Two-Loops of Agricultural Waste Recycling Practice: A Step Towards the Circular Economy

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ABSTRACT

This research suggests a two-loop biochar-based agricultural waste recycling system based on the concepts of the circular economy. The study focuses on using pyrolysis to convert waste coconut shells into biochar, which is subsequently applied for two purposes: agricultural soil enhancement and wastewater treatment. In the first experimental loop, the biochar was enriched with nutrients using an NPK solution and with copper using copper (II) sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$), thereby simulating nutrient and heavy-metal pollutants commonly found in wastewater. To assess its capacity for nutrient retention, fertilizer-use reduction, and support of sustainable farming practices, the enriched biochar was subsequently repurposed as a soil amendment in the second experimental loop. A Completely Randomized Design (CRD) was employed for the nutrient leaching tests, with treatments consisting of soil amended with biochar at rates of 0%, 2.5%, 5%, and 10% (w/w). The concentrations of nitrogen (N), phosphorus (P), potassium (K), and copper (Cu) in the leachate were monitored over a period of four to eight weeks. Seed germination tests were also conducted under controlled laboratory conditions to evaluate the effects of enriched biochar on germination percentage and early plant growth, as well as to assess potential chemical risks associated with its application. Results show that leaching of NO_3–N, P, and Cu increased with increasing enriched biochar application rates, with treatment of 10% biochar exhibiting the highest cumulative leaching. Leaching of NO_3–N, P, and Cu increased with increasing enriched biochar application rates, with treatment T3 (10% biochar) exhibiting the highest cumulative leaching. The 10% enriched biochar treatment (T3) exhibited the highest Germination Index (23.59) and the lowest Mean Germination Time (2.63 days), indicating faster and more effective seed germination. Overall, this study supports circular economy principles and environmental sustainability by demonstrating the potential of enriched biochar as a multipurpose bio-based material for pollution treatment, nutrient recycling, and sustainable agricultural practices. However, the heavy metal from leaching is needed to concern as well.

Keywords: Biochar/ Circular economy/ Agricultural waste recycling/ Wastewater treatment / Soil enhancement

1. INTRODUCTION

To manage leftovers from farming is becoming a more important environmental problems, especially when agricultural wastes are burned outdoors. Burning leads to air pollution, climate change, and hazardous health issues by releasing PM2.5, CO_2, CO, and VOCs [3]. Therefore, it is possible to lessen these effects while promoting resource efficiency and circular economy by turning crop leftovers into value-added products.

Biochar is a rich-carbon material produced through pyrolysis of organic residues and forest wastes as known as biomass. For physical properties include black color, porous structure, light and having a huge space on its surface. It boosts soil microbe growth and maintains nutrients. It can reduce fertilizer and pesticide consumptions, improve the quality of the soil, waste management and raise crop production. Its structure is suitable for absorbing things including heavy metals and nutrients from wastewater [1] [4]. After using with wastewater treatment, however, spent biochar may retain nutrients and contaminants. Instead of being discarded, this material may be further utilized as a soil amendment or biofertilizer, creating an opportunity to close the material loop.

This study proposes a two-loop biochar-based agricultural waste recycling system (Figure 1). In the first loop, agricultural waste, specifically coconut shell, is converted into biochar and used for

wastewater treatment. In the second loop, the enriched biochar is used for soil to recover nutrients and potentially reduce the use of synthetic fertilizers. Biochar can improve soil properties and nutrient and water retention, supporting more sustainable agricultural practices [2] [5].

However, the agricultural reuse of enriched biochar requires evaluation of nutrient release, contaminant leaching, and its effects on plant establishment. Therefore, this study aims to (1) evaluate the amount and rate of leaching from enriched biochar and (2) determine its effects on seed germination and early plant growth under different soil-to-biochar ratios.

The study is controlled in the laboratory scale using coconut-shell biochar enriched with nutrients and selected wastewater contaminants, including heavy metals. The study highlighted on leaching behavior and seed germination and does not cover field scales , detailed economic feasibility, or large-scale implementation. The findings are expected to demonstrate the potential of sequential biochar utilization for wastewater treatment and soil application, while contributing to agricultural waste reduction, resource recovery, reduced fertilizer dependence, and circular economy development.

