STUDY ON BIOCHAR PREPARATION FROM BAMBOO AND PIGEON PEA STALK AND ITS APPLICATION FOR ENHANCING BIOGAS PRODUCTION AND CROP YIELD

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by

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Dedicated to my beloved parents

“Smt. Anasuya Sahoo

&

Read. Prasanna Kumar Sahoo”

CERTIFICATE

This is to certify that the thesis titled "**Study on biochar preparation from bamboo and pigeon pea stalk and its application for enhancing biogas production and crop yield"**, being submitted by **Ms Swapna Sagarika Sahoo**, is a report of bonafide research work carried out by her under our guidance and supervision. This thesis has been prepared in conformity with the rules and regulations of the Indian Institute of Technology Delhi, New Delhi, India. We further certify that the thesis has attained a standard required for the award of the degree of **Doctorate of Philosophy** in the Institute. The research reported and results presented in the thesis have not been submitted, in part or full, to any other Institute or University for the award of any degree or diploma.

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Place: New Delhi, India

Date: **SWAPNA SAGARIKA SAHOO**

ABSTRACT

This study investigates the potential of an unexplored agricultural biomass waste, i.e., pigeon pea stalk produced in tremendous amounts during harvesting of pigeon pea. Another biomass waste, bamboo biomass, was subjected to pyrolysis at different temperatures (400 ℃,500 ℃ and 600℃) at a pyrolysis time of 1 h. The bamboo and pigeon pea stalks were characterized, and their resulting biochar samples (proximate, ultimate, SEM, BET, FTIR and XRD). More mass fraction of lignin in the bamboo biomass yields more biochar (32.20–27.00%) compared to pigeon pea stalk biomass (29.80–21.70%) at the same pyrolysis temperature. The mass fraction of biochar samples' fixed carbon was observed to be 81.85–85.68%, much higher than the biomass. The mass fraction of carbon in the derived biochar samples was in the range of 76.17–88.43%. Biochar samples with low atomic ratios of H/C (0.03–0.06) and O/C (0.04–0.21) confirmed their highly carbonized, aromatized and hydrophobic nature. The BET surface area and total pore volume of biochar samples ranged from 16.90 to 307.10 m^2/g and (0.057–0.18 cm^3/g, respectively; biochar with the higher surface area was obtained at a pyrolysis temperature of 600 ℃. At the same pyrolysis temperature, bamboo-derived biochar samples had a higher total pore volume (0.057–0.18 cm^3/g) than pigeon pea stalk-derived biochar samples. The alkalinity of all biochar samples increased in tandem with the pyrolysis temperature, along with the removal of acidic and polar functional groups. In biochar derived at the temperature of 500 ℃ and 600 ℃, simultaneous loss of crystalline cellulose along with an increase in aromatization and formation of more turbostratic carbon structure were observed.

A batch study of the effect of biochar at different doses (0.5, 0.75 and 1.00 g/g TS of substrates) was investigated on the biogas and methane production on co-digestion of

kitchen waste and cattle dung. The digestion experiment was conducted at a mesophilic temperature of 35±2 °C for an HRT 0f 40 days in a temperature-controlled room at TS of 5%. During the study, it was observed that biochar added at a lower dose of 0.5 g/g TS of substrate enhanced the biogas and methane production compared to control and other biochar doses (0.75 and 1.00 g/g TS of substrates) and surface area (PPS600, BB500 and BB600) added digesters. From this study, it was observed that biochar with lower surface area (PPS500 and BB500) produced higher biogas (6.29% and 20.78%) and methane (20.38% and 35.55%) than the control digester. The nutrient content of raw and digested slurry in biochar added digesters was significantly ($\alpha<0.05$) higher than in the control digester. In contrast, the heavy metal content of raw and digested slurry was significantly reduced ($\alpha<0.05$). The H_2S and CO_2 yield was reduced by 80.70% - 85.33% and 7.22% - 56.54%, respectively, in biochar added digesters compared to the control digester, which enhanced the quality of produced biogas by in-situ upgradation. The field study was conducted in a 300 L volume digester with PPS500 biochar at a dose of 0.5 g/g TS of substrates at 5% TS. The biogas and methane yields were enhanced by 13.21% and 21% in biochar added digester compared to the control digester. Even though the field study was affected by unforeseen climatic conditions, the biochar added digesters maintained the optimum pH conditions (7.02 to 7.36) required for biogas production. In contrast, the pH in the control digester remained in the range of 6.05 to 6.67.

