Towards Agricultural Sustainability : Exploring the Potential of Biochar Pellets for Phosphorus Loss Reduction from Tile-drained Agroecosystems

Highlights

- Engineered biochar pellets were applied to reduce phosphorus loss from tile drainage systems for the first time.
- Smaller-size biochar pellets achieved a notable 41% reduction in dissolved reactive phosphorus from tile-drained agroecosystems.
- Techno-economic analysis demonstrated that the application of biochar pellets is economically viable for nutrient loss reduction.
- A sustainable management paradigm was proposed to boost biochar pellets adoption and benefit farmers and stakeholders.

Abstract. *Artificial drainage has led to significant amounts of dissolved reactive phosphorus (DRP) loss from intensified agroecosystems, jeopardizing water quality and challenging agricultural sustainability. Biochar has shown great promise on the laboratory scale for removing DRP from contaminated water with co-benefits in terms of soil quality and crop productivity. However, whether its excellent performance, stability, and engineering application values can be sustained under field conditions over time remains unclear. This study reported the first engineering application of biochar pellets used in an intensely tile-drained agroecosystem to reduce agricultural diffuse DRP losses from tile drainage. Two types of biochar pellets were applied into the specifically designed P removal structures (i.e., biochar-sorption chamber) to comparatively investigate their DRP loss reduction performance at field-scale demonstrations: Phase I - biochar pellets size 2~3 cm (operated for 170 days) vs Phase II - biochar pellets size <1 cm (operated for 250 days). The field study revealed that the DRP removal efficiency of the small-size biochar pellets (<1 cm) exhibited a substantial increase compared to the biochar pellets with large particle size (2-3 cm). Techno-economic analysis indicated that this study has notable economic benefits. Biochar pellets can economically remove DRP from tile-drain agroecosystems with an average unit production cost of $412.6/ton biochar pellets and unit removal cost of $325.9/kg DRP from tile-drained agroecosystems under wide economic and system design parameters. Furthermore, a sustainable management paradigm was proposed to boost biochar pellet adoption that benefits stakeholders, environmental agencies, and farmers and achieves nutrient loss reduction, carbon sequestration, energy production, and crop production.*

Keywords. *Diffuse phosphorus pollution; Nutrient loss reduction; Biochar; Sustainable intensification; Engineering application; Economic assessment*

Introduction

In the most intensive cultivation regions, agricultural intensification is often accompanied by considerable land improvement with a distinctive feature: artificial tile drainage systems (Gramlich et al., 2018). Extensive artificial drainage networks benefit crop growth but present a major diffuse non-point source to accelerate the transfer of nutrients from the lands into the receiving water bodies, leading to an increased incidence of eutrophication and harmful algal blooms (Castellano et al., 2019). In particular, phosphorus (P) loss through tile-drained agricultural fields has been recognized as a problem for large watersheds that causes long-term environmental damage (Saadat et al., 2018). For instance, the drainage networks in Western Lake Erie account for 49% of the soluble P loss and 48% of the total P (TP) exported from the watershed (Smith et al., 2015). While there is increasing evidence that implementation of conservation practices can reduce the TP and particulate P, their effectiveness in removing dissolved reactive phosphorus (DRP), a significant factor contributing to algal blooms, is known to be less pronounced (Scott et al., 2023). Recent studies have shown that owing to the expansion of conservation agriculture and tile drainage dissolved P concentrations in watersheds have been increasing since the early 2000s (Jarvie et al., 2017; Singh et al., 2023), underscoring the complexity of DRP loss mitigation from non-point drainage sources in the tile-drained agroecosystems.

Landscape-scale filters, known as P removal structures, which are installed at the edge of fields, are important technologies for removing DRP from drainage/runoff (Scott et al., 2023). The core component of P removal structures consists of a series of phosphorus sorbing materials (PSMs), including natural minerals (e.g., rich in iron, aluminum, or calcium), by-products (such as metal shavings, fly ash, and steel slag), and engineered materials (Zhou et al., 2022). Although some PSMs, such as metal shavings and steel slag, have been shown to perform well in field-scale applications, the use of these PSMs still encounters numerous barriers due to considerations of cost, maintenance, and environmental impacts (Wang et al., 2021). In addition, landfilling spent PSM is facing increased challenges including land space restriction, labor/transportation costs, and concerns of contamination.

Biochar has demonstrated a potential for removing pollutants from wastewater. The intersection between the drainage infrastructure and the need to reduce DRP loss offers a unique opportunity to examine biochar technology at the field and watershed scales. Some attempts have been made to explore the potential of the application of biochar to remove DRP from contaminated water in laboratory-scale experiments. Mehrabinia et al. (2022) observed that active nano-biochar can achieve P removal of higher than 47.8% from agricultural drainage. Furthermore, biochar has been a proven soil amendment to improve soil health and enhance crop production (Yadav et al., 2023). Land application of spent biochar into nearby farms can further retain nutrients and reduce disposal costs (Zhou et al., 2023). Therefore, biochar could be an emerging alternative to traditional PSMs, which can renovate in-situ nutrient loss reduction technology. Yet, studies under real-world application (field conditions) have rarely been available. Historically, most studies on biochar application in water treatment have used short-term laboratory batch sorption or columns as proxies. Consequently, biochar's effectiveness may not be as generally applicable as commonly believed. Furthermore, the potential negative impacts of the practical application of biochar on human health and the environment, such as biochar-induced dust emissions (Gelardi et al., 2019), highlight the importance of establishing a deployment strategy to manufacture biochar suitable for best practices in real-world scenarios. To date, there has been no comprehensive analysis to explore the engineering-scale biochar application on the in-situ drainage DRP loss reduction from the perspectives of performance and economic consideration.

