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Transformation of Cotton Stalk Biochar into a Sustainable Slow-Release Potassium Fertilizer: Adsorption-Desorption Dynamics and Tomato Growth Impact

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A SLOW-RELEASE potassium fertiliser (KBC) was prepared from biochar (BC) produced from cotton stalks. Zeta potential (negative charge), SEM (porous, smooth, oval shaped holes), EDX (potassium confirmed by a strong peak 3.31 keV), FTIR (C=C bonds in the Amine group in BC, in impregnated BC unsaturated compounds with C=O and C=C bonds, stretching of C-C bonds), and BET (SSA for BC: 2.566 m²/g & KBC: 2.145 m²/g) techniques were used for characterisation. Adsorption and desorption study of potassium using different models were assessed. Redlich isotherm model (R^2= 0.99) outperformed other isotherm models. Tomato plants were utilised to evaluate the impact of BC-based potassium fertiliser on growth metrics. ANOVA was utilised to assess the statistical significance of these growth characteristics. The findings demonstrate that the BC-enhanced slow-release potassium fertiliser increases potassium availability and its use efficiency, and fosters prolonged plant development, providing a sustainable and effective solution for potassium as a slow release fertilizer in agriculture.

Keywords: Adsorption isotherm, Biochar, Fertilizer, Pot study, Release kinetic, Slow-release.

1. Introduction

Agricultural sector has a key role in ensuring global food security, economic development, and environmental preservation. Due to the increasing demands on agricultural outputs caused by the world's population and the decreasing amount of arable land, there has been a significant load on remaining agricultural land (Wang et al., 2022; Sharma et al., 2023, 2024). To overcome the load, excessive amount of fertilizers are used in the field (Singh et al., 2024). So sustainable nutrients management becomes a key factor in deciding agricultural soil health (Singh et al., 2025; Kumar et al.,2025). The N, P, and K in fertilizers are the three main nutrient elements necessary for crop growth and development. However, the soluble nature of modern commercial fertilizers often results in nutrient release rates that exceed the crops' absorption capacity over time. A suitable supply of nutrient promote plant growth and increase yield, but excessive or inappropriate nutrient supply can cause nutrient accumulation in crops, and also do harm to human health (Das and Ghosh, 2023).

Current study focused on the management of potassium (K) which is an essential macronutrient that influences the physiological and biochemical processes in plants by regulating photosynthate transport, turgor pressure, and hydration levels (El-Metwally et al., 2025). Potassium, a non-renewable nutrient, is classified into four types: water-soluble, exchangeable, non-exchangeable, and structural (mineral) potassium (Zhang et al., 2022). Both weathering and the exchange process can gradually transform non-exchangeable potassium into exchangeable potassium, and mineral potassium into exchangeable potassium. Several studies have shown that controlled-release fertiliser can reduce environmental problems caused by nutrient leaching and increase nutrient utilisation (Sashidhar et al., 2020; Piash et al., 2021; Wang et al., 2022). The carrier for controlled-release fertiliser can be a material with a high nutrient loading, the ability to manage its release behaviour, not being harmful, and being biodegradable (Purnomo et al., 2017; Sashidhar et al., 2020; Rashid et al., 2021; Malik et al., 2024). According to An et al., (2021), BC's unique pore structure and physicochemical features make it a potential carrier for controlled-release fertilisers. Modern research has shown that BC's raises the pH of soil, inhibit runoff, & immobilise d-block elements mainly in soil (Ahmadi et al., 2020; Hou et al., 2020; Rafiq et al., 2020). Thermochemical processing of biomass in an oxygen-limited environment produces BC (An et al., 2020; Chen et al., 2022). Based on its versatility, durability, and capacity to provide a strategy for nutrient recovery, pyrolysis is the most promising thermochemical conversion method (Afif et al., 2019). Adekiya et al (2022) studied the effect of *Prosopis Africana* based biochar slow release K fertilizer on performance of sweet potato with main focus on soil properties.

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So going ahead current study was designed to find the leaching potential of biochar-based slow-release K fertilizer in soil column along with its effects on potato plant.

2. Materials and Methods

The experiment design of the study has been shown through Fig. 1.

2.1. Preparation of cotton stalk BC

Agricultural residue (*Gossypium* stalks) was used as carrier for controlled-release fertiliser. In order to eliminate the dust and contaminants from the surface, collected cotton stalk was rinsed with water and subsequently dried in the sun to remove moisture. The desiccated stalk was pulverised into a fine powder in a flour mill, then muffle furnace at 450°C for a duration of 2 hrs.

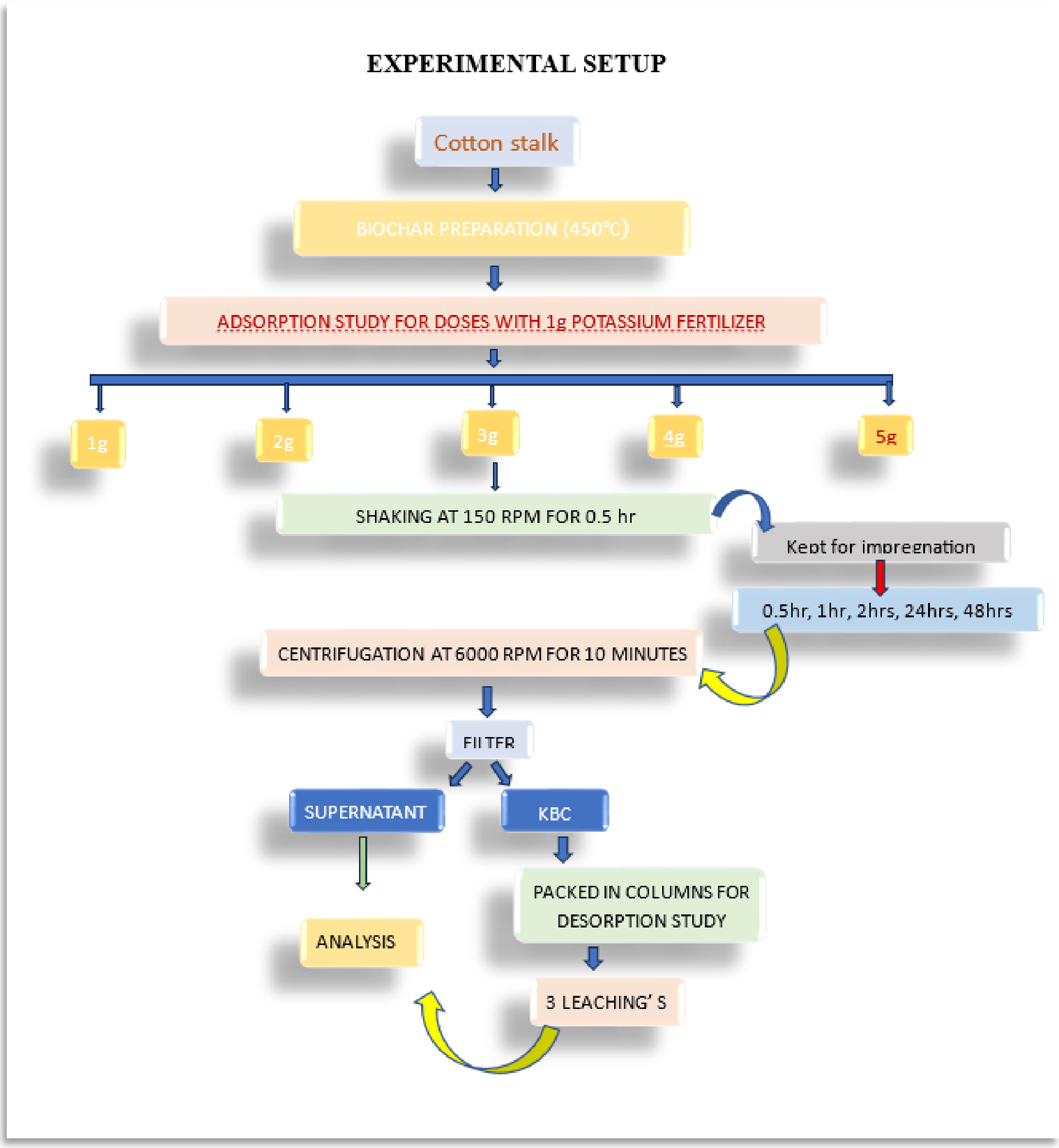


Fig. 1. Flow chart of experiment design of the study.