The outcomes of the interactive effect of biochar and elevated CO_2 concentration (CO_2 concentration of 650±10 ppm) on the crop growth parameters showed that except for root length, the leaf area, dry shoot biomass and total biomass yield under elevated CO_2 conditions were significantly increased ($\alpha<0.05$) compared to the control condition at the same biochar dose. However, the effect was more pronounced at a higher biochar dose of 10 t/ha and 15 t/ha compared to the control plot (without biochar addition) under control and elevated CO_2 conditions. The marketable yield and total biomass yield of spinach were significantly increased ($\alpha<0.05$) by 212.11% to 475.72% and 207.74% to 446.26%, respectively, in the elevated CO_2 condition compared to the control condition. The nutrient content of spinach was significantly increased ($\alpha<0.05$) under elevated CO_2 conditions compared to the control conditions except for Mn. The nutrient and heavy metals content like Cu, Ni, Pb and Cd content of the soil was significantly reduced ($\alpha<0.05$) in elevated CO_2 treatments compared to the control conditions after harvesting, indicating increased uptake of nutrients by plants under elevated CO_2 treatment. The soil bulk density and particle density reduced significantly with the application of biochar, whereas the porosity and water holding capacity significantly increased ($\alpha<0.05$) with the application of biochar compared to control soil. The pH and EC of the soil significantly increased ($\alpha<0.05$) with the increase in biochar doses under both control and elevated CO_2 conditions. The higher EC and lower pH of soil under elevated CO_2 conditions indicated more availability of soil nutrients compared to soil nutrient content under control conditions.

Thus, the threatening impact of unsustainable management of agricultural biomass wastes can be arrested by biochar production. This biochar can be used at a suitable dose as a supplement to restrain various inhibitory effects during the anaerobic digestion of highly degradable organic wastes such as kitchen waste and cattle dung. The improved biogas quality with higher methane content can be used as cooking as well as transportation fuel as a green energy. The higher nutrient content of digestate obtained from biochar added digesters can be used in agricultural field as a replacement of chemical fertilizers. This restore the degraded soil health, depleted soil nutrients and microbial activity that is resulted from huge amount of chemical fertilizer application. Biochar also retards the greenhouse gas emission and nutrient leaching from the soil by sequestering carbon and enhanced adsorption of nutrients on its surface. Biochar application increases the soil nutrient content hence reducing the need of chemical fertilizer application and restrain its entrance into the food chain. Biochar, along with elevated CO_2, can be used to produce nutrient-rich crops with higher biomass yield to resolve the issue of nutrient-deficient food and many human diseases.

This study provides a gateway for the use of pigeon pea stalk biochar in various adsorption studies such as removal of various pollutants from soil and water, use of biochar along with elevated CO_2 on other crops in different soil conditions. The potential of pigeon pea stalk biochar on anaerobic digestion of different substrates at different operation conditions can be explored. The biochar added biogas digestate can be used in agricultural field to study its long-term effect on soil physicochemical properties, soil nutrients as well as crop yield.

