



Exploring the Sodicity Reclamation Efficiency of Coalchar

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ABSTRACT

This study aimed to assess the impact of Coalchar application alone and in combination with gypsum, organic amendments like vermicompost (VC) and pressmud compost (PMC) on soil chemical properties, particularly pH, electrical conductivity (EC) and exchangeable sodium percentage (ESP) reduction in sodic soil. Here various treatments including: T₁- absolute control (no amendment), T₂-VC alone @ 2t ha⁻¹, T₃- PMC alone @ 3t ha⁻¹, T₄-gypsum alone @ 50% gypsum requirement (GR), T₅- Coalchar alone @ 3t ha⁻¹, T₆- Coalchar +VC (1:1) @ 3t ha⁻¹, T₇- Coalchar + PMC (1:1 mixture) @ 3t ha⁻¹, T₈- Coalchar + gypsum (1:1mixture) @ 3 t ha⁻¹ amendments were experimented in incubation study. Reclamation efficiency was evaluated based on the reduction in soil exchangeable sodium percent (ESP). Among the different treatments, the Coalchar + Gypsum (1:1) (based on Ca equivalence) combination showed the most significant reduction in ESP from 31.8 to 16.5% and soil pH from 8.92 to 7.92 over 30 days of incubation, and it was on par with the application of coalchar alone @ 3 t ha⁻¹. Coalchar + Gypsum (1:1) treatment differed significantly from other treatments in reclamation parameters, with a reclamation efficiency of 50% ESP reduction over the absolute control (p< 0.05). The results demonstrate that coalchar alone or in combination with gypsum (1:1), can effectively reclaim sodic soils. These results provide that the field scale study be initiative for sodicity reclamation and in the legitimacy to the use of coalchar in sodic soil management as a partially viable and sustainable alternative to gypsum.

Keywords: Coalchar, Gypsum, Sodic soil, Sodicity reclamation, Exchangeable sodium percent

Introduction

Indian refractory enterprises have become leaders in worldwide innovation by embracing state-of-the-art technologies in the constantly evolving refractory industry. This commitment to innovation increases the durability and performance of refractory products and significantly reduces manufacturing costs, allowing Indian firms to compete globally. Instead of importing refractory bricks for insulating the inner walls of refractories from foreign nations, it is recommended that locally available resources be used in their production. Coal, the “largest source of solid fuel in the world”, sparked a revolution by enabling the development of general manufacturing, iron and steel production, power generation (such as steam), railroads, and other industries (Finkelman *et al.*, 2021). Since the

enormous demand for coal as fuel, mining, and industrial operations it produce a large amount of waste/ residue to the tune of 3.4 billion tonnes of waste annually by 2050, according to a conservative statistical projection. Coal combustion residues are pyrolyzed or sintered at high temperatures (usually above 1000°C) to produce coalchar. One of the most important environmental impacts of these coal-fired refractory plants is the safe disposal of final by-product *i.e* coalchar (Vasic *et al.*, 2021). Because of its advantageous qualities as a soil conservant in semiarid agroecosystems, the use of coalchar yielded from refractory industries has attracted interest as a possible soil amendment in the place of gypsum for sodic soil amelioration.

Sodic soils are characterized by excessive exchangeable sodium on its solution and

exchangeable phases, exhibit poor structure, low permeability, and reduced nutrient availability, ultimately resulting in limited crop growth and productivity (Basak *et al.*, 2022; Sundha *et al.*, 2017). Reclaiming sodic soils is critical for improving soil health and enhancing sustainable agricultural output. Conventional reclamation approaches commonly involve the application of gypsum, which supplies calcium to replace sodium on the cation exchange sites. However, limitations such as low availability of mineral gypsum, and increasing demand of gypsum in other industrial section increase the research interest to evaluate alternative sodicity reclaimant materials (Sundha *et al.*, 2025). Therefore, particularly those derived from industrial byproducts *i.e* Coalchar. Therefore, the present experiment was conducted with the objective of the evaluation of reclamation efficiency of coalchar for soil sodicity reclamation.

Materials and Methods

Materials collection

The coalchar was obtained from RHI Magnesita India Limited Dalmia Puram, Tiruchirappalli, Tamil Nadu.

Physicochemical analysis of coalchar

The physicochemical parameters like particle size, bulk density (BD), particle density (PD), percent pore space, water holding capacity (WHC), pH, electrical conductivity (EC), total N, P, K, Ca and Mg, organic carbon (OC), free CaCO₃ and

micronutrients (Fe, Mn, Zn, and Cu) were analyzed by adopted standard procedures (Table 1).

