable for environmental applications after it has been spent.

Evaluating Acid Activation Parameters of Biochar for Ammonia Adsorption

REFERENCES

- Baral, K. R., McIlroy, J., Lyons, G., & Johnston, C. (2023). The effect of biochar and acid activated biochar on ammonia emissions during manure storage. *Environmental Pollution*, 317, 120815. <https://www.sciencedirect.com/science/article/pii/S0269749122020309>
- Howlett, T., Ocampo, A., Rupiper, A. *Ammonia Adsorption Performance of Biochars from Agricultural Waste Feedstocks: Implications for Air Pollution Control*. Unpublished manuscript, Department of Chemical and Environmental Engineering, University of California Riverside, in preparation.
- Huang, C.-C., Li, H.-S., & Chen, C.-H. (2008). Effect of Surface Acidic Oxides of Activated Carbon on Adsorption of Ammonia. *Journal of Hazardous Materials*, 159(2-3), 523-527. <https://doi.org/10.1016/j.jhazmat.2008.02.051>
- Joseph, S., Cowie, A. L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., Cayuela, M. L., Graber, E. R., Ippolito, J. A., Kuznyakov, Y., Luo, Y., Ok, Y. S., Palansooriya, K. N., Shepard, J., Stephens, S., Weng, Z. (Han), & Lehmann, J. (2021). How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy*, 13(11), 1731-1764. <https://doi.org/10.1111/gcbb.12885>
- Ro, K., Lima, I., Reddy, G., Jackson, M., & Gao, B. (2015). Removing Gaseous NH₃ Using Biochar as an Adsorbent. *Agriculture*, 5(4), 991-1002. <https://doi.org/10.3390/agriculture5040991>
- Tang, L., Chen, S., Wang, N., & Jiang, X. (2025). Comparative study of adsorption and slow-release performance and mechanism of phosphoric acid and ammonia-modified biochars on 2,4-dichlorophenoxyacetic acid. *Separation and Purification Technology*, 358, 130470. <https://doi.org/10.1016/j.seppur.2024.130470>
- Vu, T. M., Trinh, V. T., Doan, D. P., Van, H. T., Nguyen, T. V., Vigneswaran, S., & Ngo, H. H. (2017). Removing ammonium from water using modified corncob-biochar. *The Science of the Total Environment*, 579, 612-619. <https://doi.org/10.1016/j.scitotenv.2016.11.050>
- Wyer, K. E., Kelleghan, D. B., Blanes-Vidal, V., Schaubberger, G., & Curran, T. P. (2022). Ammonia emissions from agriculture and their contribution to fine particulate matter: A review of implications for human health. *Journal of Environmental Management*, 323(116285), 116285. <https://doi.org/10.1016/j.jenvman.2022.116285>
- Zhang, M., Song, G., Gelardi, D. L., Huang, L., Khan, E., Mašek, O., Parikh, S. J., & Ok, Y.S. (2020). Evaluating biochar and its modifications for the removal of ammonium nitrate, and phosphate in water. *Water Research*, 186, 116303. <https://doi.org/10.1016/j.watres.2020.116303>