सार

यह अध्ययन एक अनछुए कृषि बायोमास कचरे की संभावना की जांच करता है, यानी अरहर की कटाई के दौरान बड़ी मात्रा में उत्पन्न अरहर का डंठल। एक और बायोमास अपशिष्ट बांस बायोमास 1 घंटे के पायरोलिसिस समय पर विभिन्न पायरोलिसिस तापमान (400 °C, 500 °C और 600 °C) पर पायरोलिसिस के अधीन था। बांस और अरहर के डंठल की विशेषता थी, साथ ही उनके परिणामी बायोचार नमूने (निकटतम, अंतिम, एसईएम, बीईटी, एफटीआईआर और एक्सआरडी)। बांस बायोमास में लिग्निन का अधिक द्रव्यमान अंश समान पायरोलिसिस तापमान पर अरहर के डंठल बायोमास (29.80–21.70%) की तुलना में अधिक बायोचार (32.20–27.00%) उत्पन्न करता है। बायोचार नमूनों के स्थिर कार्बन का द्रव्यमान अंश 81.85-85.68% की सीमा में पाया गया, जो कि बायोमास की तुलना में बहुत अधिक था। व्युत्पन्न बायोचार नमूनों में कार्बन का द्रव्यमान अंश 76.17-88.43% की सीमा में था। एच/सी (0.03–0.06) और ओ/सी (0.04–0.21) के निम्न परमाणु अनुपात वाले बायोचार नमूनों ने उनके अत्यधिक कार्बोनेटेड, सुगंधित और हाइड्रोफोबिक प्रकृति की पुष्टि की। बीईटी सतह क्षेत्र और बायोचार नमूनों की कुल छिद्र मात्रा 16.90 से 307.10 एम 2 / जी और (0.057–0.18 सेमी 3 / जी, क्रमशः उच्च सतह क्षेत्र के साथ बायोचार 600 °C के पायरोलिसिस तापमान पर प्राप्त की गई थी। उसी पायरोलिसिस तापमान पर। अरहर के डंठल से प्राप्त बायोचार नमूनों की तुलना में बांस व्युत्पन्न बायोचार नमूने उच्च कुल छिद्र मात्रा (0.057–0.18 सेमी 3/जी) थे। अम्लीय और ध्रुवीय कार्यात्मक समूहों को हटाने के साथ-साथ पायरोलिसिस तापमान के साथ सभी बायोचार नमूनों की क्षारीयता में वृद्धि हुई। 500 °C और 600 °C के तापमान पर प्राप्त बायोचार में, क्रिस्टलीय सेलुलोज की एक साथ हानि के साथ-साथ सुगंध में वृद्धि और अधिक टर्बोस्ट्रैटिक कार्बन संरचना का गठन देखा गया।

5% TS पर सब्सट्रेट के 0.5 g/g TS की खुराक पर PPS500 बायोचार के साथ 300 L वॉल्यूम डाइजेस्टर में फील्ड अध्ययन किया गया था। कंट्रोल डाइजेस्टर की तुलना में बायोचार एडेड डाइजेस्टर में बायोगैस और मीथेन की पैदावार में 13.21% और 21% की वृद्धि हुई। भले ही क्षेत्र अध्ययन कुछ अप्रत्याशित जलवायु परिस्थितियों से प्रभावित था, बायोचार जोड़ा डाइजेस्टर अभी भी बायोगैस उत्पादन के लिए आवश्यक इष्टतम पीएच स्थितियों (7.02 से 7.36) को बनाए रखता है, जबकि नियंत्रण डाइजेस्टर में पीएच 6.05 से 6.67 की सीमा में बना हुआ था।

फसल वृद्धि मापदंडों पर बायोचार और उन्नत CO_2 सांद्रता (650 ± 10 पीपीएम की CO_2 सांद्रता) के अंतःक्रियात्मक प्रभाव के परिणामों से पता चला कि जड़ की लंबाई को छोड़कर, उच्च CO_2