Incubation experiment

To evaluate the potential of coalchar on sodic soil reclamation, an incubation study was conducted in Department of Soil Science and Agricultural Chemistry, ADAC&RI, Tiruchirappalli, for one month period at room temperature and maintain moisture percent of 60 percent in factorial completely randomized design (FCRD) design with three number of replication with following treatment T₁ – absolute control (no amendment); T₂ – Vermicompost alone (VC) @ 2 t ha⁻¹; T₃ – Pressmud compost (PMC) @ 3 t ha⁻¹; T₄ – Gypsum @ 50% GR (based on Ca equivalence); T₅ – Coalchar alone @ 3 t ha⁻¹; T₆ – Coalchar + VC (1:1) @ 3 t ha⁻¹; T₇ – Coalchar + PMC (1:1) @ 3 t ha⁻¹; T₈ – Gypsum + Coalchar (1:1 mixture) @ 3 t ha⁻¹. A set of defined treatments Coalchar alone or in combination with gypsum 50% GR and organic amendments, was applied to assess changes in soil chemical properties, particularly in reduction of pH, EC and exchangeable sodium percent (ESP). The soil samples were collected and analyzed throughout the incubation period, at periodic interval of at the starting of experiment, 7th, 14th and 28th days after incubation (DAI). The parameters analyzed were soil pH, EC and ESP, which are known to be the key indicators of assessment of soil sodicity (Richard, 1954). The initial characteristics of experimental soil like pH,

Table 1. Methods adopted for physicochemical characterization

Sl. no	Parameters	Methods	References
A. Physical Properties			
1.	Particle size	Particle size analyzer	Jackson (1973)
2.	Bulk density	Cylinder method	Gupta and Dakshinamurthi (1981)
3.	Water holding capacity	Keen – Raczkowski box method	Keen- Raczkowski (1921)
B. Physio-chemical properties			
1.	pH	Coalchar: water (1:2.5) suspension using pH meter	Jackson (1973)
2.	Electrical Conductivity (EC)	Coal char: water (1:2.5) suspension using wheatstone bridge	Jackson (1973)
C. Chemical properties			
1.	Organic carbon	Chromic acid wet digestion	Walkley and Black (1934)
2.	Free CaCO ₃	Rapid titration method	Piper (1966)
3.	Total Ca and Mg	Triacid digestion and Versenate method	Jackson (1983)

EC, exchangeable sodium percentage (ESP) was measured using standard procedures as given in Table 1.

Results and Discussion

Characterization of coalchar

In terms of appearance, the coalchar was dark black and odourless, which is typical of carbonaceous materials made by carefully regulated heat treatment (Table 2). A porous structure of Coalchar was indicated by its bulk density (BD), which was significantly lower at 0.91 Mg m⁻³ than the particle density, which was measured at 2.0 Mg m⁻³. The compactness of soil lower down when less compacted material is used for soil reclamation and this was similar to Thapa *et al.* (2024). Its light and porous structure, which might encourage aeration and water retention when applied to sodic soil and is further confirmed by the computed pore space of 54.5%. With an average particle size of 0.2 mm, the soil matrix may be mixed uniformly and enable the easy application. With a low moisture content of 3.2%, the self stability was satisfactory. Its remarkable water-holding capacity of 22.5% demonstrated its potential to keep moisture, which is an essential characteristic for use in coarse-textured or water-deficient soils. The total organic carbon (TOC) was 40.4 g kg⁻¹, which increased microbial activity and added to soil organic matter. With a pH of 8.51, the coalchar was in the alkaline range, which,

when applied in the right proportions, may help to neutralize or buffer acidic/ sodic soils. When applied in small amounts, the electrical conductivity (EC) of 1.14 dS m⁻¹ indicates a moderate quantity of soluble salts, which is within the permitted range for most crops (Table 2). The high calcium content (4.80%), significant quantities of magnesium (2.16%), and free calcium carbonate (3.2%) are particularly may take the role of exchange with sodium on the soil exchange complex, these findings point to a Ca supplementation and promising use in sodic soil reclamation as described in earlier study Yang *et al.* (2019). Therefore, coalchar's physical and chemical characteristics showed a wide range of qualities that suggest its potential as a soil amendment, especially for enhancing degraded or sodic soils.