In this study, biochar pellets were developed to meet engineering application requirements in tile drainage. The objectives of this study are to: (*i*) evaluate the efficacy of biochar pellets for DRP loss reduction from agricultural tile-drained lands under a field-scale demonstration, (*ii*) unfold the application potential and economic benefits of this work using techno-economic analysis (TEA), and (*iii*) outline an agricultural sustainable management strategy to boost engineering-scale biochar technology adoption in the context of nutrient loss reduction. The findings of this study offer first-hand information to strengthen the engineering application of biochar in agricultural water quality improvement and to help understand their costs and benefits in the context of agricultural DRP loss management.

MATERIALS AND METHODS

2.1 MANUFACTURING BIOCHAR PELLETS FOR ENGINEERING APPLICATION

Biochar pellets were manufactured from powdered biochars that have previously demonstrated effective DRP removal capability at the experimental laboratory level. A comprehensive elucidation of the biochar can be found in Yang et al. (2021). However, powder-form biochar is unsuitable for engineering-scale field applications due to *i*) potential dust emission and environmental concerns, *ii*) limited ability to maintain a stabilized condition under dramatic hydrology changes, and *iii*) difficulty in recollection and replacement after systems saturation. Therefore, to facilitate engineering applications, biochar pellets with uniform particle sizes (ranging from <1 cm to 2~3 cm) were produced under a pelleting miller (MILL-10 Pellet Mill 10HP, Colorado Mill Equipment, USA).

2.2. STUDY SITE AND FIELD-SCALE APPLICATION

The experiments were conducted at the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) Fulton County site (40°28′38.99″N, 90°6′10.75″W), IL, USA. Over the past decades, Fulton County site has experienced a long-term use of sewage sludge from wastewater treatment plants to reclaim surface-mined land. To contribute to statewide nutrient loss reduction, the MWRDGC's Fulton County site has established an experimental research platform to test and demonstrate the effects of a variety of practices on nutrient loss reduction (Oladeji et al., 2023). During the experiment period (2021 to 2022), corn was planted in 2021 and received 224 kg N ha^{-1} and 50 kg P ha^{-1} fertilizer as urea ammonium nitrate and diammonium phosphate fertilizer, respectively. The fertilizers were split-applied in November 2020 and April 2021. In 2022, soybeans were planted and only received 112 kg ha^{-1} of diammonium phosphate fertilizer (equivalent to 20 kg N ha^{-1} and 52 kg ha^{-1}), and the fertilizer was applied in April 2022.

The engineering-scale *in-situ* field demonstration was conducted in a 9.71 ha field, divided into two equal subfields (i.e., Field A and Field B). Each subfield was installed with drainage tiles below the soil surface (1 m) at intervals ranging from 8 to 40 m with existing woodchip bioreactors well-constructed in the main drainage outlets to remove nitrate from drainage water. In each subfield, a biochar-sorption chamber (P removal structure, Length: 35 cm; Width: 25 cm; Height: 25 cm) was designed and constructed in the main tile drain to fill biochar pellets and allow drainage water to pass through (Figure 1). The experiments were operated in two phases spread over 14 months with two experimental phases: Phase I (May 13, 2021, to November 4, 2021, total 170 days) and Phase II (November 4, 2021, to July 12, 2022, total 250 days). In Phase I, approximately 10 kg of biochar pellets with particle sizes of 2~3 cm was loaded into the biochar-sorption chambers and then placed into the tile drainage systems to capture DRP (Figure 1c). Phase II started on November 4, 2021. The spent biochar pellets were replaced by about 13 kg of small-size design biochar pellets (particle sizes <1 cm) (Figure 1).