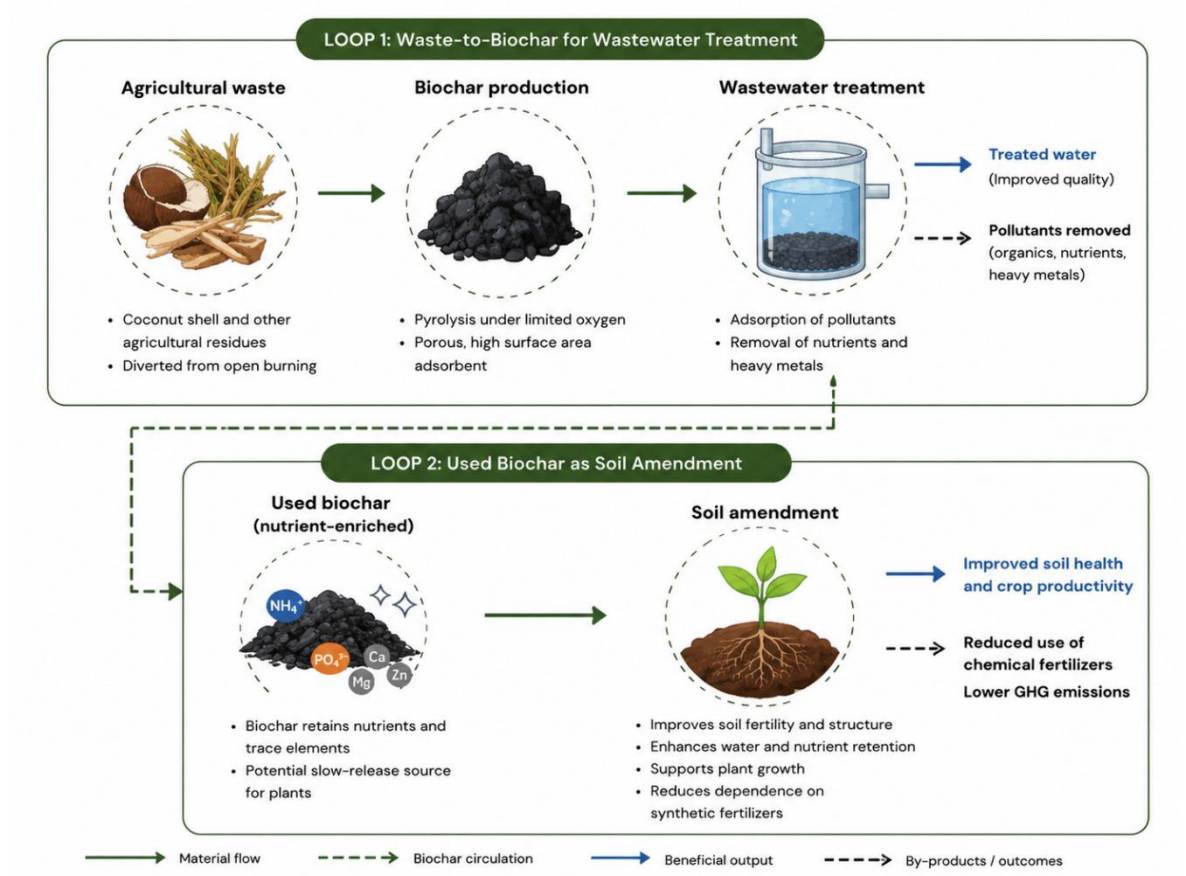

Figure 1. Diagram of the proposed two-loop biochar-based agricultural waste recycling system.

2. METHODOLOGY

2.1 Research Framework

The study employed an analytical and experimental approach to evaluate a two-loop biochar-based agricultural waste recycling system. The research focused on three main components: (1) nutrient and copper leaching test and (2) seed germination and seedling growth. The leaching test showed the release and loss of nutrients and copper from enriched biochar under controlled conditions. The germination experiment evaluated the effects of different enriched biochar application rates on seed germination and early seedling growth.

