Pilot and Full-Scale Applications of P Recovery

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Elevated phosphorus (P) levels in water sources can result in eutrophication, which in turn causes environmental pollution and adversely affects aquatic ecosystems. Additionally, there is a risk of P depletion due to intensive exploitation and utilization. Therefore, the sustainable and efficient use of P, waste reduction, and P recovery from waste sources have become urgent priorities.

Keywords: adsorption mechanism ; biochar ; phosphorus recovery ; waste streams

1. Integration of Biochar in Biological Filters

Biochar has been applied in pilot-scale biofilters for wastewater treatment, focusing on improving P-recovery efficiency (**Table 1**). Greywater treatment methods based on biochar-column filtration systems (BCFS) have gained popularity recently [1]. A pilot system repurposed greywater from a four-person household for irrigating nearby vegetables. With a 36 h retention duration, a multi-stage filtration device, including mulch, geotextile, charcoal, and gravel, removed 30.1% of total phosphorus (TP) [2]. Similarly, a filter system was implemented to treat household graywater from a family of seven in Musaffah, northeastern Jordan. This system, comprising a septic tank followed by an aerobic biochar filter, demonstrated efficient removal of 42 ± 10.8% of TP [3].

In Berlin, Germany, the Muenchehofe wastewater treatment plant conducted a ten-month pilot project to extract P from secondary wastewater, combining granular activated carbon deep layer filtration with coagulation. The project utilized two identical filter columns, each with a diameter of 0.15 m and a height of 4 m; one column utilized granular activated carbon (GAC) with quartz sand, while the other used GAC with gravel. Both configurations successfully removed P, reducing wastewater concentration to 0.1 mg/L [4]. In another innovative approach, a two-phase bio-trickling filter (BTF) system was implemented to address treatment of wastewater with elevated levels of nitrogen and P. This system incorporated sequential aerobic and anaerobic flow cell reactors, utilizing porous palm biochar as the packing material. Under optimal conditions (hydraulic retention time of 36–48 h, bicarbonate as the carbon source, and palm biochar packing), it achieved an 80% reduction in ammonium and a 68% reduction in total P [5].

A full-scale, three-stage filter was deployed to remove nitrogen and P from the effluent of anaerobic digesters in Madagascar. The system used locally available materials, including a submerged anaerobic filter containing bamboo chips for denitrification, a trickling filter made of coal granules, and a filter with scrap iron for P removal. Over 16 weeks, three parallel systems were used to treat around 70 L/day. The filters effectively removed P, chemical oxygen demand, and solids, with success rates of 31–50%, 67–75%, and 73–82%, respectively, as well as significantly transformed the nitrogen [6]. A study using bamboo biochar for improved nutrient removal in BAFs treating low C/N digested swine wastewater was implemented. The system achieved notable TP removal: 47.91% in Phase I and 53.12% in Phases II and III. Biochar in BAF encourages functional microorganism growth and enhanced microbial diversity, which are crucial for nitrogen and P removal in BAFs [7].

2. Integration of Biochar into Wetland Structures

Integrating biochar into wetland structures is one of the other promising methods for efficient P recovery (**Table 1**). Treating wastewater using constructed wetlands (CW) is a proven, effective technology that offers long-term solutions. Similarly, biochar provides inexpensive methods to clean wastewater and recover P with a low carbon footprint. Combining these two technologies can significantly increase a system’s effectiveness [8].

The horizontal flow CW (HFCW) using biochar as media was applied in synthetic wastewater treatment. The integrated system achieved an average removal rate of 79.5% for TP and 67.7% PO_4^{3-}, surpassing the performance of wetlands using only gravel [8]. Three vertical flow CW (VFCW) columns filled with wood, corn cob biochar, and gravel have been explored as devices to recover P from anaerobically treated wastewater. It was demonstrated that the corn cob biochar VFCW column and the wood biochar VFCW column provided significantly higher treatment efficiencies for P (>71%) than did the gravel-VFCW. The enhanced pollutant removal ability of charcoal-added VFCWs was primarily due to increased adsorption capacity and microbial growth in the porous biochar media [9]. Another HFCW with electrolysis integration and biochar-modified material was investigated in a pilot-scale study. The investigation demonstrated significant enhancement of P removal (74.25%) by combining electrolysis and biochar substrate. This procedure used a sacrificial iron anode to generate ferric ions in situ, which increased P removal through chemical-based deposition and physical adsorption mechanisms. Altered by ions from the iron anode, biochar proved effective in adsorbing nitrate and P, consequently enhancing effluent water quality [10].