स्थितियों के तहत पत्ती क्षेत्र, शुष्क शूट बायोमास और कुल बायोमास उपज में काफी वृद्धि हुई थी ($\alpha<0.05$) एक ही बायोचार खुराक पर नियंत्रण की स्थिति की तुलना में। हालांकि, नियंत्रण और उन्नत CO2 स्थितियों के तहत नियंत्रण प्लॉट (बायोचार जोड़ के बिना) की तुलना में 10 टन / हेक्टेयर और 15 टन / हेक्टेयर की उच्च बायोचार खुराक पर प्रभाव अधिक स्पष्ट था। नियंत्रण की स्थिति की तुलना में उन्नत CO_2 स्थिति में पालक की विपणन योग्य उपज और कुल बायोमास उपज में उल्लेखनीय रूप से 212.11% से 475.72% और 207.74% से 446.26% की वृद्धि हुई ($\alpha<0.05$)। Mn को छोड़कर नियंत्रण स्थितियों की तुलना में उन्नत CO_2 स्थिति के तहत पालक की पोषक सामग्री में काफी वृद्धि हुई थी ($\alpha<0.05$)। पोषक तत्व और भारी धातुओं की मात्रा जैसे Cu, Ni, Pb और Cd मिट्टी की सामग्री को उन्नत CO_2 उपचारों में काफी कम कर दिया गया था ($\alpha<0.05$) कटाई के बाद नियंत्रण की स्थिति की तुलना में संकेत मिलता है कि उन्नत CO_2 उपचार के तहत पौधों द्वारा पोषक तत्वों की वृद्धि हुई है। मृदा थोक घनत्व, कण घनत्व बायोचार के आवेदन के साथ काफी कम हो गया जबकि सरंध्रता और जल धारण क्षमता में काफी वृद्धि हुई ($\alpha<0.05$) नियंत्रण मिट्टी की तुलना में बायोचार के आवेदन के साथ। मिट्टी के पीएच और ईसी में काफी वृद्धि हुई ($\alpha<0.05$) नियंत्रण और उन्नत CO_2 स्थितियों के तहत बायोचार खुराक में वृद्धि के साथ। उच्च CO_2 स्थिति के तहत मिट्टी का उच्च EC और निचला Ph मिट्टी के पोषक तत्वों की तुलना में मिट्टी के पोषक तत्वों की अधिक उपलब्धता को नियंत्रित स्थिति में दर्शाता है।

इस प्रकार, कृषि बायोमास कचरे के सतत प्रबंधन के खतरनाक प्रभाव को बायोचार उत्पादन द्वारा रोका जा सकता है। इस बायोचार को एक उपयुक्त खुराक पर पूरक के रूप में उपयोग किया जा सकता है ताकि अत्यधिक सड़ने योग्य जैविक कचरे जैसे कि रसोई के कचरे और गाय के गोबर के अवायवीय पाचन के दौरान विभिन्न निरोधात्मक प्रभाव को रोका जा सके। बायोचार के साथ-साथ उन्नत CO_2 का उपयोग पोषक तत्वों की कमी वाले भोजन और कई मानव रोगों के मुद्दे को हल करने के लिए उच्च बायोमास उपज के साथ पोषक तत्वों से भरपूर फसल का उत्पादन करने के लिए किया जा सकता है।

यह अध्ययन विभिन्न सोखने वाले अध्ययनों में अरहर के डंठल के बायोचार के उपयोग के लिए एक प्रवेश द्वार प्रदान करता है जैसे कि मिट्टी और पानी से विभिन्न प्रदूषकों को हटाना, विभिन्न मिट्टी की स्थितियों में अन्य फसलों पर उन्नत CO2 के साथ बायोचार का उपयोग। विभिन्न प्रचालन परिस्थितियों में विभिन्न सबस्ट्रेट्स के अवायवीय पाचन पर अरहर के डंठल बायोचार की क्षमता का पता लगाया जा सकता है। बायोचार जोड़ा बायोगैस डाइजेस्टेट का उपयोग कृषि क्षेत्र में मिट्टी

के भौतिक रासायनिक गुणों, मिट्टी के पोषक तत्वों के साथ-साथ फसल की उपज पर इसके दीर्घकालिक प्रभाव का अध्ययन करने के लिए किया जा सकता है।

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SYMBOLS AND ABBREVIATIONS

%	=	Percentage
/	=	Per
<	=	Lower than
>	=	Greater than
≥	=	Greater and equal
±	=	Plus and minus
θ	=	Theta
º	=	degree
°C	=	Degree Celsius
°C/min	=	Degree Celsius per minute
º/min	=	Degree per minute
i.e.	=	That is
µl/g	=	Microliter/gram
µm	=	Micrometer
µmol	=	Micromole
µmol/l	=	Micromole per litre
µmol/mol	=	Micromole per mole
µS/cm	=	Microsiemens per centimeter
As	=	Arsenic
AAEs	=	Alkali and alkaline earth metals

