

Comparative Characteristics and Potassium-Sulfur Release Behavior of Paddy Straw versus Banana Peduncle based Composite Biochar Produced by Co-pyrolysis with Phosphogypsum

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Co-pyrolysis of phosphogypsum and banana peduncle wastes was reported for the production of potassium-sulphur rich biochar composite fertilizer. However, large quantity of paddy straw are left out and fired on agricultural sites as waste, which required investigation for its alternative utilization for production of biochar composite. From this view, present work explored production of biochar composites from paddy straw mixed with phosphogypsum (4:1 ratio) by regulated co-pyrolysis process conditions such as temperature: 700°C; heating rate: 10°C/minute and residence time: 1 h for gaining biochar composite and also comparing physico-chemical characteristics, potassium-sulphur release behavior, kinetics with respect to banana peduncle mixed with phosphogypsum. Near neutral paddy straw (7.03) and alkaline banana peduncle biomass (8.53) converted into alkaline biochar (10.20 and 10.50) and composites (9.78 and 9.69) due to pyrolysis. The paddy straw biochar and composites retained relatively more carbon (%) i.e., 45.84 and 37.28 than banana based biochar 41.01 and 25.07. The phosphogypsum utilization enhances sulfur (6.65–7.66%) and calcium content (3.85–4.33%) in biochar composite. The potassium and sulphur leaching kinetic behavior fitted well with the second order kinetic model, indicating their slow-release aspect, which can contribute for long-term phyto-availability in soils.

Keywords: Agriculture waste, Biochar, Co-pyrolysis, Kinetics, Soil nutrients

Introduction

Banana (*Musa Sp.*) and rice (*Oryza sativa*) are among the most extensively cultivated crops in the world, specifically found in tropical countries. India is one of the foremost producers of banana and the second leading producer of rice. During the 2021, production of banana and rice in India was about 33 and 122 million metric tons respectively.^{1,2} Almost 20 percent of the world's food grains are produced from rice which is one of the most significant food crops and about 90% of the world total rice production dominantly grown in asia.³ The banana plant in terms of biomass generates approximately 13% of Banana Peduncle (BP), i.e., stalk-holding inflorescence⁴ and it is an underutilized waste resource mainly left out in the places such as fruit market depots, dumping yards and banana processing industries (e.g., banana chips industries). The rice harvesting generates huge amounts of Paddy Straw (PS) waste biomass. Farmers in developing countries mostly burn the PS in open fields, which causes environmental pollution.⁵ In the

long run, these wastes are somehow persistent in nature due to the presence of cellulose and hemicellulose-like substances which on degradation emit carbon dioxide, methane and volatile organic compounds. To resolve these problems, valorization of BP and PS biomass to produce Pristine Biochar (PB) i.e., Banana Peduncle Biochar (BP-B) and Paddy Straw Biochar (PS-B) has been documented for soil application in earlier studies.⁶⁻⁹

Phosphogypsum (PG) is one of the major overburdens (waste) of fertilizer industry, generated during sulfuric acid treatment of phosphate rock for phosphoric acid production.¹⁰ Nearly about 5 tons of PG waste are generated during 1 ton of phosphoric acid production. The availability of PG in India was reported to be about 8 million tons (2018–19 year).¹¹ The PG contains high amount of Calcium (Ca) and Sulfur (S).¹¹ But, due to acidic pH, its application has been limited as an amendment and fertilizer for alkaline/sodic soils.¹¹ Changing the pH of PG to alkaline has potential to broaden its application in acidic soil, which is rarely studied.^{12,13} In present context, co-pyrolysis of biomass (BP, PS) and fertilizer industry waste (PG) for alkaline biochar

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composite or biochar composite fertilizer (BCF) i.e., BP + PG – B and PS + PG – B production can be a promising concept to promote waste utilization, nutrient recycling, resource conservation, and environmental protection.