Initial characteristics of experimental soil

Prior to the application of treatments, the experimental soil was thoroughly analysed for its physical and chemical properties (Table 3). The results indicated that the soil was alkali/ sodic in reaction, with a pH of 9.04, which is above the neutral range and indicative of a sodic condition. Although the salt content was not very high, the EC (0.97 ds m⁻¹) indicated that it was getting close to the point where crop performance would be restricted in sensitive situations (Table 3). A measurement of 34% for the exchangeable sodium percentage (ESP) indicated that the soil was sodic and that indicates the need of remedial amendments were necessary. With an exchangeable sodium level of 6.13 cmol_(p+) kg⁻¹ and exchangeable sodium percent 34, the soil was

Table 2. Characterization of coalchar

Physical/chemical parameter	Coalchar
Colour	Dark black
Odour	Odourless
Particle density (Mg m ⁻³)	2.0
Bulk density (Mg m ⁻³)	0.91
Percent pore space (%)	54.54
Particle size (mm)	0.2
Moisture content (%)	3.2
Water holding capacity (%)	22.52
Total organic carbon (g Kg ⁻¹)	40.4
pH	8.51
Electrical conductivity (dS m ⁻¹)	1.14
Total Ca (%)	4.80
Total Mg (%)	2.16
Free CaCO ₃ (%)	3.2

Table 3. Initial characteristics of experimental sodic soil

Particulars	Soil
pH _{1:2}	9.04
EC _{1:2} (dS m ⁻¹)	0.97
Exchangeable sodium percentage	34
Exch Na [cmol _(p+) kg ⁻¹]	6.13
Exch Ca [cmol _(p+) kg ⁻¹]	15.68
Exch Mg [cmol _(p+) kg ⁻¹]	0.68
CEC	
[cmol _(p+) kg ⁻¹]	18.50
Walkley Black organic C (g Kg ⁻¹)	2.2

further classified as sodic. The levels of magnesium [$0.68 \text{ cmol}_{(p+)}\text{kg}^{-1}$] and exchange-able calcium [$15.68 \text{ cmol}_{(p+)}\text{kg}^{-1}$] on the other hand, indicate a relative imbalance in the cation composition of the soil. The modest capacity of soil to hold and provide cations for plants was indicated by the cation exchange capacity (CEC), which was measured at $18.50 \text{ cmol}_{(p+)}\text{kg}^{-1}$. The soil's extremely low organic carbon content, at only 2.2 g kg^{-1} , reflected poor organic matter status and limited microbial activity. Overall, the preliminary analysis showed that the soil had low organic carbon, and sodicity, which required the application of corrective measures to enhance its fertility, structure, and appropriateness for plant development.

Functional groups identified in Coalchar and gypsum for sodic soil reclamation

The functional groups identified in the Coalchar and gypsum that are responsible for the reclamation of sodic soil (Table 4). In addition to the significant portion of calcium from gypsum (23%) and Coalchar (2.11%), the alkyl halide group of gypsum and nitrile, carboxylic acid group of Coalchar are highly responsible functional groups identified for sodic soil reclamation either through substitution/elimination reactions.

The FT-IR spectrum of Coalchar revealed distinct absorption bands at 2219.5 cm^{-1} and 1427.2 cm^{-1} represents $\text{Ca}\equiv\text{N}$ stretching and O-H bending, confirming the presence of nitrile compounds and carboxylic acids (Fig. 1). The FT-IR spectral analysis of the gypsum sample revealed sharp and intense peak located at 660.3 cm^{-1}

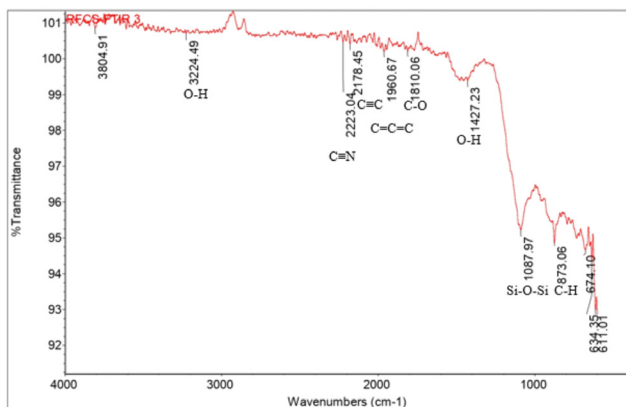


Fig. 1 Functional groups of Coalchar (Nitrile and Carboxylic acid)