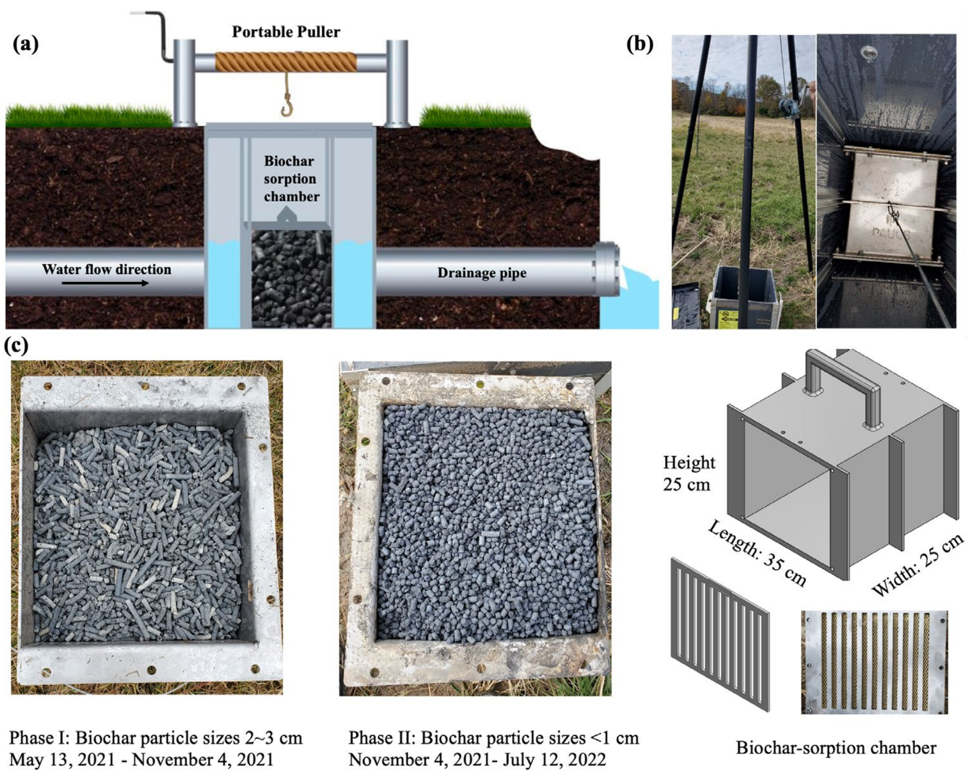


Figure 1. (a) The basic system design of incorporating biochar pellets into the drainage pipeline system; (b) Installation of biochar-sorption chamber with biochar pellets at field-scale engineering application; (c) The biochar pellets used in Phase I and Phase II, and the biochar-sorption chamber dimensions.

2.3. FIELD MONITORING

To systematically evaluate the performance of biochar pellets to reduce DRP loss during the experimental periods, the indices including (*i*) cumulative DRP load (kg), (*ii*) DRP removal efficiency (DRP_RE, %), and (*iii*) the DRP removal rate (mg_P/g) were calculated. The detailed calculation methods to obtain daily and cumulative nutrient loads can be seen in a previous study (Oladeji et al., 2023). At a time period t with the period interval (t_1, t_2), concentration (C) was estimated using the following equation:

$$C = C_1 + \frac{(C_2 - C_1)}{(t_2 - t_1)} (t - t_1) \quad (1)$$

where

C_1 and C_2 are the DRP concentrations at the time t_1 and t_2.

Biochar DRP removal efficiency was calculated using DRP concentrations from water samples collected before and after treatment with the biochar-sorption chambers. The drainage flow rate and water temperatures were measured using HOBO pressure transducers with dataloggers and V-notch weirs. Water samples before and after biochar-sorption chambers were collected bi-weekly and within 24 hours of a rain event equaling or exceeding 1.3 cm (0.5 inches).

2.4. Economic assessment

Techno-Economic Analysis (TEA) was performed to evaluate the economic viability and benefits of the proposed work, which is crucial for promoting large-scale application. Costs include the production cost of biochar pellets at the pilot scale as well as the engineering application of biochar pellets in the Phosphorus Removal Structure to effectively reduce excess DRP by 40% from the tile drainage water (based on the field performance). Moreover, this study evaluated the feasibility of the proposed system at the wide uncertainties of economic circumstances, system design and field application strategies. Further, DRP removal and cost efficiency under different field strategies were analyzed using biochar replacement scenarios under benchmark assumptions to guide future implementation.

The benchmark case considers 40% cumulative DRP removal of the 15-year load for all structures as the removal goal. The DRP removal system was designed for 15 ha of tile-drained fields with an anticipated DRP load of 8 kg/year. The assumed DRP load is in the typical range of DRP reported in the tile-drained systems in the USA and was similar to the average unit DRP observed (0.48 kg/ha/year) in the fields. The size of the structure and quantity of biochar was linearly scaled up to 15 ha from 4.85 ha (experimental field). For the benchmarking of TEA, a 10% discount rate was used to allow weighting of future cost at the present value

(PV) for over 15 years of the life of the structures. PV is the summation of costs incurred throughout the project life which accumulates the cost occurring for installation, labor and transportation, biochar replacement, operation, and maintenance given by,

$$\text{Present Value (PV)} = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \qquad (2)$$

where

C_t = cost occurring at 't' years in the future

r = discount rate by calculating the average cost of P removal

t = operation year

An inflation rate of 5% was used, which was applied to the recurring cost throughout the project life to calculate the cost/unit P removal (per kg) for each year.

Capital cost for the biochar production comprised of a pellet mill, electric kiln (furnace), related accessories and the inventory while materials cost accounted for clay, saw dust and lime sludge. Operation cost comprised the labor (manpower) and energy consumption for the operation of equipment, transportation of materials over 80 km distance and general repair and maintenance of the machineries. Production of 1 kg of biochar pellets required 0.42 kg of sawdust, 1.68 kg of lime sludge and 0.42 kg of bentonite clay as raw ingredients (Yang et al., 2019). The cost of materials required for biochar production, structures and equipment were retrieved from several retailers' data and labor cost was obtained from the Bureau of Labor Statistics (BLS, 2023). While some retailers advertise the cost of sawdust as low as \$5 to \$9/ton, it can cost up to \$50 or more in bulk, thus \$50/ton for sawdust was adopted. Bentonite clay is the most expensive material required for biochar production and costs approximately \$100/ton (average price from 2015 to 2022) (Statistia, 2023). Lime sludge being a waste material can be readily available at zero while \$10/ ton was adopted as an additional cost of lime sludge (besides transportation). To optimize and scale up the biochar production based on the pilot scale biochar production, this study considered the operation of a pellet mill (MILL-10 Pellet Mill 10HP, Colorado Mill Equipment, USA or similar) that inputs the feeding of raw materials for pelletizing at 260 kg/hour operating for 2.4 hours a day and four Skutt electric Kiln (furnace, 6.4 KW) with feeding rate 100 kg/hour operating four hours a day to match the production rate of biochar.