Biochar (B) is a carbonaceous material prepared through thermochemical conversion of biomass under oxygen limited conditions, and mainly intended for soil application. Other benefits of biochar are carbon sequestration and waste management.¹⁴ Biochar possesses highly heterogeneous characteristics dependent on feedstock chemical composition and production process parameters.^{15–17} Production of nutrient enriched biochar is an emerging research area and could be used to reduce the consumption of chemical fertilizers. Several methods were investigated for production of nutrient rich biochars.¹⁸ Direct pyrolysis of nutrient rich feedstock such as bone wastes¹⁹, animal manures²⁰ and sewage sludge²¹ were documented for biochar fertilizer production.

Recently, research studies also explored the co-pyrolysis of mixtures of different materials (biomass and inorganic fertilizer) as feedstocks for production of biochar with better nutrients characteristics.¹⁸ Biochar composites were produced by co-pyrolysis of wood dust and switchgrass biomass premixed along with triple superphosphate and bone meal for potential application as slow-release phosphatic fertilizer.²² Biochar based fertilizers production from mixture of poultry litter waste, triple superphosphate, mono-ammonium phosphate, phosphoric acid, and magnesium oxide was also explored earlier. The biochar-based fertilizer was alkaline with improved phosphorus release kinetics due to formation of $Mg_2P_2O_7$ and $Ca_2P_2O_7$ having low water solubility.²³ Co-pyrolysis of mixture of cotton straw biomass, potassium phosphate and bentonite was also reported for production of biochar based slow-release fertilizer. Presence of bentonite was found to facilitate generation of phosphatic chemical bonds and favorable chemically structured for slow release of phosphorous from biochar based fertilizer.²⁴ Potassium and phosphorous rich biochar were produced by the pyrolysis of BP with effluent sludge of phosphate fertilizer industry.²⁵

Overall, the prior-art review indicated mostly the research studies were mainly focused on P enrichment in biochar, other nutrients like potassium (K) and sulphur (S) were scarcely investigated.¹⁸ Karim *et al.* (2019) reported about K-S rich biochar production by plasma processing technique, where composite

mixture of BP biomass and PG are used as feedstocks.²⁶ However, the major challenge of thermal plasma pyrolysis system is not commonly feasible and accessible. In India, huge quantity of PS biomass are available in coastal regions, where phosphatic fertilizers industries are also located due to logistic reasons like sea route transport of rock phosphates etc. It highlights the need to explore the opportunity to utilize PS as an alternative waste for production of biochar composite fertilizers (BCF) along with PG. The release behavior of K and S from biochar are minimally studied, which is important to know their long-term phyto-availability potential in soils. In pre-discussed context and for research advancement, the present research work investigated abundantly available BP and PS biomass waste co-pyrolysis with PG for production BCF. The core objectives of the present study are 1) Studying BP and PS based BCF production and comparative characterization 2) For evaluation of the K and S release behavior of the biochar and BCF.

Materials and Methods

Feed stocks Collection and Processing

The feedstock waste was brought from selected nearby area: BP (*Musa Sp.*) was collected from Unit-1 fruit market and PS (*Oryza sativa*) from nearby villages of Hanspal area, Bhubaneswar, Odisha, India. The collected biomass feedstocks were properly cleaned with tap water to decontaminate surface impurities. Then, it was shredded using a chipper cum shredder machine (7.5 HP, FRED'S Engineering Pvt. Ltd., India). The PG waste in dried powder form was collected from Paradeep Phosphates Limited (PPL), Paradeep, Odisha, India. Both biomass (BP and PS) and PG powder were oven dried separately at 60°C for 48 h. Subsequently, oven dried feedstocks were powdered using a grinder and sieved to retain below 500 microns size sample. The mixture of biomass (BP/PS) and PG with 4:1 wt/wt ratio were utilized as feedstock for production of BCF, whereas BP and PS biomass are for PB. The 4:1 ratio to produce biochar composite was selected on the basis of previous finding.^{22,25} The samples of biomass, mixture of biomass were stored in airtight plastic containers for analysis.