Table 4. Functional groups identified in Coalchar, gypsum and coalchar + gypsum (1:1 mixture)

Peak (cm^{-1})	Coalchar			Gypsum			Coalchar + Gypsum (1:1 Mixture)			
	Intensities	Group	Vibration	Compound class	Peak (cm^{-1})	Intensity	Compound class	Peak (cm^{-1})	Intensity	Class/Compound type
3224	Strong	O-H	Stretching	Alcohol	3391.16	Medium	Amine	2982.40	Strong, broad	Carbonyl acid
2223.04	Weak	Ca \equiv N	Stretching	Nitrile	2158.49	Medium	Alkyne	2159.10	Medium	Alkyne
2178.45	Weak	Ca \equiv C	Stretching	Alkyne	1682.46	Strong	Carbonyl compound	2219.47	Medium	Nitrile
1960.67	Medium	C=C=C	Stretching	Allene	660.26	Strong	Alkyl halide	2030.72	-	Transition metal carbonyl
1810.06	Strong	C=O	Stretching	Acidhalide				1031.38	-	Primary amine
1427.23	Medium	O-H	Bending	Carboxylic acid				797.22,	Strong	Alkyl halide
1087.97	Strong	Si-O-Si	Stretching	Organic siloxane or silicone				778.98,		
873.06	Strong	C-H	Bending	1,3-disubstituted				693.87		
674.10	Strong	C-Br	Stretching	Halo compound						

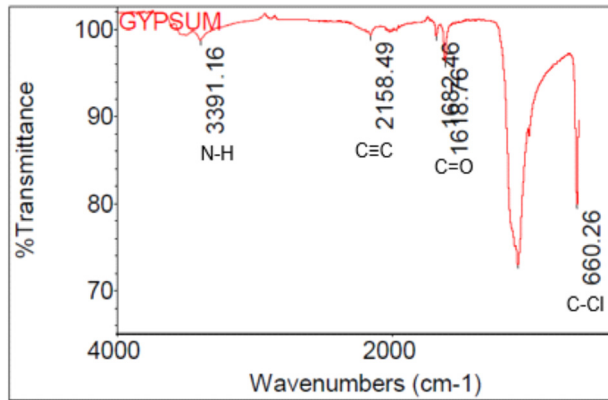


Fig. 2 Functional groups of Gypsum (Alkyl halide)

corresponds to the bending vibration of C–Cl bonds, which indicates alkyl halide compounds (Fig. 2). Furthermore, the FTIR spectra clearly showed the both functional groups when they are mixed at a ratio 1:1 in T₈.

The FTIR spectrum for unamended sodic soil clearly indicated the absence of nitrile and alkyl halide group, whereas the Coalchar as an tested amendment for gypsum having nitrile and carboxylic acid functional groups which may play a critical role in the reclamation of sodic soils by acidulating effect. This acidulation effect of nitrile groups could facilitate the supply of proton (H₂O⁺) and neutralize carbonates of bicarbonates and the replacement of exchangeable sodium by more desirable cations, thereby enhancing the cation exchange process and promoting soil structural improvement. It also acts as substrates and signaling molecules for certain nitrile degrading bacteria like *Rhodococcus*, *Pseudomonas* spp, these microbes can hydrolyze the nitrile compounds into ammonia and organic acid which in turn indirectly aiding sodium displacement and pH moderation.

However, the existing amendment gypsum was found to have the high concentration of calcium in addition to the functional group of alkyl halide which is known to replace the exchangeable sodium from the sodic soil. Since the dissolution rate of gypsum is very low the nitrile and carboxylic acid group carrier *i.e* the Coalchar, when they are blended in 1:1 ratio, the polar nitrile groups slowly hydrolyze to produce amides and then carboxylic acids in alkaline environments, releasing protons (H₃O⁺) which is