Different replacement scenarios of biochar were assumed (annually, every two years, every three years, every four years, and every five years) with a P reduction efficiency of 40% during the first year and a consecutive efficiency decrease of 5% every year before replacement. This allows us to anticipate the application scenario that leads to the least cost/unit (per kg) DRP removal since the replacement scenario every five years costs less but also removes less DRP due to reduced efficiency than the annual replacement of biochar. For each scenario, the capital cost was converted to annuity and added with recurring costs (for replacement, operation, and maintenance) to evaluate unit removal cost for the particular year.

Annuity (AV) of the PV is the fixed sum of money required to pay each year at specific discount rate given by

$$Annuity = PV * r \frac{(1+r)^n}{(1+r)^n - 1} \quad (3)$$

where

r = discount rate

n = project life

Practically, the cost of biochar has been relatively volatile since the variations in production costs are influenced by technology and the source of materials. This volatility introduces the possibility that the future replacement cost could differ significantly from the anticipated current cost. Similarly, the age of the structure, efficiency of biochar performance, and hence the estimated P removal might differ from field to field which poses a risk to the adoption of new technology to the practitioners and farmers to make the decision. To evaluate the viability of the project under wide economic circumstances, the PV and per unit removal costs were also evaluated under varying project life, discount rates, inflation rates, cost of biochar for different replacement scenarios, initial efficiency, and efficiency reduction rates. Stochastic simulations were performed using the Monte Carlo method (Khalfi and Ourbih-Tari, 2020) to envisage the combined impact of several circumstances. 2000 combinations of the randomly sampled input parameters within the range (Table 1) and quantile measures for PV of the total anticipated cost for capital, materials, operation, and maintenance as well as unit DRP removal cost were assessed.

Table 1: Input parameter range for stochastic simulation

Input parameters	Base value	Minimum	Maximum
Project lifetime (year)	15	10	20
Discount rate (%)	10	0	20
Inflation rate (%)	5	0	10
Efficiency of P removal (%)	40	20	60
Cost of biochar ($/ton)	400	200	600
Efficiency reduction/year (%)	0	0	5
Biochar replacement scenario (replacement year)	3	1	5
Phosphorus input into the system (kg/year)	8	4	12

2.5. REUSE OF BIOCHAR PELLETS AS SOIL AMENDMENT

Pot experiments were carried out to examine the effects of reusing biochar pellets on Cherry Belle radish growth. First, the saturated biochar pellets and field soil from the MWRDGC Fulton County site were collected and shipped to a temperature-controlled (20-25°C) greenhouse at the University of Illinois at Urbana-Champaign. Then, the saturated biochar was used as an alternative nutrient source for radishes growth. Radish cultivation experiments consisted of two experimental groups (amendment rates: 1% and 4% of biochar/soil, w/w, with 50% Nitrogen fertilizer application) and one control group (without biochar addition with 100% Nitrogen fertilizer application). 50% and 100% of nitrogen application rates which represent 28 lbs N/ha, and 56 lbs N/ha application rates, respectively. Each group had five replicates. The crop yield of radish after harvest was determined.

RESULTS AND DISCUSSION

3.1. FIELD PERFORMANCE EVALUATION OF BIOCHAR PELLETS

Figure 2a shows the daily and cumulative DRP losses from two experimental field sites. Concentrations of DRP in the drainage water ranged from 0.01 mg/L to 0.55 mg/L for Field A and 0.01 mg/L to 0.41 mg/L for Field B, with flow-weighted mean concentration of 0.13 mg/L and 0.08 mg/L for Field A and Field B, respectively, for Field A and Field B. During Phase I, cumulative DRP loss of Field A (1.56 kg) was much higher than Field B (0.34 kg). Similarly, in Phase II, DRP loss was higher for Field A (1.53 kg) compared to

Field B (0.96 kg). The above results revealed that DRP can be lost from farmland to downstream through non-point artificial drainage systems.