2.2 Preparation of KBC

BC was immersed in potassium sulphate solution at different ratios (g/mL) and agitated at 150 rpm for a stipulated time period. The experiment was carried out by varying BC dosages (1, 2, 3, 4 and 5 g), contact time of impregnation (0.5, 1, 2, 24 and 48 hrs.) with constant adsorbate concentration (1g Potassium sulphate in 50 ml water). After that, the adsorbents were centrifuged for 10 minutes at 6000 rpm. To obtain K-loaded BCs, the mixture was filtered and dried at a temperature of 50 °C for 24 h. The five KBC's formed were KBC1, KBC2, KBC3, KBC4 & KBC5 with respective doses of BC (1-5g).

2.3. Characterization

The pH and EC of the BC samples was measured using the HM Digital (pH-200) metre and EC metre respectively in the ratio of 1:20. The surface functional group were evaluated by Fourier Transform Infrared Spectroscopy (FTIR) (Perkin Elmer, Spectrum 100). The structural properties and elemental composition were investigated by scanning electron microscope (SEM) with Energy Dispersive X-ray (EDX) (FE-SEM, JEOL). UV spectroscopy analysis was performed using a UV-VIS-NIR Spectrophotometer (Shimadzu, UV-3600 Plus). Zeta potential was analysed using a Zeta sizer (Malvern, Nano- ZS).

2.4 Adsorption study of K

2.4.1. Adsorption (%)

Adsorption (%) was determined using the following equation:

$$\text{Adsorption } (\%) = \{(Ci-Cf) \times 100 / Ci\}$$

Where,

Ci - initial amount (mg)

Cf - final amount (mg)

Adsorption Capacity was calculated as per the equation below:

$$qe = Cad/ W$$

Where,

qe = Adsorption Capacity (mg/g), Cad = (Ci-Cf) adsorbed amount of fertiliser, W = Mass of adsorbent or BC (grams)

2.4.2. Adsorption Isotherm Models

The observed adsorption processes of potassium using BC was explained by the Langmuir, Freundlich and Tempkin and other isotherm models using Origin 2024 edition.

2.5. Controlled release of K

2.5.1 Column leaching experiments

The column leaching experiment was performed to assess the potassium slow-release capability of KBC as an Slow Release Fertilizer (SRF). The columns (25 cm long & 3.5cm wide) were equipped with glass wool (2cm) at the base to avert clogging and the release of samples from the pipeline. In total, 15 columns were taken as three replicates of each KBC. Subsequently, KBC1 - KBC5 were added into the columns. The control group was conducted using soil (1-5g in columns) combined with potassium sulphate (fertilizer). The soil taken was agricultural soil (loamy). Subsequently, the columns were subjected to 3 leachings with three replicates with deionised water. The columns were first saturated with deionised water followed by leaching studies over a duration of three days, during which leachates were collected to quantify potassium concentration utilising a flame photometer (Systronics).

2.5.2. Kinetics of Potassium Release

To examine the potassium release mechanism of KBC, various kinetic models, including zero-order, first-order kinetics, and the Hixon-Crowell model, were employed. The kinetic analysis for the release of K from KBC was performed based on the following equations:

- Zero order

$$Qt = Qo + Kot$$

- First order

$$\log Qt = \log Qo + (K1t/ 2.303)$$

- Hixon- Crowell

$$Wo1/3 - Wt1/3= K2t$$

Where: Qt is the cumulative release percentage of potassium at time t (hrs); Qo is the initial amount of K in zero and first-order release kinetic models. Wo and Wt are the initial and remaining amounts of potassium in the Hixon- Crowell release model. K1, K2, K3 are the release rate constants which will be calculated by Zero-order, First-order and, Hixson-Crowell model, respectively.

2.6 Pot Experiment

KBC was applied as a controlled-release fertiliser to examine its effect on the growth of *Lycopersicon*. The experimental setup included 6-treatments, T0 to T5 (Table 1). The primary goal of the pot experiment was to examine the effects on plant growth of the dose that demonstrates the highest cumulative release, 2 g for 2 hours, and the dose that was supported by release kinetics, 3g for 2 hours. Subsequently, 7 Kg of soil were added, and the top layer was mixed with respective KBC, followed by the placement of two plantlets. K and P in the soil was extracted by Diethylenetriamine pentaacetate (DTPA) as described by Lindsay and Norvell (1978) and estimated through ICP-MS (Make: Thermo Scientific, Model: ICAP6300 Duo). Pots were irrigated to retain moisture, and experiments were conducted in triplicate. On a weekly basis, plant metrics including the plant height, and leaf count were analysed. After 45 days, plant parameters including root and shoot length, dry and wet weight were measured. Length of roots and shoots was measured using a scale. Plants' fresh and dry weights were measured using the computerised weighing scale.

Table 1. Treatments for pot study.

Treatments	Details
T0	Control 1 (only soil)
T1	Control 2 (Soil + F)
T2	Soil + BC (2g)
T3	Soil + BC (3g)
T4	Soil + BC (2g) + F
T5	Soil + BC (3g) + F
*F= fertilizer (1g)	

Statistical analyses

Oneway ANOVA with Dunken post-hoc test at a significance level of 0.05 was used to find out the statistical difference among different treatments.

3. Results

3.1 .1 Characterization

The adsorption and desorption of potassium for slow release was investigated using *Gossypium* stalk BC as a matrix in both the batch and column leaching studies. The primary constituents of *Gossypium* stalk BC consisted of carbon, nitrogen, and oxygen. The physico-chemical characteristics of soil along with *Gossypium* stalk BC has been compiled in Table 2 and 3. Zeta potential analysis revealed that all the three samples exhibited a negative charge (Fig. 2A).

Table 2. Physio-chemical properties of pot soil.

Soil properties	values
pH	6.69
TOC %	0.30
EC(ds/m)	2.49
Available K (Kg/ha)	472
Available P (Kg/ha)	37.29

Table 2. Physio-chemical properties of *Gossypium* stalk BC.

Properties	BC
pH	11.2
Ash %	18.1
TOC %	76
Yield %	33.7
CEC (cmol/kg)	31.3
EC (dS/m)	3.36
Total C g/kg	663.3
Total N g/kg	13.9
SSA (m^2/g)	2.566

*SSA: Specific Surface Area. CEC: Cation Exchange Capacity; TOC: Total Organic Carbon.