responsible for the reduction of soil pH. When it is paired with calcium-rich amendments, this slow acidification can encourage the removal of Na⁺ from the cation exchange complex. Nitrile and carboxylic acid groups suggest a potential acidulating effect, While the alkyl halide (C–Cl) groups possibly aid in displacing Na⁺ through halide interactions. But the combination of alkyl halides and nitrile groups can form a specific site in the soil matrix where ionic interactions are enhanced. These interactions create a more reactive environment, leading to favourable soil conditions for storing and releasing nutrients that plants need to absorb (Amulothu *et al.*, 2023). Therefore, the unique presence of these groups (nitrile, carboxylic acid and alkyl halide) in T₈ [Coalchar + Gypsum (1:1) @3 t ha⁻¹] points to a synergistic effect of the applied amendments, supporting the observed improvements in soil properties and highlighting their relevance in the reclamation of sodic soils (Fig. 3). This was in line with the findings of Enev *et al.* (2018) who illustrated the variations in functional groups, such as carbonyl and hydroxyl, contribute positively towards nutrient cycling and soil amendments' effectiveness. This underscores the potential of the functional groups in influencing remediation efficacy of the amendment. Hu *et al.* (2024) indicated that these groups can enhance cation exchange capacity and improve soil chemical properties, contributing to increase nutrient availability.

This study revealed that Coalchar as an alternate source of amendment for gypsum could

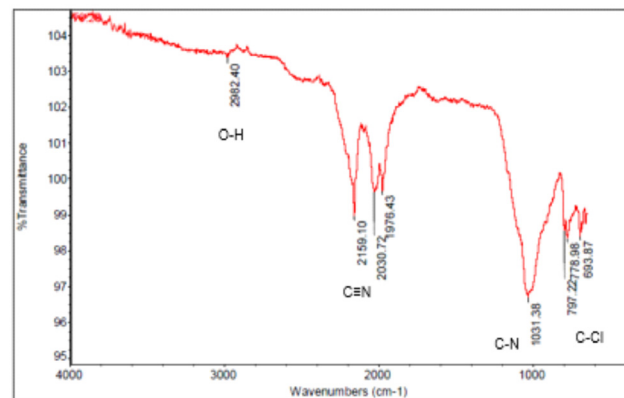


Fig. 3 Functional groups of Coalchar and Gypsum (1:1 Mixture) amended treatment (Nitrile and Alkyl halide)

Table 5. Reclamation efficiency of Coalchar along with organic amendments incubated sodic soil

Treatments	pH						EC (dS m ⁻¹)						ESP (%)											
	0 th		7 th		14 th		21 st		28 th		Mean		0 th		7 th		14 th		21 st		28 th		Mean	
	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI	DAI
T ₁ : Absolute control (No amendment)	9.04	8.96	8.84	8.78	8.53	8.81	0.98	0.89	0.83	0.78	0.65	0.83	33.40	30.78	29.89	28.76	26.91	30.00						
T ₂ : VC alone @ 3t ha ⁻¹	8.96	8.74	8.62	8.48	7.99	8.57	0.91	0.86	0.74	0.65	0.52	0.74	32.31	30.43	24.43	21.56	19.73	25.72						
T ₃ : PMC alone@3t ha ⁻¹	8.98	8.76	8.66	8.42	8.01	8.58	0.96	0.88	0.75	0.68	0.56	0.77	32.21	28.86	23.29	21.46	19.24	24.92						
T ₄ : Gypsum @ 50% GR	8.94	8.62	8.42	8.27	7.94	8.42	0.92	0.81	0.70	0.61	0.47	0.70	31.89	27.11	22	19.14	16.86	23.50						
T ₅ : Coalchar alone @ 3t ha ⁻¹	9.01	8.78	8.69	8.43	8.04	8.58	0.94	0.87	0.75	0.69	0.53	0.76	32.59	31.49	26.27	21.24	18.22	26.06						
T ₆ : Coalchar +VC (1:1) @ 3t ha ⁻¹	8.95	8.69	8.54	8.29	7.96	8.46	0.92	0.82	0.76	0.63	0.51	0.73	32.27	28.27	22.75	20.65	18.49	24.53						
T ₇ : RFCS-coalchar + PMC (1:1) @3t ha ⁻¹	8.96	8.72	8.59	8.36	7.98	8.51	0.94	0.84	0.72	0.64	0.52	0.73	32.00	22.21	22.21	20.16	17.35	22.79						
T ₈ : RFCS-coalchar+Gypsum(1:1) @3t ha ⁻¹	8.92	8.59	8.37	8.22	7.92	8.40	0.91	0.74	0.68	0.56	0.46	0.67	31.83	27.07	21.72	18.86	16.49	23.22						
Mean	8.97	8.72	8.60	8.40	8.01	8.40	0.94	0.84	0.74	0.66	0.53	0.67	32.31	28.28	24.23	21.48	19.16							
SE(m)	0.127						0.011.0						0.38											
CV	2.58						2.61						2.59											