Biochar and Biochar Composite Production

The dried biomass of BP and PS or mixtures of BP/PS + PG with 4:1 wt/wt ratio were taken in a quartz boat and pyrolyzed in a 4kW small-scale

tubular furnace (Ants Ceramics Pvt. Ltd., Maharashtra, India) operated with a PID controller system. Pyrolysis was performed at 700°C temperature with 10°C/minutes heating rate and 1 h residence time to produce PB and BCF. The optimized temperature and residence time parameter was selected with based on prior study of Karim *et al.*, Similarly, BP and PS biomass were also pyrolyzed with aforesaid mentioned condition. The oxygen limited condition was controlled by locked aluminium flanges and purging N₂ gas flow (1liter/h) to reactor. After thermochemical treatment biochar samples were collected from the reactor and stored separately in an airtight container. The produced biochar samples were named as banana peduncle biochar: BP-B; paddy straw biochar: PS-B [both BP-B and PS-B are pristine biochar (PB)] and biochar composite: Banana peduncle mixed phosphogypsum biochar: BP + PG - B and paddy straw mixed phosphogypsum biochar: PS+PG-B. The experimental studies for biochar production were carried out at Centre for Waste Utilization, Environment and Sustainability Department and characterization at CSIR-Institute of Minerals and Materials Technology, Bhubaneswar, Odisha, India.

Characterization of Biochar

The biochar yield (%) was calculated based on weight of biochar and input feedstocks i.e., dried biomass or biomass-phosphogypsum mixture (4:1 wt/wt ratio).²⁷ The pH of biomass and biochar sample were analyzed through digital pH meter (OAKTON, 310 series)²⁸, by taking suspension 1:20 (w/v) ratio of feedstocks or biochar samples in distilled water after keeping over vertical shaker for 120 minutes. Total carbon, hydrogen, nitrogen, and sulphur content in feedstocks and biochar samples were measured by CHNS analyzer (Leco, Truspec). Acid digestion method involving thermal treatment of feedstocks/biochar samples with HNO₃ and H₂O₂ at 180°C was used to extract nutrients in suspension. Suspension were filtered using Whatman-41 filter paper, which were used for nutrients analysis.²⁹ Total Ca and K concentration were estimated using flame photometric method (Systronics-128, Flame Photometer).³⁰

Nutrients Release Behavior of Biochar

The K and S nutrients leaching phenomenon from biochar were estimated by following Filho Lustosa *et al.* method.²³ Biochar (1g) was mixed with 200 mL of de-ionized water and the suspension were shaken, and thereafter 5 mL of liquid was separated using syringe

filtered at selected time intervals i.e., **0.15, 0.3**, 1, 2, 12, 24, 48, 72, 96, and 120 h. The K and S concentrations in extracted solutions were determined based on the flame photometric³⁰ and turbidimetric methods^{31,32} respectively. The K and S release behavior were determined on the basis of changes in concentration with respect to time using different chemical kinetics models/equations:^{22,23}

$$K_{\infty} - K_t = a - bt \text{ linear model}$$

$$\ln(K_{\infty} - K_t) = a - bt \text{ first order model}$$

$$\frac{1}{K_t} = bt + \frac{1}{K_{\infty}} \text{ Second order model}$$

$$K_t = a - b \ln(t) \text{ Elovich model}$$

$$\frac{K_t}{K_{\infty}} = a - bt^{0.5} \text{ Parabolic diffusion model}$$

Here, the terms are extrapolated as: “K_t” denoted the cumulative K/S released at time t; “a” is denoted as K/S initially released; “b” is marked as K-release constant; and “K_∞” is denote the maximum K/S released.