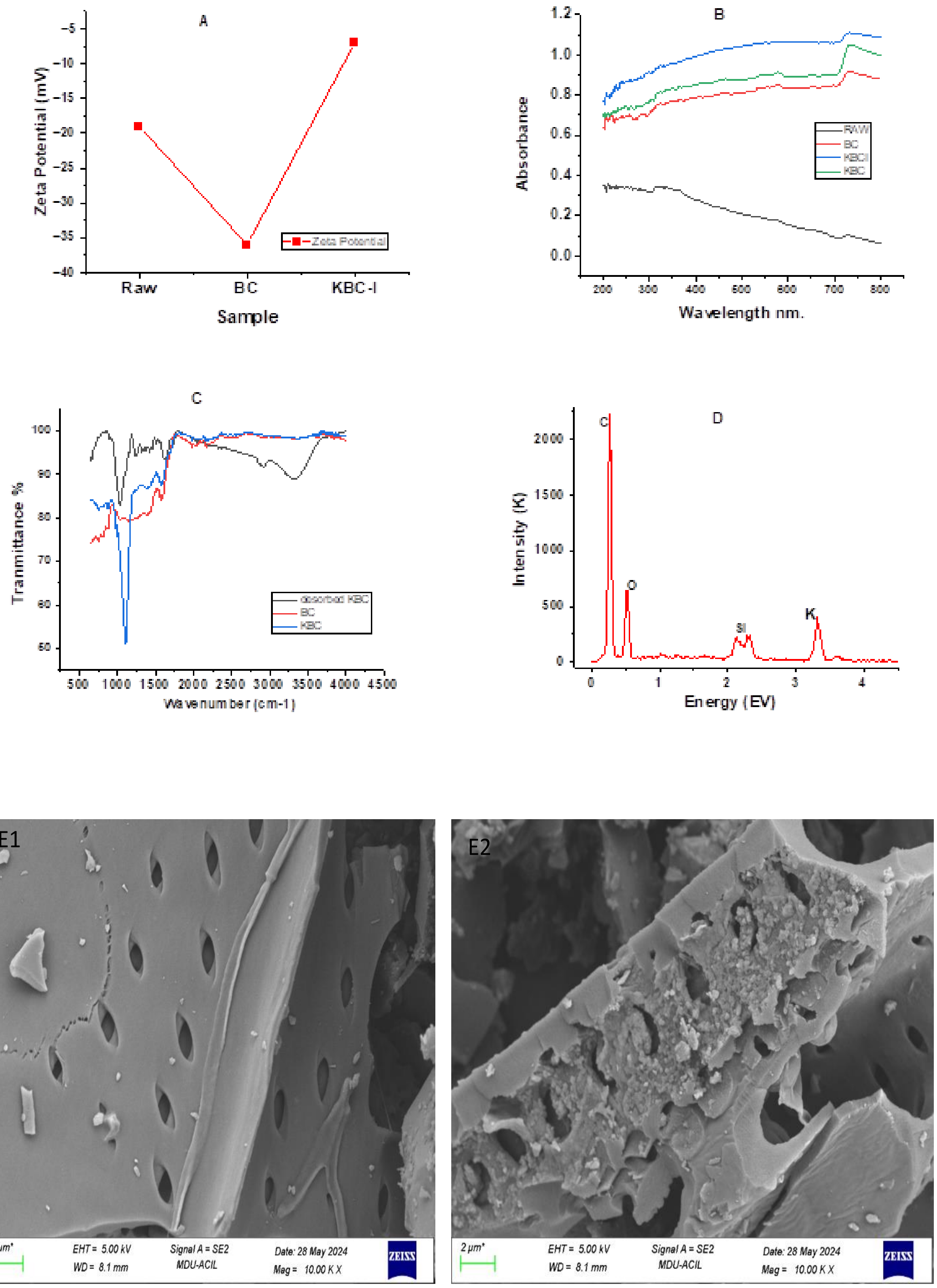


Fig. 2. A) Zeta potential of raw material, BC, KBC; B) UV analysis of raw material, BC, adsorbed and desorbed KBC; C) FTIR results of raw material, BC, adsorbed and desorbed KBC; D) EDX spectrum of KBC (adsorbed); E1) SEM image of BC; E2) SEM image of KBC (adsorbed).

3.2 Adsorption study

3.2.1 Impact of biochar dose on pH

This was clearly observed in Fig. 3 that there was a direct relation between pH and dose increment. In each contact time (0.5 to 48 hrs) with increase in dose, the pH was not increased much but had a gradual increment. There was not much higher increase it was a gradual increase in pH. The highest pH was observed in 5g dose with 1hr contact time.

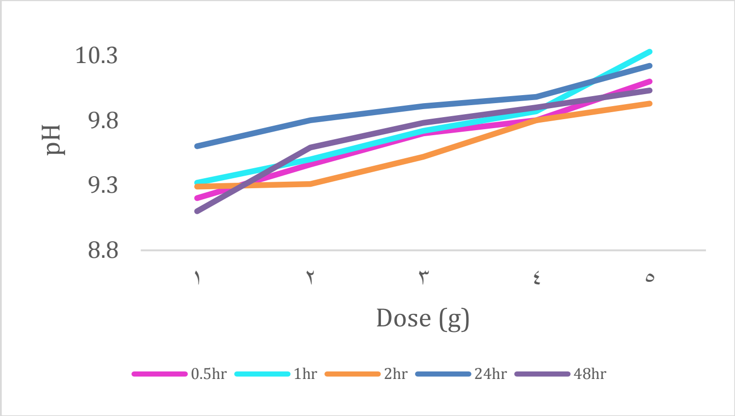


Fig. 3. Effect of biochar dose on pH with different contact times.

3.2.2 Impact of BC dose on adsorption

The impact of different amounts of BC on the adsorption of K^+ ions was examined within the range of 1–5 g, while keeping the potassium concentration constant. According to Fig.4 the adsorption % experienced a significant rise from 21% to 80% when the BC dose increased from 1 to 5 g.