AD	=	After digestion
ADF	=	Acid detergent fiber
ADL	=	Acid detergent lignin
AMF	=	Arbuscular mycorrhiza
ANOVA	=	Analysis of Variance
ASTM	=	American society for testing and materials
Å	=	Angstrom unit
B	=	Boron
BB	=	Bamboo biomass
BD	=	Before digestion
BB400	=	Bamboo biochar prepared at pyrolysis temperature of 400℃
BB500	=	Bamboo biochar prepared at pyrolysis temperature of 500℃
BB600	=	Bamboo biochar prepared at pyrolysis temperature of 600℃
BB5(0.5)	=	Bamboo biochar prepared at 500℃ added at a dose of 0.5 g/g TS of substrates
BB6(0.5)	=	Bamboo biochar prepared at 600℃ added at a dose of 0.5 g/g TS of substrates
BB5(0.5) (BD)	=	Digester added with bamboo biochar prepared at 500℃ at a dose of 0.5 g/g TS of substrates (before digestion)
BB5(0.5) (AD)	=	Digester added with bamboo biochar prepared at 500℃ at a dose of 0.5 g/g TS of substrates (after digestion)
BB6(0.5) (BD)	=	Digester added with bamboo biochar prepared at 600℃ at a dose of 0.5 g/g TS of substrates (before digestion)

BB6(0.5) (AD)	=	Digester added with bamboo biochar prepared at 600℃ at a dose of 0.5 g/g TS of substrates (after digestion)
BET	=	Brunauer-Emmett-Teller
BJH	=	Barrett-Joyner-Halenda
C	=	Carbon
Ca	=	Calcium
Ca^+	=	Calcium ion
$CaCO_3$	=	Calcium carbonate
$Ca(HCO_3)_2$	=	Calcium bicarbonate
CEC	=	Cation exchange capacity
Cmol P+/kg	=	Centimoles of phosphorus ion per kilogram
Cd	=	Cadmium
cm	=	Centimeter
cm^2	=	Square centimeter
cm^{-1}	=	Reciprocal wavelength
CH_4	=	Methane
cmolc/kg	=	Centimoles of charge per kilogram
Co	=	Cobalt
COOH	=	Carboxylic acid functional group
CO	=	Carbon monoxide
COD	=	Chemical oxygen demand
COD/L/Day	=	Chemical oxygen demand per litre per day
Control (BD)	=	Control biogas digester before digestion

Control (AD)	=	Control biogas digester after digestion
CO_2	=	Carbon dioxide
Cr	=	Chromium
Cu	=	Copper
CuKα	=	Copper K alpha radiation
Cd	=	Cadmium
CHNS/O	=	(Sum of carbon, hydrogen, nitrogen and sulphur)/(Oxygen)
C-H, CH_2	=	Methylene group
C=C	=	Alkene functional group
C=O	=	Carbonyl group
C/N	=	Carbon/nitrogen
cm^3/g	=	Cubic centimeter per gram
DAP	=	Diammonium phosphate
db	=	Dry basis
dS	=	DeciSiemens
dS/m	=	deciSiemens per meter
DW basis	=	Dry weight basis
EC	=	Electrical conductivity
EDTA	=	disodium dihydrogen ethylene diamine tetraacetate
EDS	=	Energy dispersive X-ray spectrometer
FAI	=	Fertilizer association of India
Fe	=	Iron