2.2 Biochar Enrichment

Biochar made from coconut shell and husk was screened to a size of 0.5–1.0 mm, cleaned with DI water, and oven-dried for 24 hours at 80°C. To load copper, 200 mg/L Cu^{2+} solution (1:25 w/v) was mixed with 10 g of biochar, pH was set to 5.5–6.0, and the mixture was shaken at 150 rpm for 24 hours. After filtering, the Cu-loaded biochar was given DI water rinse. Next step, For 12-hour with 200 mL of 0.05 M KH_2PO_4 solution to keep Cu stabilization, the material was filtered without washing. After that, 200 mL of NPK (15-15-15) solution (2 g/100 mL) was added, and the mixture was stirred for 12 hours to do nutrient enrichment. The enriched biochar was then filtered, oven-dried for 12 hours at 60°C, and stored for leaching and seed germination test.

2.3 Nutrient and Copper Leaching Experiment

A randomized design with 3 replicates was used in this study. 4 treatments were prepared: T0 (soil only), T1 (soil + 2.5% enriched biochar), T2 (soil + 5% enriched biochar), and T3 (soil + 10% enriched biochar) on a dry weight. Chinese cabbage seeds were used in the experiment. Soil representative of the Nakhon Pathom soil series was used as the experimental medium. The soil and enriched biochar were thoroughly mixed and placed in plastic experimental units. Deionized water was applied at a controlled rate to simulate rainfall or irrigation, and leachate was collected from the bottom of each unit. During the first week, leachate was collected daily, followed by weekly sampling during Weeks 2–4. The samples were analyzed for NO_3^--N, P, K^+, Cu, and pH using appropriate analytical methods.

2.4 Seed Germination Experiment

Seed germination test was evaluated the effects of enriched biochar application rates on germination and early seedling growth. 4 treatments were prepared: T0 (100% soil), T1 (soil + 2.5% enriched biochar), T2 (soil + 5% enriched biochar), and T3 (soil + 10% enriched biochar) on a dry weight basis. Each treatment consisted of three replicates. Seeds were uniformly distributed in the prepared media and maintained at 25 ± 2°C under controlled moisture conditions.

Seed Germination was monitored daily for 10 days and was recorded when the radicle reached the minimum length. Germination percentage, Germination Index (GI), and Mean Germination Time (MGT) were calculated. At the end of the experiment, root length and shoot length were measured to assess early seedling growth and the effects of enriched biochar application rates.

3. RESULTS AND DISCUSSION

3.1 Nutrient and Copper Leaching

The cumulative leaching of NO_3-N, P, and Cu from the soil-enriched biochar is presented in Table 1. The results showed a clear increasing trend in cumulative leaching with increasing enriched biochar application rates. For NO_3-N, the cumulative amount increased from 268.74 ± 44.20 mg/pot in the control treatment (T0, 0% biochar) to 488.67 ± 87.33, 594.70 ± 107.66, and 628.93 ± 62.10 mg/pot in T1 (2.5%), T2 (5%), and T3 (10%), respectively. Thus, the highest application rate resulted in the greatest cumulative NO_3-N leaching during the experimental period.

Phosphorus showed a comparable pattern. Cumulative P leaching increased from 0.769 ± 0.142 mg/pot in T0 to 2.721 ± 0.090 mg/pot in T1, 3.368 ± 0.102 mg/pot in T2, and 4.343 ± 0.206 mg/pot in T3. Despite the fact that the total amount of P leached was significantly less than that of NO_3-N, the steady rise through the biochar treatments shows that the amount of P accessible for release from the soil–biochar system increased as the amount of enriched biochar increased.

Additionally, Copper showed an ongoing rise as the rate of application of enriched biochar increased. From 0.137 ± 0.087 mg/pot in T0 to 0.713 ± 0.260 mg/pot in T1, 1.422 ± 0.138 mg/pot in T2, and 2.236 ± 0.490 mg/pot in T3, the cumulative Cu leaching increased. The experimental based approach, in which Cu was purposefully loaded onto the biochar throughout the enrichment process, is

compatible with the comparatively obvious rise in Cu leaching with biochar rate. As a result, adding more enriched biochar to the soil system increased the amount of Cu-containing material that could be released and transported during the leaching experiment. However, this finding provides useful information for evaluating the relationship between enriched biochar application rate and Cu mobility in the soil system.

During the study, the leachate's pH stayed mostly near neutral, with mean values typically falling between 7.0 and 8.1 across treatments and sampling durations. pH levels varied between treatments over the first seven days, but there was no evident monotonic upward or downward trend in relation to the rate of biochar application. Weeks 2-4 saw similar trends.