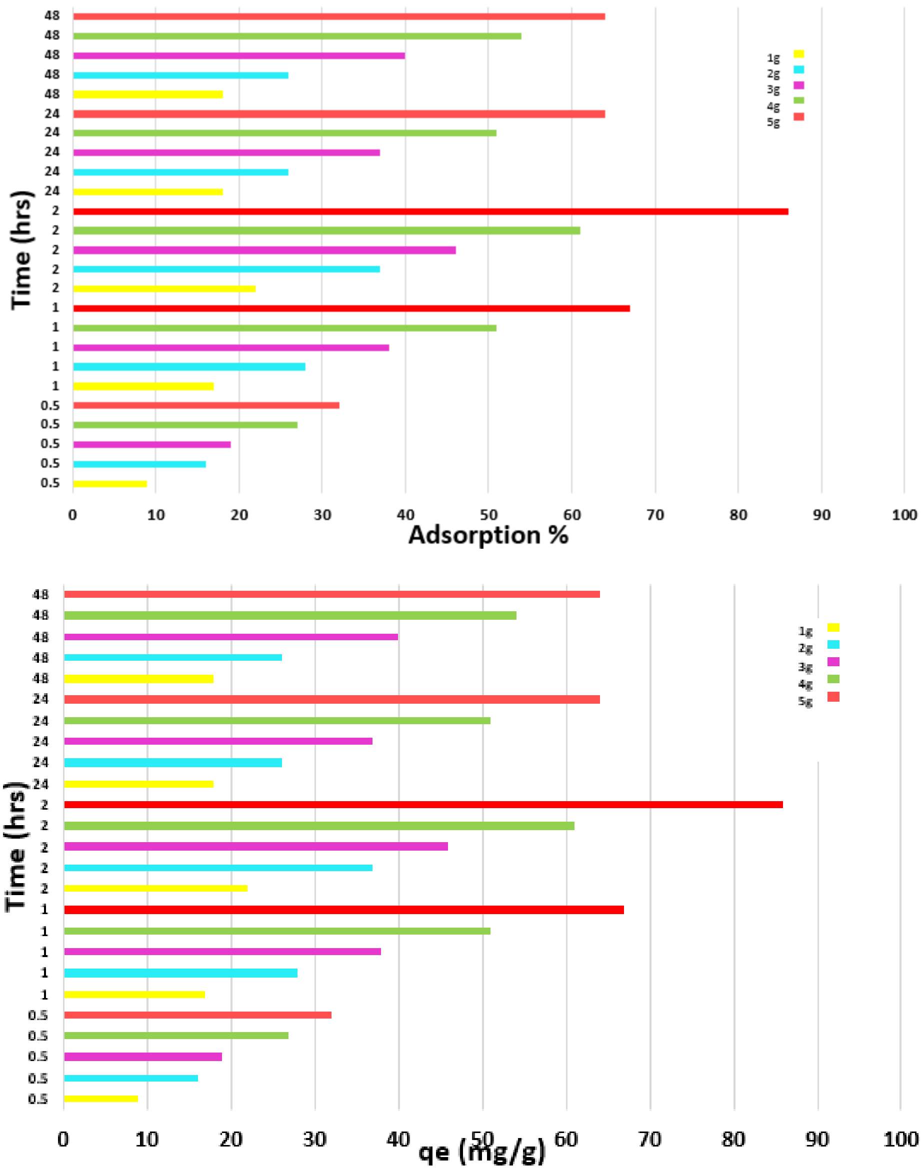


Fig. 4. Impact of biochar dose and contact time on adsorption and capacity.

3.2.3 Impact of contact time on adsorption

The impact of different contact times on the adsorption of K^+ ions was examined with 0.5h, 1h, 2h, 24h and 48h with varying BC doses but constant potassium concentration. According to Fig. 4, the adsorption % experienced a significant rise when the contact time increased from 0.5 to 2h. After 2 hours, there was decline in the adsorption, which remained relatively steady from 24 to 48 hours. The highest adsorption of 80% was observed at 5g dosage of BC, specifically at a contact period of 2 hours. qe also showed the same pattern of increasing from 0.5-2 hrs and then declined. Therefore, the most effective time of adsorption % and capacity was determined to be 2hrs.

3.2.4 Isotherm models

Isotherm models were applied to evaluate the adsorption type (Fig 5, Table S1). In the current study the order of R^2 value followed was study the was Redlich-Peterson (0.99002), Harkin-Jura (0.92483), Langmuir (0.91445), Halsey (0.83663), Elovich (0.81488) followed by Freundlich (0.71865) and Tempkin (0.71865).

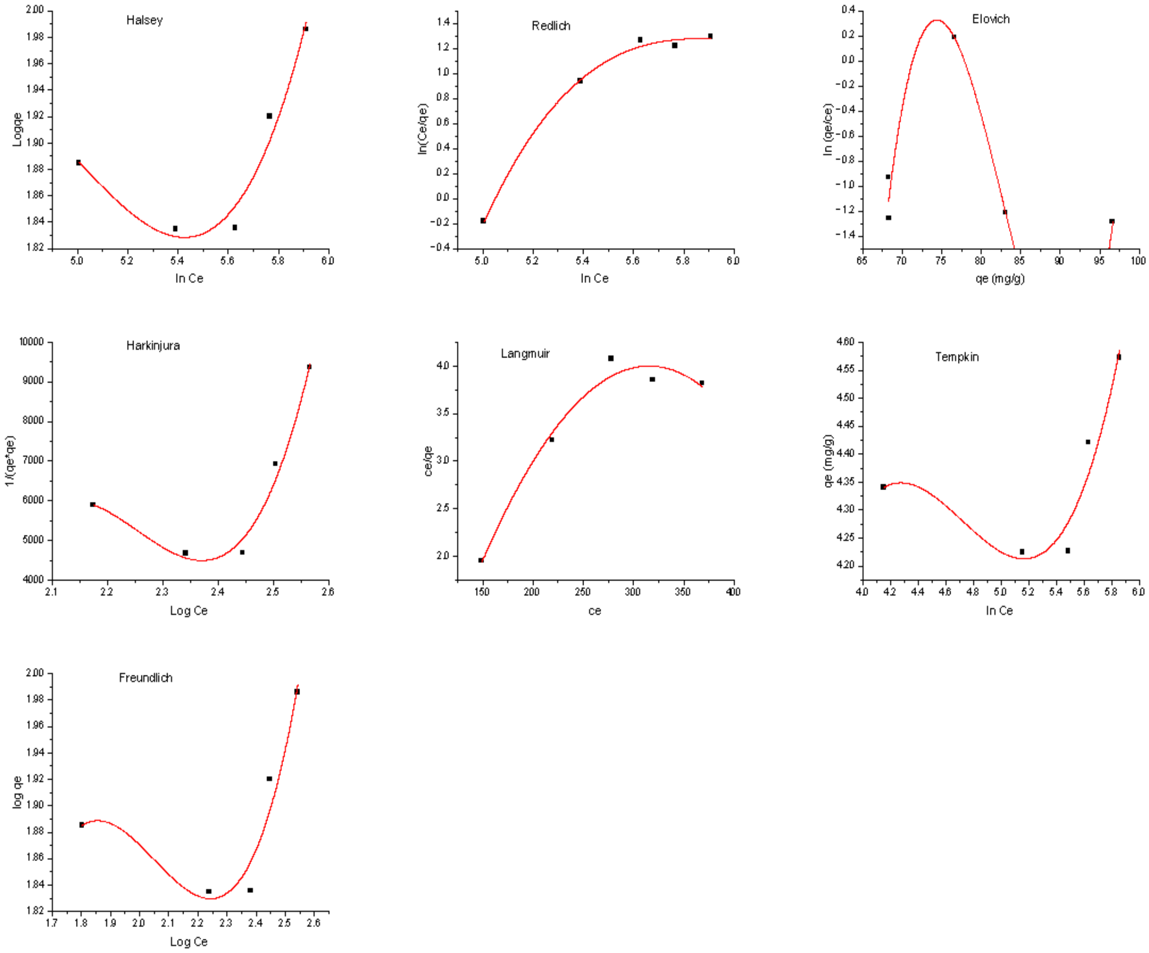
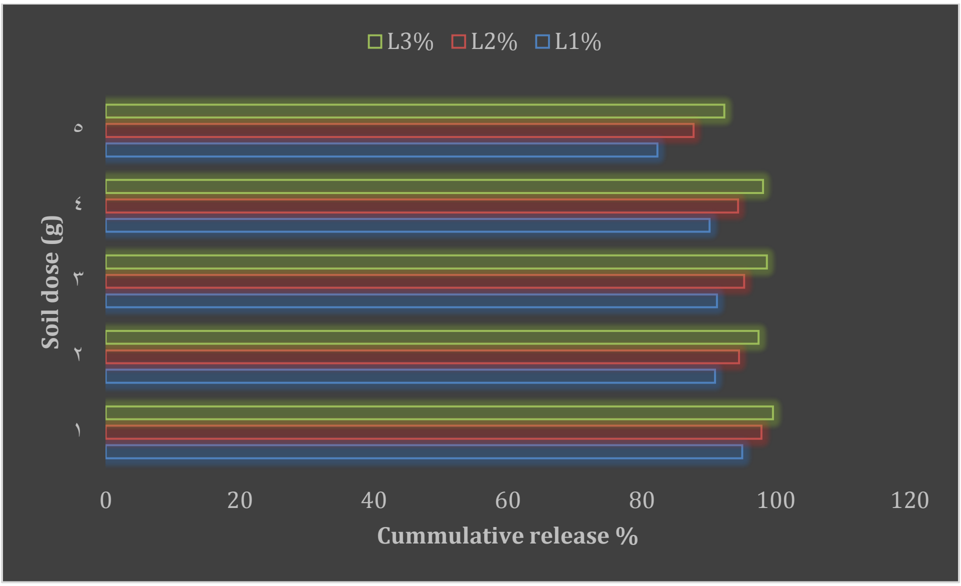


Fig. 5. Adsorption isotherm models applied to the data.