Result and Discussion

Characteristics of Feedstocks, Biochar and Biochar Composite

The composition of feedstocks and biochar characteristics represented in Table 1; pH of PG was found to be acidic nature (4.16), whereas PS and BP biomass were near neutral (7.03) and alkaline (8.53), respectively. The PG contained higher concentration of total S (12.50%) and Ca (16.67%), but very low C (0.05%). In contrast to PG, S content was very low in biomass (BP-0.02 and PS-0.22%), while C content was higher in both (PS-38.42% and BP-37.23%). While C content was estimated slightly higher in PS biomass (38.42%) than BP biomass (37.23%) because of the presence of relatively more cellulose-lignin content in paddy straw which influence the retaining of carbon in PS biomass.³³ The major differences in relation with alkali metals content was observed among biomass; BP contained 3.5 times more K i.e., 5.62% (earlier study reported 6 to 12% K in BP), which mimics the significant uptake of K in BP biomass,¹ than in PS (1.2 to 1.5%). BP biomass was found to be more suitable for production of higher K enriched biochar, due to comparatively lower inherent K in PS biomass than BP biomass. In contrast, PS contained 2.9 times more Ca (0.70%) than BP. Earlier study highlighted the role of alkali metals variations on biochar yield and characteristics due to catalytic

Table 1 — Characteristics of feedstocks and biochar

Sample Names	Yield (%)	pH	Total Carbon (%)	Total Hydrogen (%)	Total Nitrogen (%)	Total Sulphur (%)	Total Potassium (%)	Total Calcium (%)
PS Biomass	NA	7.03 (0.21)	38.42 (0.02)	5.40 (0.13)	0.78 (0.05)	0.22 (0.00)	1.58 (0.02)	0.70 (0.01)
BP Biomass	NA	8.53 (0.40)	37.23 (0.01)	4.56 (0.11)	1.46 (0.02)	0.02 (0.00)	5.62 (0.40)	0.24 (0.00)
PG	NA	4.16 (0.12)	0.05 (0.00)	NA	NA	12.50 (0.02)	NA	16.67 (0.06)
BP-B	37.05 (0.16)	10.50 (0.10)	41.01 (0.02)	1.82 (0.05)	0.65 (0.01)	0.31 (0.01)	12.85 (0.04)	0.92 (0.01)
PS-B	31.83 (0.20)	10.20 (0.05)	45.84 (0.01)	1.37 (0.03)	0.55 (0.02)	0.12 (0.02)	2.90 (0.01)	1.84 (0.01)
BP+PG-B	46.61 (0.14)	9.69 (0.12)	25.07 (0.24)	1.00 (0.30)	0.33 (0.06)	7.66 (0.18)	11.90 (0.11)	3.85 (0.18)
PS+PG-B	42.82 (0.16)	9.78 (0.10)	37.28 (0.32)	1.03 (0.16)	0.45 (0.10)	6.65 (0.22)	2.56 (0.16)	4.33 (0.15)

Note: Mean value based on triplicate analysis with standard deviation in bracket; NA: Not Applicable

influence on the thermochemical reaction and also influencing dehydration-reforming mechanism of biochar production.³⁴

Pyrolysis of BP produced BP-B yield of 37.05%, whereas PS-B yield was 31.83%. Similarly, BP+PG-B higher yield of 46.61% than PS + PG – B 42.82% was observed. The increasing yield of BCF compared to PB biochar can be due to addition of mostly inorganic constituent PG, which loses less weight due to thermal treatment and therefore biochar composite boost yield by 1.2 and 1.3 times higher than BP and PS derived biochar. Prior studies also reported higher inorganic substance in the feedstocks was responsible for improving the biochar yield^{7,35} due to PG heavier particles, thermal resistant (mildly residual moisture loses) and transformed into anhydrite.³⁶ The pH of PB biochar were more alkaline (10.20–10.50) in comparison to BCF (9.69–9.78), due to higher temperature pyrolysis at 700°C might be lead to carboxyl groups reduction, acidic groups deprotonation to conjugate bases, and enrichment of alkali/alkaline earth metals.³⁷ Also the higher temperature influences demineralization and volatilization of nutrient, whereas residence time indicate retention of nutrient and stable carbon.³⁸ However, comparing between pristine biochar and BCF, the dominance of PG in BCF decreased the pH of biochar composites. It was probably due to the retention and incorporation of acidic constituents (phosphoric and fluoric acids) of PG into biochar matrix.^{26,39}