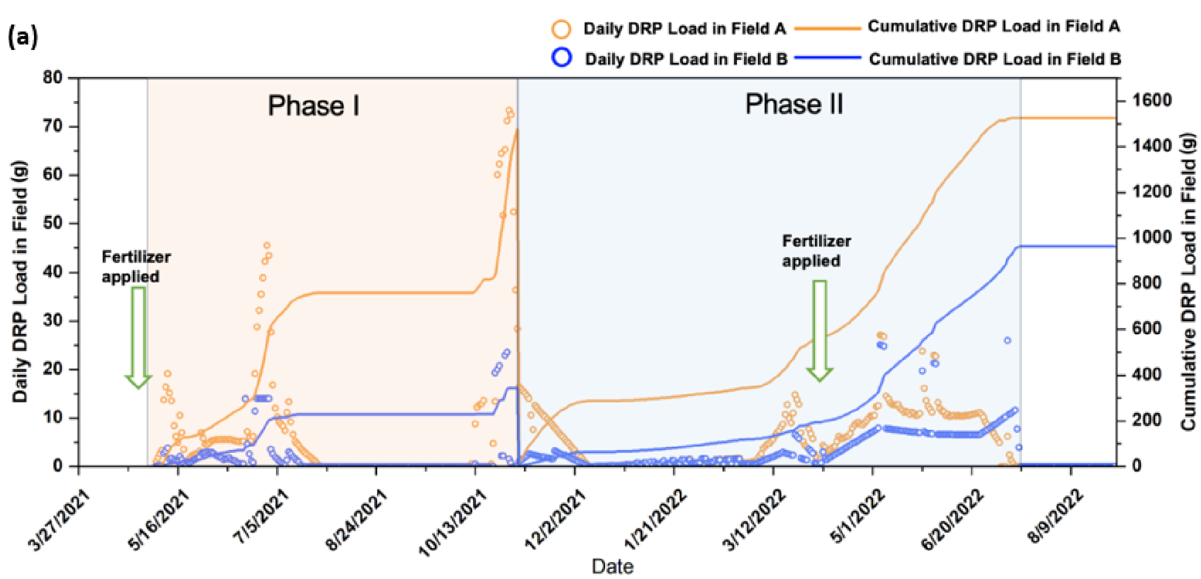
During the Phase I period, the cumulative DRP losses from Field A and Field B after biochar chamber treatment were around 1.51 kg and 0.31kg, resulting in a reduction of 0.05 kg and 0.03 kg in DRP loads from tile drainages in Field A and Field B, respectively. This study indicates that the biochar pellets with particle sizes > 2 cm had a low efficiency in removing DRP from drainage water. As shown in Figure 2b and Figure 2c, the median DRP removal efficiencies of biochar pellets are 12 % and 1.3 %, whereas the DRP removal rates were 5.2 mg/g and 3.0 mg/g for Field A and Field B, respectively.

In the beginning of Phase II, the spent biochar pellets (particle sizes 2 ~ 3 cm) were replaced with new biochar pellets (particle sizes < 1cm). The results show a higher performance in DRP reduction for new biochar pellets across all three evaluation indices as compared to the biochar pellets used in Phase I (Figure 2b-c). This DRP loss reduction enhancement was evident in both Field A and Field B. The newly implemented biochar pellets demonstrated enhanced efficacy in mitigating drainage DRP cumulative loads. In Field A, the cumulative DRP load decreased from 1.56 kg to 1.13 kg, while in Field B, a reduction of cumulative DRP load from 0.96 kg to 0.61 kg was observed. Meanwhile, the DRP removal efficiency of the biochar pellets exhibited a substantial increase, reaching 34 % in Field A and 41 % in Field B. As for DRP removal rate, the smaller particle size of biochar pellets achieved DRP removal rates were 30.4 mg/g and 27.2 mg/g for Field A and Field B, respectively.

The low DRP removal efficiency of biochar pellets in the fields might be attributable to the short retention time of flow-through drainage water in the biochar-sorption chambers, resulting in insufficient time for interaction between DRP and biochar. The improved performance in Phase II can be attributed to the biochar pellets with smaller particle sizes (<1 cm), indicating biochar particle size plays a significant role in contaminant removal (El Hanandeh et al., 2017; Bian et al., 2024). In this study, both biochar pellets are manufactured from lime sludge-incorporated designer biochar. The previous study clearly revealed that the main adsorption mechanism of DRP by the lime sludge-incorporated designer biochar is chemical precipitation

(Yang, et al., 2021). When DRP specials (i.e., $H_2PO_4^-$ and HPO_4^{2-}) in nutrient-containing water reach the alkaline surface of the designer biochar, they can readily convert to $H_2PO_4^-$ and HPO_4^{2-} and PO_4^{3-}. These two DRP specials could readily react with metal ions (i.e., Ca^{2+} and Mg^{2+}) incorporated on the designer biochar surfaces to generate $Ca_3(PO_4)_2$, $CaHPO_4$, and $MgHPO_4$ precipitates (Yang, et al., 2021). Compared to the large particle size, small particle sizes facilitate DRP specials to access to the interior of biochar pellets, resulting in faster precipitation reactions between DRP and metal ions incorporated on designer biochar. Thus, the small particle size of biochar pellets means faster sorption kinetics for DRP. From a DRP removal perspective, powered designer biochars exhibit better performance to reduce DRP loss since they can use less time to capture DRP from drainage water. In real-field applications, however, powered biochars or pellets with very small particle sizes would encounter some issues, especially in flow-through drainage systems. The powered designer biochar could be readily washed away from biochar-sorption chambers by drainage flow. If biochar with a very small particle size is used, it could clog the biochar-production chambers since the drainage water may carry sediments.

The attempt in Phase II showed that a deliberate trade-off between structural design and removal performance can be achieved for optimal use in the manufacturing and application of biochar in the context of mitigating DRP loss within tile-drainage systems.