FTIR	=	Fourier Transform Infrared spectroscopy
FYM	=	Farm yard manure
Elevated CO_2	=	Elevated carbon dioxide
FAO	=	Food and Agriculture Organization
g	=	Gram
GHG	=	Greenhouse gas
g/cm^3	=	Gram per cubic centimeter
g/d	=	Gram per day
g/kg	=	Gram per kilogram
g/L	=	Gram per litre
g/g	=	Gram per gram
g/g dry matter	=	Gram per gram of dry matter
g/g TS	=	Gram per gram total solid
g/g VS	=	Gram per gram volatile solid
g/g TS of sludge	=	Gram per gram total solid of sludge
g/g VS of sludge	=	Gram per gram volatile solid of sludge
g TS/kg	=	Gram per kilogram of total solid
g VS/L/D	=	Gram of volatile solid per liter per day
h	=	Hour
ha	=	Hectare

HCl	=	Hydrogen chloride
HDPE	=	High density polyethylene
Hg	=	Mercury
HK	=	Horvath-Kawazoe
HRT	=	Hydraulic retention time
HS^-	=	Hydrosuphide ion
$HS^-_{(ads)}$	=	Hydrosuphide ion adsorbed
H	=	Hydrogen
H^+	=	Hydrogen ion
H_2	=	Hydrogen
H_2O	=	Hydrogen oxide
H_2S	=	Hydrogen sulfide
$H_2S_{(gas)}$	=	Hydrogen sulfide gas
$H_2S_{(ads)}$	=	Hydrogen sulfide gas adsorbed
$H_2S_{(ads-liq)}$	=	Hydrogen sulfide gas adsorbed in liquid phase
H_2SO_4	=	Sulphuric acid
H/C	=	Hydrogen/carbon
ICP-MS	=	Inductively coupled plasma mass spectrometry
ISR	=	Inoculum to substrate ratio
K	=	Potassium
K	=	Kelvin
K^+	=	Potassium ion

KBr	=	Potassium bromide
kg	=	Kilo gram
Kg/ha	=	Kilogram per hectare
Kg/m^3	=	Kilogram per cubic meter
kW	=	Kilo-watt
kV	=	Kilovolt
K_2O	=	Potassium Oxide
K/s	=	Kelvin per second
L	=	Litre
L/kg TS	=	Litre per kilogram of total solid
LMT	=	Lakh Metric Tons
mean±s.d.	=	mean±standard deviation
Mg	=	Magnesium
mg	=	miligram
mg/100g	=	Milligram per 100 gram
mL	=	Milliliter
mm	=	milimeter
Mn	=	Manganese
Mo	=	Molybdenum
m	=	Meter
M_p	=	Mass of dried empty pycnometer
MPa	=	Mega Pascal

M_{ps}	=	Mass of pycnometer and soil
M_{pw}	=	Mass of pycnometer and water
m^2	=	Square meter
m^2/g	=	Square meter per gram
m^3	=	Cubic meter
m^3/h	=	Cubic meter per hour
mA	=	miliampere
mg	=	Milligram
$MgCO_3$	=	Magnesium carbonate
min	=	Minute
mL	=	mililitre
mm	=	milimeter
Mn	=	Manganese
mL/g	=	Mililitre per gram
mL/g. TS	=	Mililitre per gram per total solid
mL/g VS	=	Mililitre per gram of volatile solid
mL/l	=	Mililitre per litre
Mo	=	Molybdenum
Mg/m^3	=	Megagram per cubic meter
m^3 / kg TS	=	Cubic meter per kilogram of total solid
m^3 / kg VS	=	Cubic meter per kilogram of volatile solid
mg/g	=	Milligram per gram

mg/g of CO_2	=	Milligram per gram of carbon dioxide
mg/100 g	=	Milligram per hundred gram
mg/kg	=	Milligram per kilogram
mg H_2S/g	=	Milligram hydrogen sulphide per gram
mg/min	=	Milligram per minute
mg/L	=	Miligram per litre
mL/g	=	Mililitre per gram
mL/min	=	Mililitre per minute
Mg^+	=	Magnesium ion
Mn	=	Manganese
MJ/kg	=	Megajoules per kilogram
mmol/g	=	Millimole per gram
Mo	=	Molybdenum
N	=	Nitrogen
N_2	=	Nitrogen gas
Na	=	Sodium
NaOH	=	Sodium hydroxide
Na_2CO_3	=	Sodium carbonate
NDF	=	Neutral detergent fiber
NH_3	=	Ammonia
Ni	=	Nickel
NLDFT	=	Non-local density functional theory