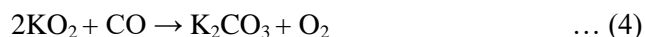
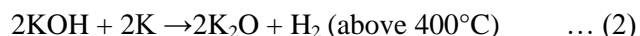
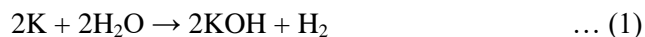
Biochar produced from PS possessed higher C content 45.84% than BP (41.01%), but application

of PG further significantly reduces the C content in PS + PG – B composite (38.28%) followed by BP + PG – B (25.07%) compared to BP-B and PS-B biochar, which is probably due to lower ash content and higher volatile constituent in PS and BP biomass.⁴⁰ According to prior art, the properties of inorganic compounds present in the feedstock influenced the charring reactions and resulting into varied biochar characteristics.^{41–43} Thus, co-pyrolysis of PG based composite probably intensified the volatilization and inhibited the polymerization reactions, which resulted into lower C content in biochar composite. In contrast to the above said trend observed for C content, the utilization of two different biomass (PS and BP) exhibited less prominent variations in N, H, and S content of biochar. The impact of different feed stocks was less prominent due to high temperature (700°C) pyrolysis condition, which led to intensive volatilization of the N, H, and S. Jegajeevagan *et al.* reported N content was getting lower in biochar produced at elevated charring temperature above 400°C, due to its intensified volatilization of amino sugars, amino acids, and amines.⁴⁴ The retention of limited amount of N (0.33 to 0.65%) and H form (1.00 to 1.82%) in biochar was probably due to the formation of recalcitrant heterocyclic compounds. The S content was enriched only in pristine BP biochar (0.31%) compared to BP biomass (0.02%). The N, H and S generally present in aliphatic form in biomass, which during high temperature pyrolysis, gets volatilized easily and become part of bio-oil and syngas; while due to thermal resistance of lignin and polymerization

reactions the C get retained in biochar. The high pyrolysis temperature also intensified the dehydration and de-oxygenation reactions, which led to more volatilization of H, O, N, and S.^{45,46} Among biochar composites, the S content was higher in BP + PG – B (7.66%) than PS + PG – B (6.65%). In comparison to pristine biochar, relatively higher S content in the biochar composites was due to the utilization of PG containing S (12.50%) in thermal resistant calcium sulfate form.²⁶

The K content in BP (5.62%) was much higher than PS (1.58%) biomass. Consequently, BP-B contained relatively higher K (12.85%). Whereas Ca contents were higher in PS-B (1.84%) than BP-B (0.92%). Mixing PG with biomass produced biochar composites with higher Ca (3.85–4.33%) but lower K (2.56–11.90%) than pristine biochar. The K and Ca enrichment in biochar were due to the volatilization and mass loss of other biomass constituents at 700°C pyrolysis temperature was also reported in earlier studies.^{18,29} Also during pyrolysis, PG undergoes thermal decomposition and formed CaO which boost pyrolysis temperature⁴⁷ and indirectly enhances the Ca content in biochar composite. Kalicinite mineral was documented as a main reason for enrichment of K in BP-B which is transformed form and derived from potassium carbonate (K_2CO_3) mineral phase found in banana peduncle. During thermochemical reaction, potassium carbonate reacts with carbon dioxide and water to form potassium bicarbonate ($KHCO_3$). Kalicinite is a colorless prismatic or elongated tubular crystals with striations parallel to the elongated direction identified through X-ray diffraction

analysis.⁴⁸ A probable mechanism for formation of Kalicinite during biomass pyrolysis¹⁸, are explained in Equation: 1 to 5 below,