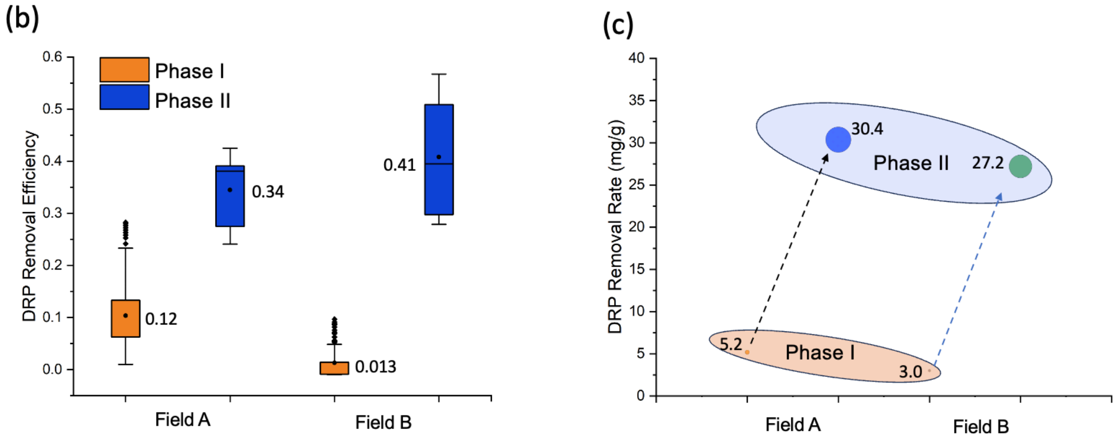


Figure 2. Comparison of biochar pellet DRP removal performance under two particle sizes in two research sites during Phase I and Phase II periods: (a) Daily and cumulative DRP load measured in the main drain lost from tile-drain agroecosystems before biochar chamber treatment in Phase I and Phase II; (b) The average DRP removal efficiency at different biochar particle pellets in Phase I and Phase II; (3) DRP Removal rate of different biochar particle pellets in Phase I and Phase II.

3.2 Techno-Economic Analysis of biochar pellets for DRP loss reduction

The techno-economic analysis was performed to explicate the economic feasibility of this work from the manufacturing of biochar pellets to the field application to remove DRP from drainage water. The cost analysis is divided into two main categories: (a) the production cost of biochar pellets (e.g., capital cost, operation cost, and materials cost), and (b) the construction cost of the biochar-sorption chambers (e.g., structure construction cost, materials cost, and installation, operation and maintenance). As shown in Table 2 - 3, the biochar pellets cost had an average production cost of $412.6/ton of biochar pellets. This cost is in between market biochar production costs, which is less than powdered activated carbon with costs varying between $800 and $2500/ton (He et al., 2022). The cost advantage of biochar pellet production that is directly applicable in P removal structures comes from the inexpensive raw materials (mostly from the waste) and no additional activation procedures compared to the granular activated carbon. The operation, materials, and capital costs contributed 71.81 %, 19.34 %, and 8.85 %, respectively, at pilot-scale production for the biochar pellets. The production includes the operations of a pellet mill with a raw material feeding rate of 260 kg/hour for two and half hours a day and four electric furnaces with a feeding rate of 100 kg/hour to convert raw pellets to biochar pellets for four hours a day to match the performance and operation during general working days (260 days) every year.

The conversion rate of pellet materials to biochar was nearly 40% with 60 % as a byproduct during the pyrolysis process which required an additional disposal cost of $15/ton.

Table 2: Cost estimates for production of biochar at pilot scale

Description	Quantity	Unit	Unit cost ($)	Unit of unit cost	Total cost	Expected life (years)	Salvage value	Annual cost	Cost at PV	References
1. Capital cost										
Pellet mill	1	-	7900	$/No	15800	15	20%	988.9	7521.8	(CME, 2024)
Skutt electric Kiln (Furnace)	4	-	2500	$/No	10000	15	20%	1251.8	9521.2	(Pottery Pulse, 2024)
Container	40	-	100	$/No	12000	5	20%	1502.2	11425.5	
Shovel	10	-	50	$/No	1500	5	20%	187.8	1428.2	Home Depot
Skid loader	1	-	160	$/No	160	15	20%	20.0	152.3	Lowes
Inventory cost	1	per 15 years	15000	$	15000	-	-	1972.1	15000	
							Subtotal	5922.8	45048.9	
2. Operation cost										
Labor (group A)	2	-	15.51	$/hour	32260.8			32260.8	245378.2	(BLS, 2023)
Repair and maintenance	1	-	1000	$/year	1000.0			1000.0	7606.1	
Waste disposal	0.9	tons/day	15	$/ton	3679.6			3679.6	27987.4	
Electricity	121.0	kWh/day	0.2	$/kWh	5003.7			5003.7	38058.1	(BLS, 2024)
Transportation	50	miles	0.3	$/(ton-mile)	6132.7			6132.7	46645.6	
							Subtotal	48076.7	365675.4	
3. Materials cost										
Saw dust	262.1	kg/day	50	$/ton				3407.0	25914.2	(OEC, 2024)
Lime sludge	1048.3	kg/day	10	$/ton				2725.6	20731.4	
Clay	262.1	kg/day	100	$/ton				6814.1	51828.4	(Statista, 2023)
							Subtotal	12946.8	98474.0	
							Total cost	66946.2	509198.4	
							Biochar production/Ton	162.1		
							Cost/ ton biochar	412.6		

Based on the results from Section 3.1, the P removal structure loaded with biochar pellets with small particle size (<1.0 cm) achieved nearly 40% DRP load removed in terms of cumulative P reduction load. By applying these biochar pellets to the field-scale drainage DRP reduction from tile drainage, the PV analysis showed that, under the benchmark assumption of a 15-year lifespan of the structure, with annual biochar pellets replacement and discount rate of 10%, the total cost of the system at the PV was $7931.6.The average unit removal cost of $325.9/kg DRP which can remove 3.2 kg DRP each year with a cumulative 48 kg of DRP over 15 years (Table 3). It is important to note that this was the actual estimated cost incurred during the design period, while the PV cost/kg of DRP removal was $165 /kg DRP. This disparity underscores the importance of factoring in the time value of money and the discount rate when evaluating the economic feasibility of such systems over an extended period.