N/C	=	Nitrogen/Carbon
Nm^3/ h	=	Normal cubic meter per hour
NPK fertilizer	=	Nitrogen, Phosphorus and Potassium fertilizer
nm	=	Nanometer
NO_X	=	Nitrogen oxides
N_2O	=	Nitrous oxide
-OH	=	Hydroxyl functional group
OH^-	=	Hydroxide ion
O_2	=	Oxygen
O/C	=	Oxygen/Carbon
(O+N)/C	=	(Oxygen+Nitrogen)/Carbon
P	=	Phosphorus
Pb	=	Lead
ppb	=	Parts per billion
ppm	=	Parts per million
PPS	=	Pigeon pea stalk
PPS400	=	Pigeon pea stalk biochar prepared at pyrolysis temperature of 400°C
PPS500	=	Pigeon pea stalk biochar prepared at pyrolysis temperature of 500°C
PPS600	=	Pigeon pea stalk biochar prepared at pyrolysis temperature of 600°C
PPS5(0.5)	=	Pigeon pea stalk biochar prepared at 500°C added at a dose of 0.5 g/g TS of substrates

PPS5(0.75)	=	Pigeon pea stalk biochar prepared at 500°C added at a dose of 0.75 g/g TS of substrates
PPS5(1.00)	=	Pigeon pea stalk biochar prepared at 500°C added at a dose of 1.0 g/g TS of substrates
PPS6(0.5)	=	Pigeon pea stalk biochar prepared at 600°C added at a dose of 0.5 g/g TS of substrates
PPS5(0.5) (BD)	=	Digester added with pigeon pea stalk biochar prepared at 500°C added at a dose of 0.5 g/g TS of substrates (before digestion)
PPS5(0.5) (AD)	=	Digester added with pigeon pea stalk biochar prepared at 500°C added at a dose of 0.5 g/g TS of substrates (after digestion)
PPS5(0.75) (BD)	=	Digester added with pigeon pea stalk biochar prepared at 500°C added at a dose of 0.75 g/g TS of substrates (before digestion)
PPS5(0.75) (AD)	=	Digester added with pigeon pea stalk biochar prepared at 500°C at a dose of 0.75 g/g TS of substrates (after digestion)
PPS5(1.00) (BD)	=	Digester added with pigeon pea stalk biochar prepared at 500°C at a dose of 1.00 g/g TS of substrates (before digestion)
PPS5(1.00) (AD)	=	Digester added with pigeon pea stalk biochar prepared at 500°C at a dose of 1.00 g/g TS of substrates (after digestion)
P_2O_5	=	Triple Super Phosphate
rpm	=	Revolution per minute
Se	=	Selenium
SEM	=	Scanning electron microscope
S^0	=	Elemental sulphur
SO_2	=	Sulphur dioxide
SO_4^{2-}	=	Sulphate
SO_X	=	Sulphur oxides

STP	=	Standard temperature and pressure
TGA	=	Thermo-gravimetric analysis
Tg pollutant/year	=	Teragram pollutant/year
Tg N/year	=	Teragram nitrogen/year
TKN	=	Total Kjeldahl Nitrogen
TS	=	Total solid
TS/kg	=	Total solid per kilogram
TVFA	=	Total volatile fatty acid
TVSMRE	=	Total volatile solid mass removal efficiency
t/ha	=	Tons per hectare
UASB reactor	=	Upflow anaerobic sludge blanket reactor
VS	=	Volatile solid
VS/L/D	=	Volatile solid per litre per day
v/v	=	Volume per volume
VM/FC	=	Volatile matter/Fixed carbon
VFAs	=	Volatile fatty acids
WHC	=	Water holding capacity
wb	=	Wet basis
Wt. %	=	Weight percentage
w/v	=	Weight per volume
w/w	=	Weight per weight
XRD	=	X-Ray Diffraction
Zn	=	Zinc
$ZnCl_2$	=	Zinc chloride