3.3 Desorption study

3.3.1 Potassium release dynamics using column leaching method

The column leaching experiment was carried out to assess the nutrient release from potassium impregnated BC and soil as a control with same doses as BC. Water was poured into the columns every 24 hours, and readings were taken over three consecutive days. In control (soil only) set 92-99 % of potassium was released in three days as shown through Fig. 10. 2-hour contact time with BC resulted in the highest cumulative release percentage for each dose (Fig. 6, 7). 2g dose resulted in the highest cumulative release with each contact period. So, altogether, a 2g dose with 2 hours of contact time resulted in the highest cumulative release.



*L1: leaching 1; L2: leaching 2; L3: leaching 3 (three consecutive days)

Fig. 6. Potassium release from soil (control) of varying doses: 1g, 2g, 3g, 4g and 5g with constant fertilizer for 3 leachings.

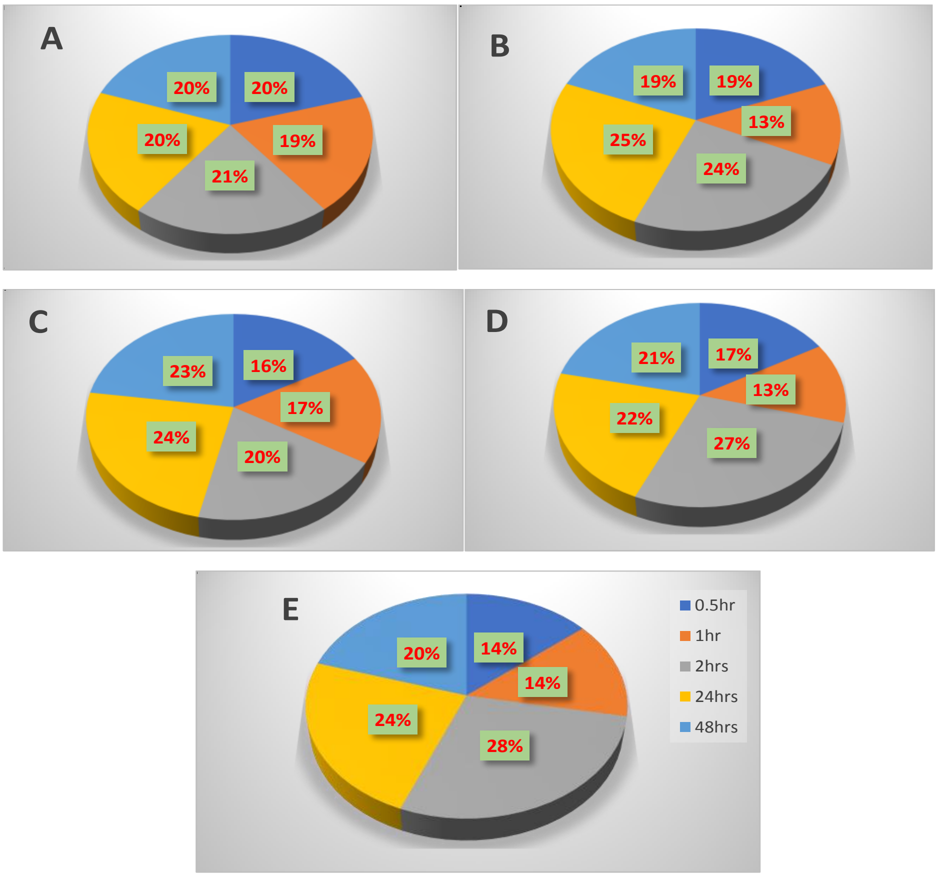


Fig. 7. Cumulative Release of K^+ from KBC of varying doses: (A)1g, (B) 2g, (C) 3g, (D) 4g, (E) 5g for different adsorption times.

3.3.2 Kinetic release models

Zero-order, First-order kinetics, and the Hixson-Crowell model were used for slow-release kinetic models (Fig. 8, TableS2). It was found that all three models showed highest R^2 values for 3g dose (2hrs) which were 0.9987, 0.9811, and 0.9978 (Zero order, First order and Hixon-Crowell) for K release from KBC among three leaching.

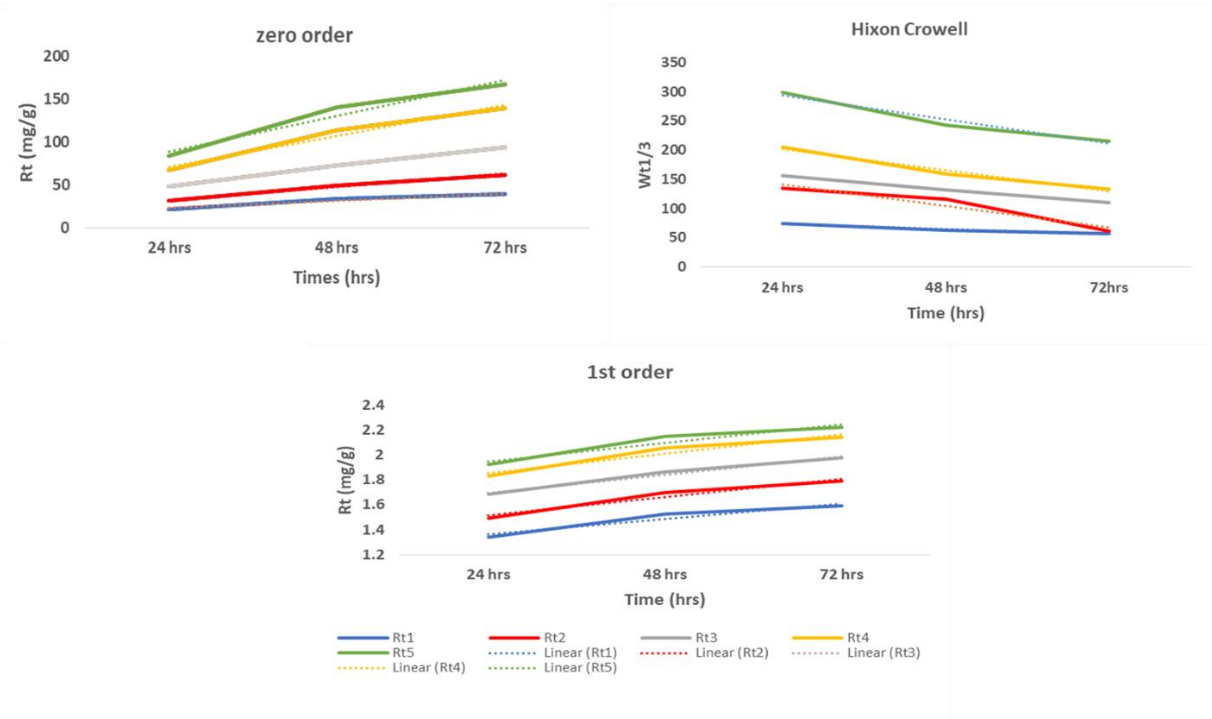


Fig. 8. Kinetic release models of varying doses (1g, 2g, 3g, 4g, 5g) for different contact times (Rt is release of K at time {24,48,72 hrs}; Wt is initial conc - cumulative release).

3.4 Pot study

Pot experiments for validating the effects of KBC-SRF (potassium slow release fertilizer made from biochar) on the growth of Lycopersicon were performed (Fig 9).