Table 3: Cost estimates for field application of biochar at base scenario[a]

Item/Description	Years incurred	Quantity	Unit	Unit cost	Cost/year ($)	Total cost, PV ($)	References
1. Capital cost							
Engineering design	0	1	No	1500	197.2	1500	
Excavation for structures and backhoeing	0	8	m^3	2.77	2.9	22.2	Law et al., 2023
Labor + equipment for construction	0	6	hour	20	15.8	120	
Water control structures	0	2	No	1200	315.5	2400	Tyndall & Bowman, 2016
Chamber to store biochar	0	1	No	500	65.7	500	
Pipes and fittings	0	1	No	500	65.7	500	Lump sum
Plastic lining	0	4	m^2	5	2.6	20	Law et al., 2023
Miscellaneous	0	1		1000	131.5	1000	
				Sub Total	797.0	6062.2	
2. Operation and Maintenance							
Labor for excavation of biochar	0-15	6	hour	15.5	93.0	707.4	(BLS, 2023)
Biochar application	0-15	0.22	ton	412.6	90.8	690.5	Table 2
Operation and Maintenance	0-15	4	hour	15.5	62.0	471.6	(BLS, 2023)
				Sub Total	455.2	1869.4	
				Total	1042.8	7931.6	
				Total P removed	3.2 kg/year		
				Average cost of P removal	325.9 $/kg		

[a] Base scenario: Annual biochar pellets replacement from the P removal structure and an average discount rate of 10% and age of structure and horizon was 15 years.

This study further demonstrated how estimated removal and cost vary during the 15 years of study. Stochastic simulations were conducted to estimate how the prices of the structures and unit cost of removal are affected by the uncertainties in seven input parameters based on the key assumptions that the volatility of biochar cost, age of the structure, efficiency of biochar performance, inflation, and discounts rates. The stochastic simulation shows that the total cost of DRP removal structure at PV for a 15-year horizon ranged from \$6318 to \$8941 with an average of \$7304. The mean average unit DRP removal cost/year was \$358.7/kg P (\$160.5 /kg P at PV) and ranged from \$68.0 /kg P to \$899.1/kg P (Figure 3). Under different replacement scenarios, the average unit cost of DRP removal was least (\$348.3/kg P) for replacement every three years and highest for replacement every year (\$402.5/kg P). In the biennial replacement scenario, the system removes a cumulative 45.20 kg of DRP over 15 years as compared to 48 kg with replacement every year and 42 kg with replacement every three years. The average unit cost of removal for replacement every year was statistically different (p<0.05) compared to other scenarios, however, the average cost of removal for replacement every three years was not statistically different at (p<0.05) compared to replacement every two, four or five years. Thus, biochar replacement every two years was recommended as the best option for trading off between DRP removal and cost of removal because replacement of biochar every two years also offers higher DRP removal compared to that of every three years and costs significantly less than replacement every year.

Out of the total cost, capital cost of the structure, cost of materials, operation and maintenance were 78 %, 15 % and 7.6 % respectively. These costs are comparable to the existing P removal structures which range from \$ 100 - \$1300/kg P removal (Scott et al., 2023). Though the cost of removal was not the cheapest compared to the existing PSM structures, the spent biochar pellets for soil application provide additional benefits including carbon sequestration, soil amendment and potential use as a slow-release fertilizer. Moreover, this provides net waste recycling and can further reduce the cost of disposal of PSM since the spent biochar can be directly applied back to the field after saturation.

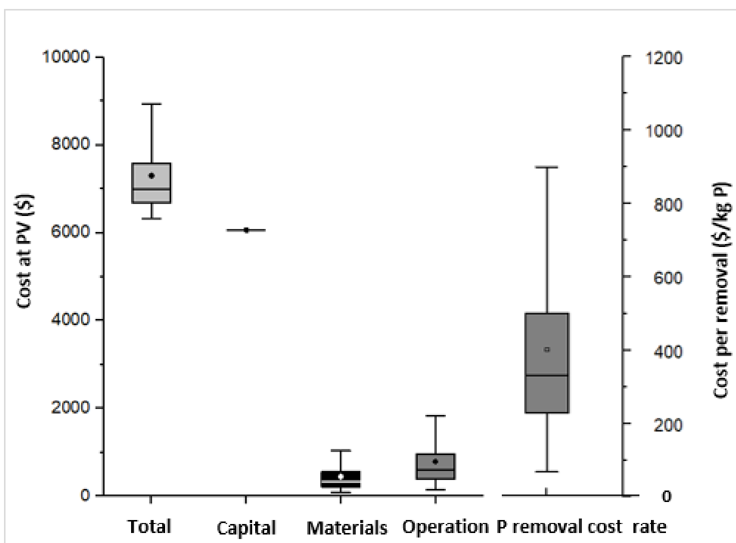


Figure 3. Breakdown of DRP removal cost under stochastic simulations

3.3. POTENTIAL TO BOOST TECHNOLOGY ADOPTION

If biochar pellets are to be employed in practice, scientific communities must consider how to bring direct benefits to farmers and stakeholders in order to boost technology adoption. The feasibility of reusing spent biochar pellets as a soil amendment for crop production was further investigated. Previous studies have fully demonstrated the benefits of biochar application in soil health and crop growth. The synergetic effect may be attributed to the enhancement in nutrient retention and extra carbon source with biochar application to improve soil fertility and structure. These results (Table 4) not only show higher radish weights after using 2% of spent biochar compared with the control group (increased by 15.57% to 30.76% by weight) but also suggest the possibility of reducing fertilizer application while maintaining comparable or better agronomic yields.