Other inorganic potassium minerals reported in biochar were Sylvite (KCl), Chlorocalcite ($KCaCl_3$), Struvite ($KMgPO_4 \cdot 6H_2O$), Archerite (KH_2PO_4), and Pyrocoprite ($K_2MgP_2O_7$).¹⁸ During co-pyrolysis of biomass with PG, Ca and S exists mainly in the form of calcium sulfate (thermal resistant) and it enriched in biochar composites.²⁶

Potassium Release Behavior of Biochar

Leaching behavior of K from biochar with respect to selected time intervals and its second order kinetic model fitting are illustrated in Figs. 1 (a) and (b) Values of different kinetics model parameters are depicted in Table 2. The nutrient release phenomenon deciphered about higher K release from BP-B than PS-B i.e., BP + PG – B > BP – B > PS – B > PS + PG – B. The K release from biochar was non-uniform at different time intervals. Maximum release of K (57.76 g/L) from BP-B was estimated at 0.5 h; in addition, BP + PG – B released maximum K (64.12 g/L) after 1 h time. The PS + PG – B released maximum K (7.00 g/L) at 2 h, whereas PS-B achieved 8.64 g/L

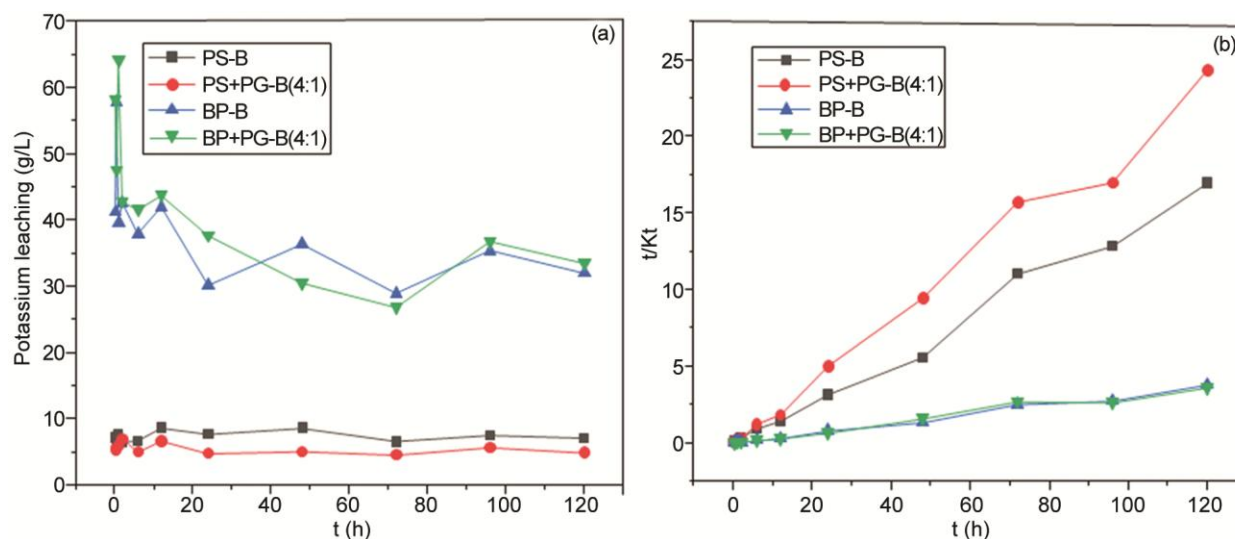


Fig. 1 — (a) K leaching behavior from biochar at different time intervals and (b) second order kinetic model graph