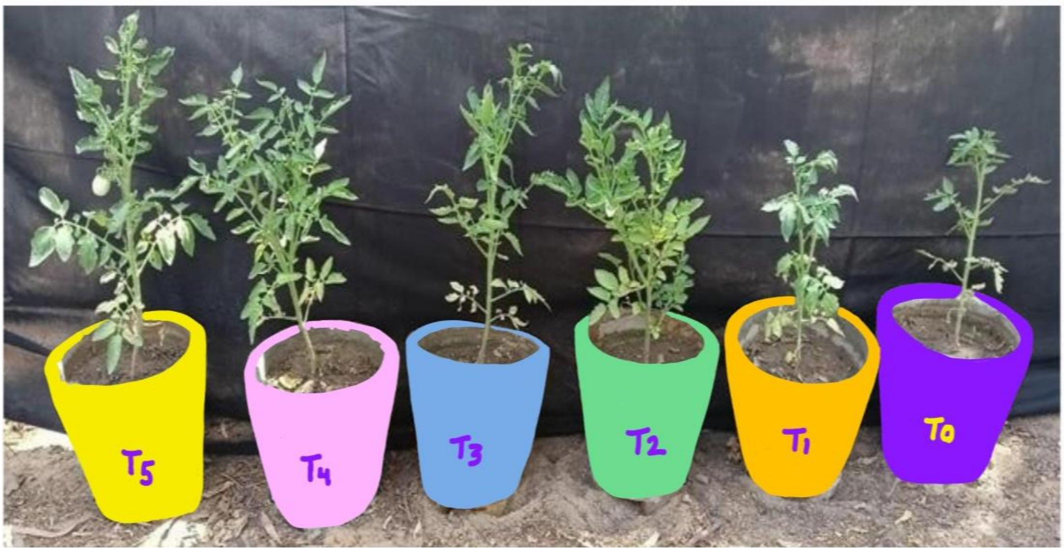


Fig. 9. *Lycopericon* plants under different treatment and control (T0:control; T1-T5 are treatments as mentioned in methods).

A significant (p<0.05) increase in shoot dry weight (g) and wet weight was observed in all treatments as compared to control (Fig. 10a,b). In shoot dry weight the effect of addition of BC and fertilizer was found significantly different (p<0.05) as compared to control. Highest fresh weight was observed in (T4 & T5) combination of BC and fertilizer, followed by BC (T3>T2), fertilizer (T1) and soil only (T0). But the difference was non-significant (p<0.05) between T4 & T5 as shown in Fig. 10a. In shoot wet weight there was steep increase from T0 to T1 to T2, then T2-T4 it was almost similar but had a difference between T2 & T3, T4 followed by an increment in T5 as shown in Fig. 10b. In comparison to T1 i.e. fertilizer only all other treatments were having a significant increase in weight. In shoot weight (dry & wet) BC with 3g dose outperformed among all.

A significant (p<0.05) increase in root dry weight (g) and wet weight was observed in all treatments as compared to control (Fig. 10c,d). In root dry weight the effect of addition of BC and fertilizer was found significantly different (p<0.05) as compared to control. Highest dry weight was observed in (T5) combination of BC (3g) and fertilizer, followed by BC (T4>T3=T2), fertilizer (T1) and soil only (T0). But the difference was non-significant (p<0.05) between T2, T3 & T5 as shown in Fig. 10d. In root wet weight there was steep increase from controls (T0=T1) to (T2<T3) to (T4=T5) as shown in Fig.10c. In root weight (dry & wet) BC with fertilizer outperformed among all.

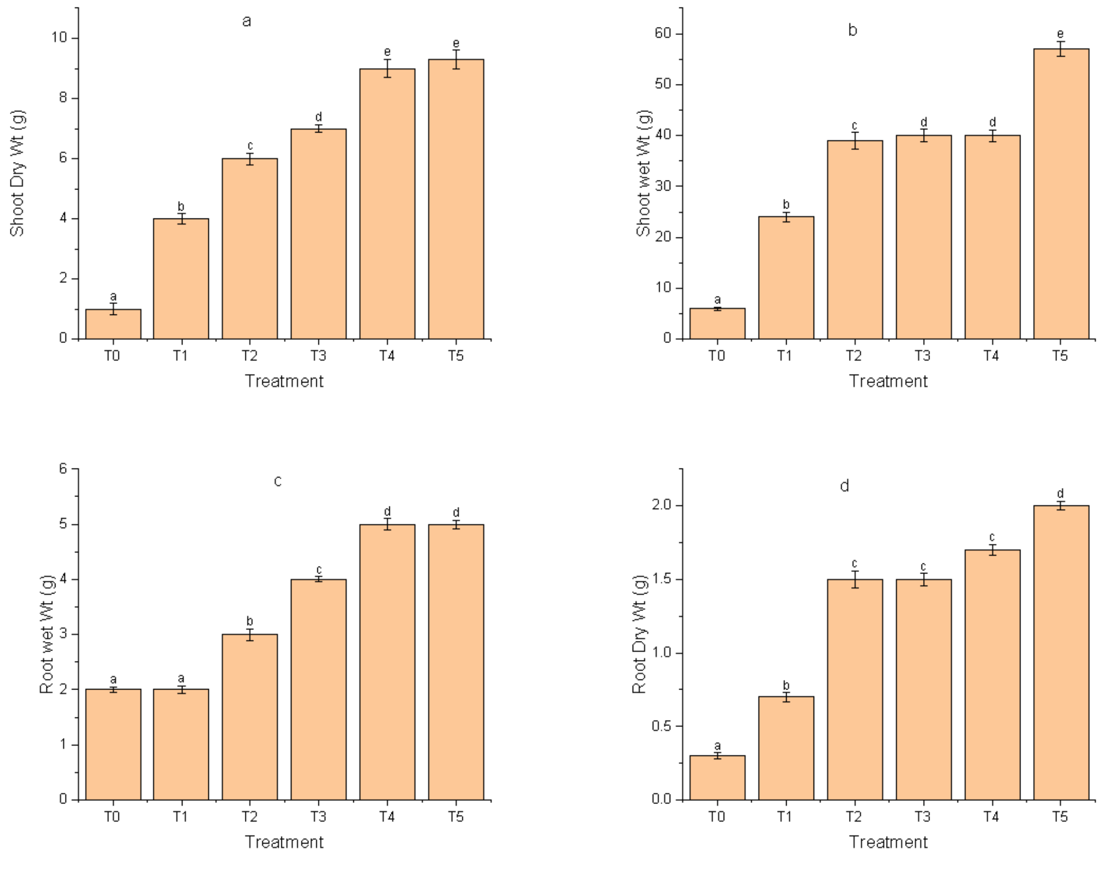


Fig. 10. Comparison of (a) shoot dry weight, (b) shoot wet weight (c) root wet weight and (d) root dry weight of control and respective treatments using ANOVA.

A significant (p<0.05) increase in shoot length (cm) was observed in trend as highest in (T5) followed by (T4) > (T3) > (T2) > (T1) (Fig. 11a). For root length (cm), a significant difference (p<0.05) was observed in the treatments as compared to control but not much among themselves. There was a great increase in root length from T0 to T1 but after that there was no observable increment. There was a significant difference between T0 & T2-T5; T1 & T3-T5; T2 & T4-T5. T4 & T5 showed no significant difference in root length (Fig. 11b).