Overall, the leaching experiment showed that the mobility of N, P, and Cu within the soil system was affected by enriched biochar. For cumulative NO_3-N, P, and Cu leaching, one-way ANOVA revealed significant differences between treatments. According to Tukey's HSD, NO_3-N considerably rose with each increase in the amount of biochar application, but N variations were mostly seen between the control and biochar-amended treatments. Cu also exhibited a rising tendency as the rate of biochar increased. These results suggest that the pace of biochar application affects element mobility and nutrient availability. The findings serve as a foundation for assessing nutrient interactions in the soil-water system and, in conjunction with the ensuing germination and plant-growth results, for figuring out a suitable enriched biochar rate of application for sustainable nutrient recycling in the proposed two-loop biochar-based agricultural recycling system.

Table 1. Cumulative nutrient and copper leaching from enriched biochar treatments.

Treatment	Cumulative NO_3-N (mg/pot)	Cumulative P (mg/pot)	Cumulative Cu (mg/pot)
T0 (0%biochar)	268.74 ± 44.20	0.769 ± 0.142	0.137 ± 0.087
T1 (2.5%biochar)	488.67 ± 87.33	2.721 ± 0.090	0.713 ± 0.260
T2 (5%biochar)	594.70 ± 107.66	3.368 ± 0.102	1.422 ± 0.138
T3 (10%biochar)	628.93 ± 62.10	4.343 ± 0.206	2.236 ± 0.490

Remark: total weight of soil mixture is 500 g in pot.

3.2 Seed Germination and Seedling Growth

The effects of enriched biochar incorporation on seed germination and early seedling growth are presented in Table 2. Four treatments were evaluated: T0 (100% soil), T1 (soil + 2.5% enriched biochar), T2 (soil + 5% enriched biochar), and T3 (soil + 10% enriched biochar). Overall, the incorporation of enriched biochar improved several germination parameters compared with the soil-only treatment.

In T0, the germination percentage (%G) was 84.00%; in T1, T2, and T3, it was 93.33%, 92.67%, and 94.67%, as a result. T3 which contained 10% enhanced biochar, showed the best germination percentage. This suggests that, in comparison to the control, the addition of enriched biochar generally supported a larger percentage of effectively germinating seeds. The enhancement might be linked to biochar's capacity to alter the growing medium's appearance, especially water storage and nutrient accessibility, which would strengthen a favorable environment for seed germination.

A similar trend was for the Germination Index (GI). GI increased from 16.61 in T0 to 21.89 in T1, 20.26 in T2, and 23.59 in T3. In a higher GI indicates both a greater number of germinated seeds and faster germination, the results suggest that T3 provided the most favorable conditions for germination among the tested treatments. The relatively high GI of T1 also indicates that a low enrichment rate was sufficient to improve germination performance compared with the control.

Despite, Mean Germination Time (MGT) decreased with enriched biochar incorporation. T0 had an MGT of 3.60 days, while T1, T2, and T3 had values of 3.15, 3.32, and 2.63 days, as a results. The lowest MGT in T3 indicates that seeds germinated more rapidly under the 10% enriched biochar treatment. The combination of the highest GI and lowest MGT therefore suggests that T3 provided the most favorable overall germination response.

In addition to, Mean root length for seedling up from 2.03 cm in T0 to 3.72 cm in T1, 2.87 cm in T2, and 3.72 cm in T3. T1 and T3 had longest roots, demonstrating that enriched biochar especially encouraged root growth. Improvements in nutrient accessibility and water retention capabilities in the biochar-amended medium may be linked to increased root development. Because longer and more developed roots can enhance seedlings' access to water and nutrients, root growth is a key indication of early plant formation.

Shoot length responded differently. The mean shoot length was 1st rank for T0 (5.86 cm), followed by T1 (5.64 cm), T2 (5.10 cm), and T3 (5.09 cm). Therefore, there was no comparable increase in shoot growth when the percentage of enriched biochar was increased. This implies that during the early growth stage, the favorable effects of enhanced biochar were more noticeable for germination and root development than for shoot extension. Differences in the accessibility of nutrients, moisture levels, or other physical characteristics of the growing media could be the cause of the decrease in shoot length at increased biochar rates. To identify the precise mechanism, more chemical and statistical analyzes would be necessary.