Table 4. Effect of combined biochar and nitrogen fertilizer on radish plants

% BC	N level	Avg Weight (g)	Standard deviation
2%	0 N[a]	30.2	7.28
0%	0 N	24.6	3.10
2%	50 N	34.8	6.68
0%	50 N	29.4	3.76
2%	100 N	46.9	11.34
0%	100 N	32.5	1.79

[a]0N – No nitrogen fertilizer; 50N – 50% nitrogen fertilizer (28 lbs N/ ha); and 100N-100% nitrogen fertilizer (56 lbs N/ ha)

The results are promising since farmers and operators could receive benefits beyond DRP loss reduction. Farmers can reduce their fertilizer costs if spent biochar pellets benefit their crop production. The potential for cost savings is a significant motivator and a clear economic incentive for farmers to embrace this technology. On the other hand, the co-location of expanded tile drainages and surrounding drained croplands offers an immediate opportunity to use biochar pellets and reuse spent biochar pellets, instead of landfilling (a common strategy to dispose of spent media), which will further reduce disposal costs and subsequent waste management issue. Biochar pellets are easy to replace and apply to the soil without dust emissions. Most biochar has a lower bulk density (<0.6 g/cm^3) than soil (~1.25 g/cm^3), which is likely to float on the soil surface and be easily carried away by runoff or blow away by wind, while biochar pellets with a higher bulk density can be integrated into the soil. Therefore, this work proposed a systematic approach that integrates waste management, biochar pellets for nutrient loss reduction, and reusing spent biochar pellets to design agricultural practices that mitigate nutrient pollution and enhance sustainability (Figure 4). In this context, biochar can and should be incorporated into sustainable agricultural conservation practice for further bolstering efforts to achieve nutrient loss reduction. In our unpublished work, the application of biochar pellets to reduce DRP from tile-drained agroecosystems could further achieve benefit beyond nutrient loss reduction, including carbon sequestration and energy production.

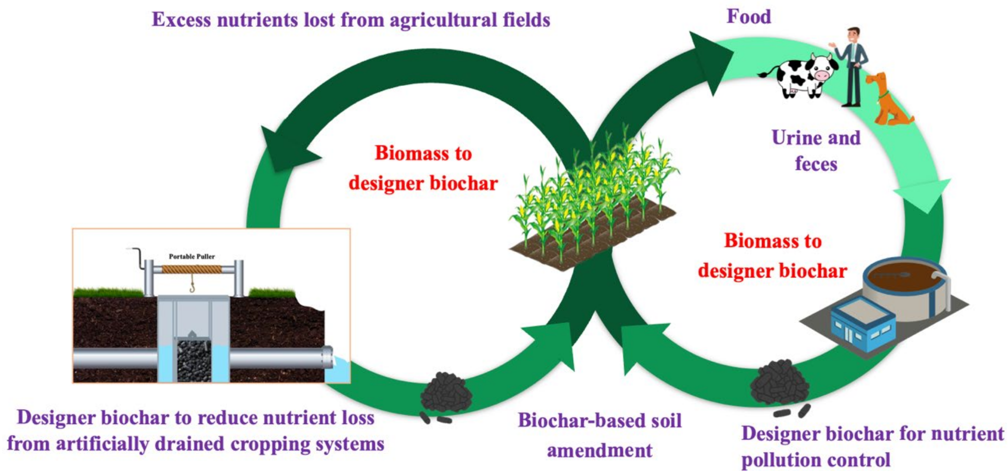


Figure 4. A systematic approach for sustainable best management practice that integrates waste management, nutrient loss reduction, reusing spent biochar pellets as soil amendment.

CONCLUSIONS

The results indicate that the utilization of biochar pellets offers agricultural practitioners and water quality managers a promising avenue to reduce DRP from tile-drained agroecosystems and promote sustainability. Compared with biochar pellets with particle sizes of 2~3 cm in Phase I, a comprehensive DRP loss reduction performance improvement in terms of cumulative DRP load reduction, DRP removal efficiency, and the DRP removal rate has been achieved in Phase II using smaller-sized biochar pellets (particle sizes of < 1cm). The biochar pellets were found to be financially viable. The biochar pellets cost had an average production of $ 412.6/ton. Under the benchmark assumptions, the average unit cost of removal was $325.9/kg DRP. Moreover, under wide assumptions of economic parameters such as inflation, discount rates, cost of biochar and project life; and system design parameters such as Phosphorus input, removal efficiency and replacement scenarios, the unit cost of removal was ($402.5 ± 262)/kg DRP which is comparable to the existing P removal structures ranging from $ 100 - $1300/kg DRP removal. The whole practice, from the production of biochar pellets to the application of biochar pellets to drained-filed to remove DRP, and reuse of spent biochar pellets as soil amendments - can achieve benefits beyond nutrient loss reduction, including carbon sequestration, soil amendment, energy production, and reduction of eutrophication potentials. Future research will focus on optimizing strategies and scalability for biochar and structures to accommodate sustainable agricultural systems and support policymaking in water quality management.

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