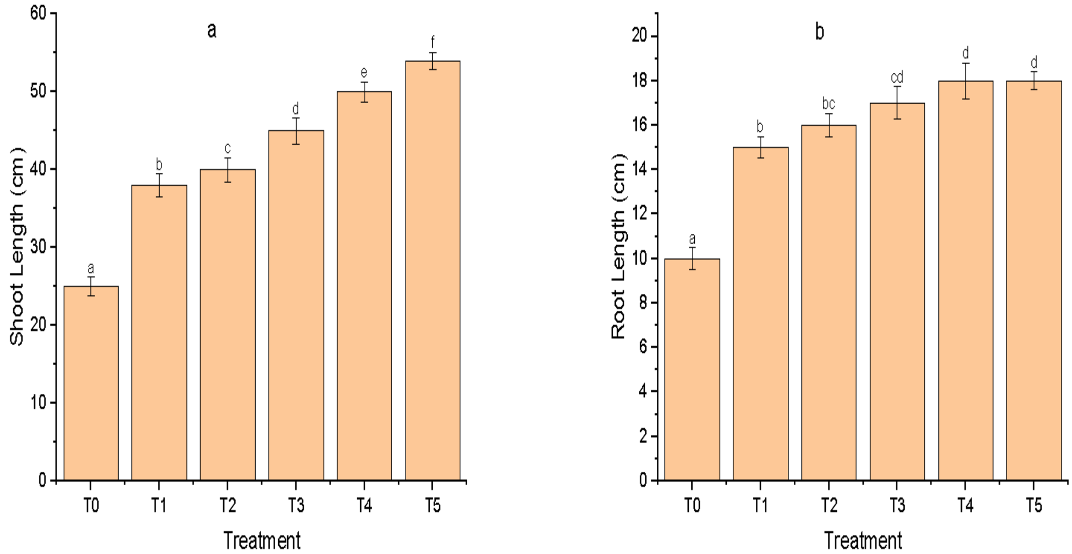


Fig. 11. Comparison of (a) shoot lengths, and (b) root lengths of control and respective treatments using ANOVA.

Plant height was estimated for all the treatments at an interval of one week for 4 consecutive weeks. All the treatments were significantly different (P<0.05) from control in all the weeks except T1 for first week. Treatment 5 showed the highest increase in the plant height as compared to other treatments. Incremental order of plant height was observed going from control to T5 for all the weeks (Fig. 12).

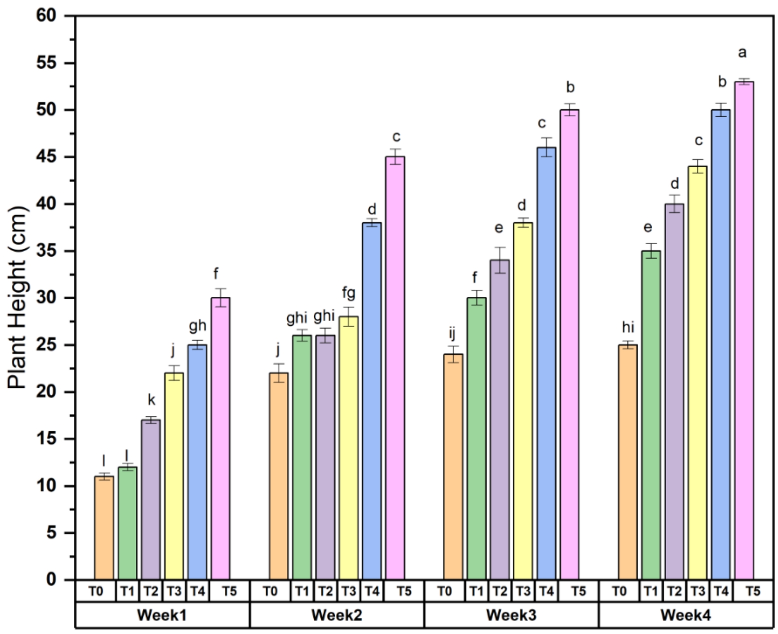


Fig.12. Effect of different treatments on Tomato plant height.

Leaf counts were also observed for all the treatments at an interval of one week for 4 consecutive weeks. There was significant difference (P<0.05) of control in all the weeks except T1for first week and 2nd week and T2 for first week only. Treatment 5 showed the highest increase in leaf count as compared to other treatments (Fig. 13).

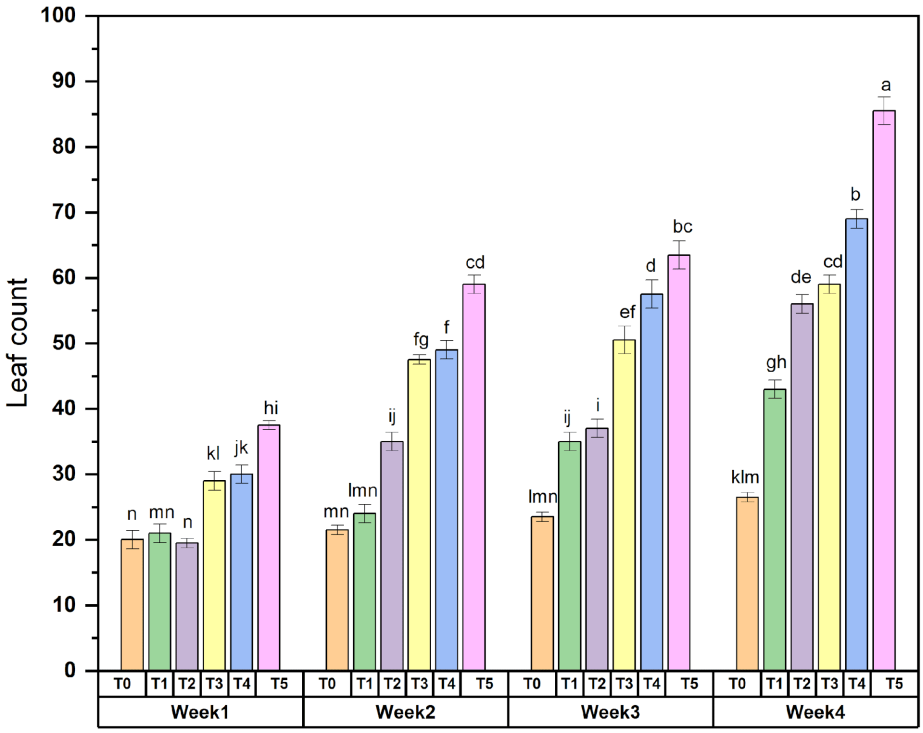


Fig.13.Effect of different treatments on Tomato plant leaf count.

4. Discussion

The BC sample displayed the highest negative charge, whereas the impregnated BC sample displayed the lowest negative charge. The carbonisation process and the presence of additional surface functional groups, such as carboxyl and hydroxyl groups, resulted in rise in negative charge from the raw material to the BC. In impregnated BC, the charge was greatly reduced because of the presence of positively charged potassium ions which were absorbed onto the surface. Based on UV-solid analysis, the absorbance showed an increase from K loaded BC (KBC) to other three, with a high increase observed in raw material followed by a gradual increase in BC and desorbed KBC. BC exhibits a larger absorbance peak as a result of its extensive surface area and available bonding sites in comparison with raw. The absorption peak of impregnated BC is minimised because of the introduction of positively charged K+ salt to the bonding sites on the BC's surface along with that the highest absorbance was observed in desorbed sample. FTIR spectroscopy is commonly used to analyse the mineralogy and chemical functional groups, including aromatic and aliphatic groups, in BC. This technique has been extensively studied by various researchers (Mukome et al., 2013; Nanda et al., 2013; Zhou et al., 2013; Usman et al., 2015; Inyang et al., 2016). FTIR analysis revealed that the BC exhibited the most prominent peaks at 1599 cm^{-1}, which can be attributed to the stretching of the C=C bonds in the Amine group. Additionally, the impregnated BC displayed both major and minor peaks at 1115cm^{-1} and 1614 cm^{-1}, respectively, indicating the presence of unsaturated compounds with C=O and C=C bonds, as well as the stretching of C-C bonds. FTIR analysis also depicted the chemical composition of the cellulose material. Upon adsorption, the spectra corresponding to the functional groups, such as the amine group, benzene ring, and unsaturated molecules, exhibited significant changes when BC was loaded with K^+ salt. BC samples exhibited a low silica concentration, as indicated by the peak at 982 cm^{-1} and further validated by the EDX data.