Table 2 — Chemical kinetic models parameters for K release from biochar

Kinetic models		PS-B	PS+PG-B (4:1)	BP-B	BP+PG-B (4:1)
Linear model	R^2	0.0077	0.1945	0.3526	0.4511
	b	-0.0017	0.0078	0.109	0.1753
	a	1.441	1.2257	15.465	15.944
1st Order	R^2	0.014	0.1429	0.1688	0.2458
	b	-0.0045	0.0045	0.0089	0.0121
	a	0.0982	0.2076	2.4426	2.3904
2nd Order	R^2	0.9928	0.9907	0.9905	0.9785
	b	0.19	1.073	0.06	3.65
	a	-0.1033	-0.0363	0.0159	-0.0034
Elovich	R^2	0.111	0.1742	0.5405	0.7289
	b	0.1276	-0.1437	-2.6343	-4.3476
	a	6.9928	5.8211	44.155	51.413
Parabolic diffusion	R^2	0.1156	0.0657	0.4357	0.6333
	b	-0.0524	0.0439	0.1426	-0.2201
	a	0.8711	0.7607	0.5827	0.4731

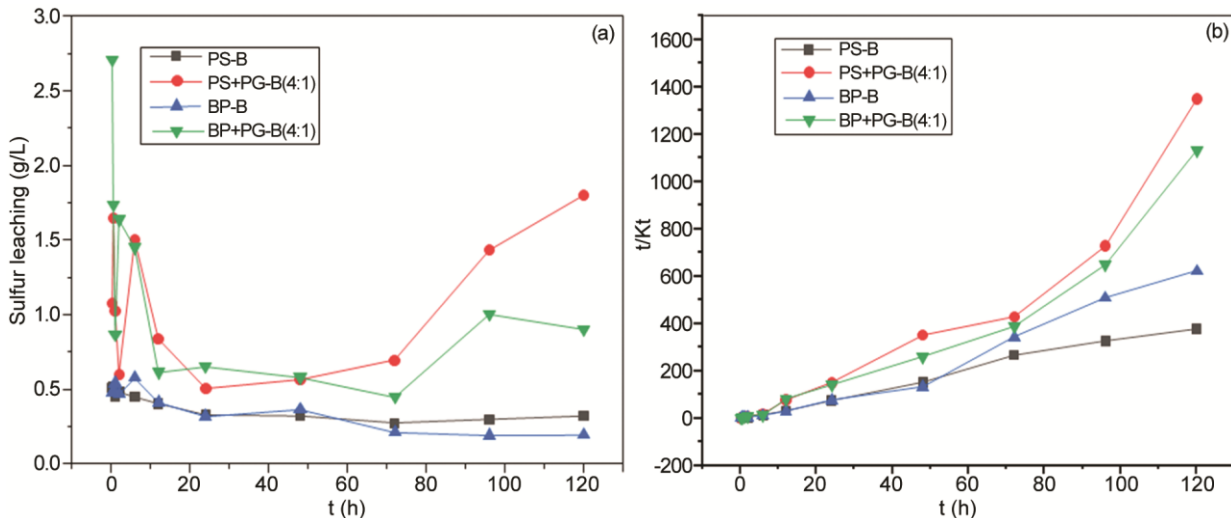


Fig. 2 — (a) S leaching behavior from biochar at different time interval and (b) second order kinetic model graph

maximum K release after 12 h. Sizeable range and variation in K release were observed for BP-B (26.79–64.12 g/L) than PS-B (6.11–8.64 g/L). Application of different kinetic mathematical models such as linear, first-order, second-order, Elovich model and parabolic diffusion were evaluated for K release values of biochar. The K release from BP-B, PS-B, BP + PG - B and PS + PG - B were more fitted to second order kinetic model due to comparatively high R^2 value 0.99, 0.99, 0.97, and 0.99, respectively with corresponding b-values 0.06, 0.19, 3.65 and 1.07. The results highlight about the K release from biochar were mainly engaging the chemical reactions and primarily depends on the initial K content in biochar. The leachability of K from biochar in water suspension depends prominently on its bonding (ionic/organic) and

inherent chemical (minerals) form. The pyrolysis at low and intermediate temperature produced biochar with more water-soluble K forms such as chlorides, carboxylates, and carbonates. Whereas, pyrolysis at higher temperature indicates about transformation of K into lesser water-soluble form due to formation of oxides and direct bonding in biochar matrix.^{49–51}