An enriched hemp charcoal substrate was applied to HFCW cells for the pilot-scale residential wastewater treatment. During the 7-month study period, with a mean P injection of 15.5 mg/L (after primary treatment), the biochar-added HFCW continuously decreased PO_4^{3-}-P concentrations in sewage to below 2 mg/L [11]. Saeed et al. investigated pilot-scale CW systems to treat raw sewage and recover P. The results showed that vertical flow CW that was filled with bamboo and wood biochar improved P removal, as follows: an inlet P concentration of 14.1 ± 8.2 mg/L (Phase I) and 7.0 ± 2.0 mg/L (Phase II) and an outlet P concentration of 6.1 ± 4.5 to 6.9 ± 5.5 mg/L (Phase I) and 6.5 ± 3.5 to 7.8 ± 2.1 mg/L (Phase II). Green walls in urban environments can be both an aesthetic feature and of practical use in greywater treatment [12]. Sami et al. evaluated the efficiency of treating actual greywater from a city district in a pilot-scale green wall with five different filter materials as substrates (biochar, pumice, hemp fiber, spent coffee grounds, and composted fiber soil). The biochar material showed promising TP treatment efficiency, with 57% [13].

Table 1. Integrated biochar in pilot and full-scale wastewater systems for P recovery.

Wastewater Types	Country	Q (L/d)	Technology Types	Biochar Types	HRT (h)	Input PO_4^{3-}-P (mg/L)	Output PO_4^{3-}-P (mg/L)	Input TP (mg/L)	Output TP (mg/L)	Refs.
Greywater	**Uganda**	**60**	**Filter system**	**Charcoal**	**36**	**NA**	**NA**	**24.1 ± 3.5**	**16 (30.1%)**	[2]
Synthetic wastewater	**Korea**	**10**	**CW**	**Woody biochar**	**72**	**16.3±1.1**	**5.3 ± 0.4 (67.7%)**	**36.1 ± 1.8**	**10.8 ± 1.1 79.5%**	[8]
Greywater	**Jordan**	**490**	**Filter system**	**Biochar**	**36**	**NA**	**NA**	**2.94–10.4**	**3.7 ± 1.4 (42 ± 10.8%)**	[3]
Municipal wastewater	**Germany**	**4.38**	**GAC and coagulation/filtration**	**Granular activated carbon**	**NA**	**NA**	**NA**	**0.54**	**0.1**	[4]
Synthetic wastewater	**China**	**NA**	**Bio-trickling filter (BTF)**	**Palm biochar**	**36–48**	**NA**	**NA**	**40–70**	**68%**	[5]
Synthetic wastewater	**China**	**30**	**Electrolysis-integrated CW**	**Bamboo biochar**	**24**	**0.5**	**0.17 (65.98%) (I) and 0.02 (96.73%) (II)**	**NA**	**NA**	[10]
Domestic wastewater	**Australia**	**NA**	**CW**	**Enriched hemp biochar**	**111.4**	**7.07–29.87**	**<2 (94.3%)**	**NA**	**NA**	[11]
Municipal wastewater	**Bangladesh**	**NA**	**CW**	**Bamboo and wood biochar**	**NA**	**NA**	**NA**	**14.1 ± 8.2 (I) and 12.7 ± 2.0 (II)**	**6.1 ± 4.5–6.9 ± 5.5 (I) and 6.5 ± 3.5–7.8 ± 2.1 (II)**	[12]
Low C/N digested swine wastewater	**China**	**NA**	**Bioreactor**	**Bamboo biochar**	**NA**	**NA**	**NA**	**20–35**	**14.98 (47.91%) (I) and 53.12% (II, III)**	[7]

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Greywater	Sweden	18	Greenwell	Biochar	NA	NA	NA	1.5	0.5 57 (%)	[13]
Anaerobic digester wastewater	Madagascar	71.3 (I) and 35.6 (II)	Trickling filter	Commercial biochar	NA	NA	NA	224 ± 51 (I) and 231 ± 17 (II)	139 ± 59 (I) and 202 ± 33 (II)	[6]

I, II, and III: Phases.

Many studies detailing biochar application for P recovery are typically conducted at the pilot stage, with full-scale publications remaining relatively rare. This underscores the need for comprehensive insights into the effectiveness, on a full-scale level, of biochar application for P recovery. Strengthening research demonstrations at a full-scale level regarding the implementation of biochar for P recovery is imperative. However, full-scale implementation can also encounter challenges, including those relevant to capacity limitations, real-world conditions, long-term performance and sustainability, economic considerations, policy aspects, and regulations. Using biochar for P treatment must align with local regulations, including those governing waste management, nutrient management plans, and environmental protection. Therefore, full-scale research results will provide valuable information to designers, builders, researchers, and managers seeking to implement P recovery using biochar on a larger scale.

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