Overall, the results indicate that 10% enriched biochar (T3) produced the most favorable germination performance, as demonstrated by the highest %G and GI and the lowest MGT, while both T1 and T3 promoted root elongation compared with the control. Nevertheless, increasing enriched biochar concentration did not improve shoot length. These findings suggest that enriched biochar has potential as a soil amendment for improving seed germination and early root establishment, although the optimum application rate should be considered in relation to both germination and subsequent plant growth.

Table 2. The effects of enriched biochar incorporation on seed germination and early seedling growth.

Treatment	% biochar	% G	GI	MGT (day)	Root length (cm)	Shoot length (cm)
T0	0%	84	16.61	3.60	2.03	5.86
T1	2.5%	93.33	21.89	3.15	3.72	5.64
T2	5%	92.67	20.26	3.32	2.87	5.10
T3	10%	94.67	23.59	2.63	3.72	5.09

3.3 Integrated assessment of germination and leaching results

The process to the application of enriched biochar varied across the tested rates when the germination and leaching data were taken into account together. With the highest germination percentage (%G), germination index (GI), and mean germination time (MGT), T3 (10% biochar) had the best germination achievement. But T3 also produced the largest cumulative P and Cu leaching, suggesting that a higher release of nutrients and Cu from the enhanced biochar accompanied the stronger germination response. As a result, the improved germination success at 10% biochar should not be taken as proof that T3 is the best application rate for the system as a whole.

While having a lower rate of biochar implementation, T1 (2.5% biochar) developed the longest roots alongside T3 and demonstrated germination rate that was comparable to that of T3. Furthermore, there were no statistically significant changes in cumulative NO_3-N leaching when the biochar rate was increased from T1 to T2 and T3. On the other hand, as the rate of biochar application rose, cumulative P and Cu leaching considerably increased. These findings suggest that adding more enriched biochar may improve germination and nutrient availability while simultaneously raising the possibility of P and Cu leakage.

When examined in combination, the findings show that, under the circumstances of this experiment, T1 (2.5%) offers a compromise between germination performance, early root development, biochar application rate, and leaching behavior. T3 (10%) showed the highest cumulative P and Cu leaching in addition to the strongest germination response. Therefore, the amount of biochar used, nutrient release, Cu mobility, and germination rate should all be taken into account when choosing an acceptable application rate. The current findings show a trade-off between plant-growth response and possible nutrient and Cu losses rather than establishing a single ideal application rate.

Overall, enhanced biochar showed possibilities as a soil amendment that contains nutrients and affects the mobility of Cu and nutrients in the soil system. The findings emphasize how crucial it is to choose an application rate that strikes a balance between nutrient availability for plant growth, nutrient retention, and environmental concerns. That balance is especially important for the recommended agricultural circular economy systems, which uses enriched biochar to minimize nutrient losses and unintentional Cu movement while returning nutrients to agricultural soil.

4. CONCLUSIONS

Based on laboratory experiments and data analysis in this study. Some conclusions were drawn as follows:

1. Leaching of NO_3–N, P, and Cu increased with increasing enriched biochar application rates, with treatment T3 (10% biochar) exhibiting the highest cumulative leaching.

2. Leachate pH remained near neutral throughout the experimental period, with no differences among treatments.

3. Higher biochar application rates increased the mobility of nutrients and Cu, indicating that the application rate should be carefully considered when determining an appropriate rate for the two-loop agricultural recycling system.

4. Compared with the soil-only control (T0), enriched biochar enhanced seed germination, with the germination percentage increasing from 84.00% in T0 to 94.67% in T3 (10% enriched biochar).

5. The 10% enriched biochar treatment (T3) exhibited the highest Germination Index (23.59) and the lowest Mean Germination Time (2.63 days), indicating faster and more effective seed germination.

6. Enriched biochar promoted root growth, with T1 (2.5%) and T3 (10%) exhibiting the longest mean root length of 3.72 cm, compared with 2.03 cm in the control treatment.

7. Shoot height decreased from 5.86 cm in T0 to 5.09 cm in T3, indicating that increasing the enriched biochar application rate did not result in greater shoot growth. Therefore, the selection of an appropriate application rate should consider its effects on subsequent shoot development. Overall, enriched biochar showed potential to enhance seed germination and early root development.

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