Sulfur Release Behavior of Biochar

The release of S from biochar suspension with respect to different time periodicity are shown in Figs. 2 (a) and (b) and values for different chemical kinetic models are presented in Table 3. By and large, the retention of S content in biochar depends upon its volatilization rate and chemical transformation at different pyrolysis temperature. The S mainly transformed as water soluble alkali sulfates and water-insoluble aromatic organic sulphur forms during low

Table 3 — Chemical kinetic models parameter of S release from biochar

Kinetic Models		PS-B	PS+PG-B (4:1)	BP-B	BP+PG-B (4:1)
Linear Model	R ²	0.5146	0.3553	0.8251	0.3611
	b	0.0021	0.0014	0.0030	0.0022
	a	0.1974	0.1648	0.0893	0.2288
1st Order	R ²	0.0817	0.0163	0.2662	0.0635
	b	0.0033	0.0018	0.0108	0.0039
	a	-1.2656	-1.4431	-1.9959	-1.2327
2nd Order	R ²	0.9932	0.9226	0.9750	0.9334
	b	4.4294	2.0098	1.16042	1.7823
	a	-2.5081	-44.358	-23.204	-36.435
Elovich	R ²	0.6526	0.4204	0.685	0.5479
	b	-0.0453	-0.0287	-0.0525	-0.0520
	a	0.5081	0.2598	0.4967	0.3715
Parabolic Diffusion	R ²	0.4315	0.4025	0.3777	0.5865
	b	0.1885	0.2382	0.2356	0.3320
	a	0.4935	0.3435	0.5284	0.2658

and high pyrolysis temperature respectively.⁵⁰ The S release from BP + PG - B was found to be comparatively higher (2.70 g/L) and faster (0.25 h) than BP-B (maximum release 0.53 g/L at 1 h) and other biochar. For PS + PG - B, S release concentration was maximum (1.80 g/L) at 120 h. Whereas, within 0.15 h, descending S release pattern was observed as BP + PG - B (2.70 g/L) > PS + PG - B (1.08 g/L) > PS - B (0.51 g/L) > B - PB (0.47 g/L). Similar to K, the S release kinetics from biochar also adhered relatively better fit relationship for second order kinetic model: PS - B (R² = 0.99), BP - B (R² = 0.97), BP + PG - B (R² = 0.93), PS + PG - B (R² = 0.92). It indicates about presence of S is in lesser water soluble chemically bonded form such as aromatic organic S and calcium sulfate (due to the use of PG). Therefore, S release from biochar would be at slow rate, which enhances its phyto-availability in the soils.^{52,53}

Conclusions

Suitable biomass waste to valorize industrial waste remains a challenge. The use of different biomass impacted mainly the K, Ca, S and C contents in biochar. Utilization of the BP biomass was found to be more suitable for production of higher K enriched biochar than PS biochar. However, PS biochar contained more C, Ca, and S and the PG mixing were the main reason of enrichment of Ca, and S in biochar composites. Biochar exhibited slow-release rate of K and S, which highlighted their potential long term phyto-availability potentials in soils for crop growth and development. Overall, the present study concluded about the PS + PG and/or BP + PG co-pyrolysis to produce biochar composite slow-release

fertilizers for replenishing K and S in acidic degraded soils and may be undertaken depending upon the specific soil requirement and feedstock availability. Further, in view of the present work findings, additional experimental studies are necessary to investigate the combined effect of triple feedstock-based biochar composite such as BP + PS + PG or any other biomass waste.

Conflict of Interest

The authors report there are no conflict of interests.

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