be well utilized during the scarce period of gypsum availability for sodic soil reclamation. The functional groups like nitrile and carboxylic acid identified in Coalchar was found to reduce the sodic soil pH from 9.01 to 8.04, EC from 0.94 to 0.53 dS m⁻¹, exchangeable sodium percent (ESP) from 32.6 to 18.2% (nearly 50% ESP reduction) at the end of four weeks incubation. This was at par with application of Coalchar along with gypsum (1:1 mixture). This study concluded that during the scarce period of gypsum availability the refractory derived Coalchar waste products could be well utilized as an alternate source of amendment for sodic soil amelioration, Application of Coalchar @ 3t ha⁻¹ (based 50%GR) was found to be a good amendment for fine, calcareous, isohyperthermic very deep Ustropepts sodic soils of Alathur series having pH 9.01 and ESP 32.6%.

Reclamation efficiency of coalchar for sodic soil

The reclamation of sodic soils is a significant concern for agricultural productivity, particularly when managing pH, electrical conductivity (EC), and exchangeable sodium percentage (ESP) analyzed for four-week incubation period (Table 5). According to this study, gypsum and Coalchar are two amendments that can positively change these soil properties. Interestingly, the treatments using Coalchar and gypsum @ 50% GR (1:1) showed significant decreases in these parameters which was at par with Coalchar @ 3 t ha⁻¹ application, throughout the incubation period *i.e.* a decrease in pH to 7.92, EC to 0.46 dS m⁻¹, and ESP to 16.49% by the end of the experiment (28 days after incubation) and it was at par with Coalchar alone application @ 3t ha⁻¹. These findings highlight the effectiveness of Coalchar application for sodic soil (pH 9.04, EC 0.97 ds m⁻¹ and ESP 34%) amelioration in the place of gypsum a traditional ameliorant and the increased amelioration potential of Coalchar was noticed when it is applied in combination with gypsum @ 50% GR (Ahmed *et al.*, 2016). The high initial pH of soil, which is most likely generated by Na₂CO₃, can be lowered by adding and dissolving gypsum, a source of Ca²⁺ that precipitates as CaCO₃ and Ca(HCO₃)₂ (Table 5). In addition to producing protons (H₃O⁺) for further reductions,

the addition of coalchar will instantly lower the pH of the soil (Foronda and Colinet, 2022). Coalchar have the capacity to enhance soil structure and encourage microbial activity which is crucial for reclaiming sodic soil conditions was similar to earlier study Cucci *et al.* (2012) and Zhang *et al.* (2023). Furthermore, the synergistic effects of mixing gypsum with Coalchar are consistent with other research that highlights the advantages of combining inorganic and organic amendments as reported by Khalifa (2022). Effective sodic soil management requires the use of amendments, as evidenced by the increased reclamation impact seen in the treatment T₈ [Coalchar + gypsum @50% GR (1:1 mixture) compared to the absolute control (T₁)] (Shi *et al.*, 2021; Ahmad *et al.*, 2016). In order to neutralize alkalinity, lessen the impact of sodium adsorption ratio of soil water saturation paste extract (SAR_e), and replace excess Na⁺ in the cation exchange complex, external calcium (Ca²⁺) or CaCO₃ mobilizer is often used in sodic soils as reported in the earlier study (Minhas *et al.* (2019; Sundha *et al.*, 2020, 2018). If left in the soil, the displaced Na⁺ and extra soluble salts can be leached from the plough layer by irrigation water. Though coal is in alkaline pH (8.51), the observed decrease in soil pH was due to the dilution effect of adding Coalchar, which has a nitrile compound known to supply hydronium ions to soil that might have reduced the soil pH (Panday *et al.*, 2020).

Conclusion

This study demonstrates the possibility of using Coalchar alone or combination with gypsum for alternate amendment to successful sodic soil reclamation with a significant amount of exchangeable sodium percent reduction. Hence, refractory-derived Coalchar waste products can be tested for field trial to capture field scale performance and work out its suitable substitution or partial replacement for gypsum in sodic soil during the scarce period of gypsum availability for sodic soil reclamation.

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Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

Authors' Contributions

All authors have made substantial contributions to the conception, design, analysis, and interpretation of data for the work.

Consent

Not applicable as no participants were involved.

Ethical approval

Not applicable

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