The examination of the surface morphology of *Gossypium* stalk BC, as depicted in Fig. 2E1 and 2E2, indicated that it possessed a very porous structure. Prior to adsorption, the *Gossypium* stalk BC had a smooth surface and displayed elongated oval-shaped holes that were evenly distributed. However, upon adsorption, the pores became obstructed by potassium ions, resulting in a highly rough surface and again it was seen smooth after desorption. Based on the study of the surface morphology, it can be inferred that the *Gossypium* stalk BC surface has undergone adsorption of potassium ions. This indicates that the BC can serve as an effective adsorbent for slow-release fertiliser. Fig. 2D depicted the energy levels on the x-axis using kiloelectron volts (keV), ranging from 0 to 7 keV. Each peak corresponds to the unique energy of X-rays emitted by different elements. The intensity of detected X-rays on the y-axis indicates the existence and relative abundance of each element. The peak with the highest energy level is around 0.27 kiloelectron volts (keV), suggesting the presence of carbon.

The presence of oxygen on the surface of BC following pyrolysis is shown by a distinct peak at around 0.52 keV, which is attributed to residual organic molecules and functional groups. The presence of minerals in the early biomass causes silicon to exhibit a lower peak at around 2.34 keV. The presence of potassium ions in the BC sample is shown by a strong peak at 3.31 keV. The EDX analysis indicated that potassium ions were adsorbed onto the surface of *Gossypium* stalk BC.

In case of adsorption study with increase in biochar dose, increase in the adsorption was observed (Cuong et al., 2019; Begum et al., 2021; Kaya et al., 2021) which concluded that increase in pH with increase in BC doses has opposite effect on per unit adsorption capacity of BC. The potential explanation might be that under a low dosage, a multitude of K^+ ions for a limited number of adsorption sites, leading to a high qe value and a low adsorption. As the amount of BC used increases, the number of adsorption sites also increases progressively, leading to a temporary increase in adsorption. As the dose continues to increase, the concentration of K^+ in the solution remains constant, resulting in a gradual growth of adsorption. Therefore, the most effective dosage of BC was determined to be 5 g/L. Under these circumstances, the highest qe (95.5 mg/g) was achieved by using the smallest quantity of BC i.e. 1g. The observed influence of contact time (from 0.5 to 2 hours) on K^+ ion adsorption was positive as there were a lot of accessible adsorption sites on the surface of BC during the first fast adsorption phase. When potassium ions bind to these sites (qe), the adsorption percentage and capacity was greatly enhanced because of its large surface area and porous structure, biochar allows K^+ ions to migrate from solutions to its surface. When the contact period goes above 2 hours, the performance starts to drop because the majority of the conveniently accessible adsorption sites are saturated. Desorption dynamics may begin when ions detach from the biochar surface when it was in equilibrium with the solution, as shown by a reduction in (qe) and adsorption %. Then in 24-48 hours the system achieved a state of dynamic equilibrium.

The isotherm model Harkin-Jura describe the adsorption characteristics for the heterogeneous surface with R^2 value of 0.92483. The best fit model in the current study was Redlich with R^2 value of 0.99002. In the Redlich model, the numerator derives from the Langmuir isotherm approaches the Henry region at infinite dilution. This isotherm model exhibits a linear relationship with concentration in the numerator and an exponential function in the denominator, collectively representing adsorption equilibrium across a broad spectrum of adsorbate concentrations, applicable in both homogeneous and heterogeneous systems due to its versatility (Sips, 1948; Gimbert et.al., 2008). So Redlich model along with Harkin-Jura revealed that there was multilayer adsorption on heterogeneous surface.

SEM analysis (Fig. S1) of KBC revealed a higher abundance of white crystals compared to the original BC. After K^+ adsorption, the surface of BC exhibits a rough texture and the pores became obstructed. This suggested that the potassium ions had penetrated the pores of the BC after traversing the interface between the solution and the BC. This aligns with the findings of adsorption isotherms, indicating that there are several controlling factors that impact the process of adsorption. The elemental composition and distribution were subsequently examined using Energy Dispersive X-ray Spectroscopy (EDS), revealing the existence of potassium (K) at a weight percentage of 13%. These observations suggest that precipitation including potassium takes place during the adsorption phase. The results were corroborated by FTIR spectroscopy, which revealed the emergence of new absorption peaks at 1115cm^{-1} and 1614 cm^{-1} in the BC (KBC) following adsorption (Fig. 2C).

In Kinetic release models it was found that all three models showed highest R^2 values for 3g dose (2hrs) which were 0.9987, 0.9811, and 0.9978 (Zero order, First order and Hixon-Crowell) for K release from KBC among three leaching. This study falls under the criteria of SRF given by Wei et al. (2020) according to which SRF should not release >15% in 1st day and should release <85% in 28 days and this study the minimum release on 1st day was ~19% and maximum in three days was ~50%. The findings demonstrate that the potassium-related species were desorbed from KBC. Simultaneously, the pores on the BC surface expanded, facilitating the movement of nutrients from the surface into the water.

A significant ($p<0.05$) increase in dry and wet weight of shoot and root was observed in all treatments as compared to control. Highest increase was observed in (T4 & T5) combination of BC and fertilizer. Plant height and leaf counts were estimated for all the treatments at an interval of one week for 4 consecutive weeks. T5 showed the highest increase in the plant height and leaf counts as compared to other treatments for all the weeks. This proved that the slow-release fertilizer made from *Gossypium* stalk BC impregnated with potassium outperformed among all treatments.

5. Conclusion and Future Perspective

A slow-release potassium fertilizer using biochar was developed in current study, and its nutrient release characteristics were compared to those of traditional chemical fertilizers. An important component of BC for nutrient interaction and retention is its negative surface charge, which was verified by zeta potential. SEM analysis showed that it has a smooth, porous structure with oval-shaped holes, suggesting that it has a large surface area and could be loaded with nutrients. The successful impregnation process was validated by the EDX examination, which revealed a significant presence of potassium. The FTIR analysis found functional groups that could be involved in potassium adsorption and retention; the BET analysis compared the surface areas of BC and KBC showed that the latter had a slightly lower surface area but no discernible effect on the former's adsorption capacity. As the Redlich isotherm model gave the best fit ($R^2 = 0.99002$), it was concluded that the adsorption follows complex multilayer and heterogeneous surface processes. Column study verified the slow-release of KBC. Pot experiment supported the use of biochar- based slow-release-fertilizer for the growth and development of potato. An eco-friendly and cost-effective substitute for traditional potassium fertilizers, *Gossypium* stalk BC is an innovative way to repurpose agricultural residue. Additionally, the fertilizer embedded in the biochar doesn’t contain any harmful coating materials that could degrade soil quality. Moreover, the biochar particles contribute organic carbon to the soil, providing environmental benefits alongside economic advantages. Findings of current study may be utilized to synthesize a novel biochar-based slow-release fertilizer to decrease nutrient loss and to gain practical advantage in field research.

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