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Insights into the impact of amendment effect on aggregate stability and organic carbon sequestration in bauxite residues

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Bauxite residue is a large-scale solid waste that is difficult to dispose of owing due to its poor physical properties, weak aggregate stability, and low organic carbon content. Ecological engineering is a unique strategy to realize soil formation and reclamation of bauxite residue. In this study, the effects of incorporating ferric sulfate (FS) and corn straw (CS) on aggregate variation, carbon sequestration, and ryegrass growth in bauxite residue were systematically investigated. The results showed that FS and CS treatments easily facilitated the transformation of bauxite residue aggregates from microaggregates to macroaggregates and raised the MWD value and average particle size of bauxite residue aggregates. Compared with the control group (CK), the average particle sizes of bauxite residue aggregates increased from ~102 nm to ~167 nm upon FS treatment and to ~250 nm upon CS treatment. Upon FS and CS treatments, the aggregate-associated organic carbon content increased in the 2–1 mm and 1–0.25 mm bauxite residue aggregates and decreased in the 0.25–0.05 mm and <0.05 mm bauxite residue aggregates. Compared with CK, following FS and CS treatments, C content increased by 3.0 and 5.5 times and O content increased by 1.6 and 2.1 times, respectively. In addition, FS and CS treatments improved the organic functional group content and ryegrass growth. Among the different treatments, the CS treatment exhibited superior performance in reclamation of bauxite residue, which can be attributed to that CS treatment easily forms more stable aggregates for carbon sequestration and the introduction of corn straw into bauxite residue provides organic matter for microorganism proliferation and nutrients for ryegrass growth. These findings suggest that CS treatment is a facile approach to improve aggregate stability, organic carbon sequestration, and ryegrass growth in bauxite residue, showing potential for the reclamation of bauxite residue.

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Environmental significance

Bauxite residue, a large-scale solid waste, is produced during the processing of bauxite to alumina, and its sustainable reclamation remains one of the biggest challenges faced by the global alumina industry. Until now, there have been no reports on appropriate reuse methods for processing such a large amount of bauxite residue which relies on a large-area storage in purpose-built bauxite residue disposal area. Therefore, it is essential to realize the rapid disposal of bauxite residue. Herein, we report a low-cost ecological engineering strategy for changing the physicochemical properties of tailing residue (soil formation of bauxite residue) and accelerating the pedogenic process of bauxite residue, thereby enabling plant growth in bauxite residue. To realize the ecological disposal of bauxite residue, the inorganic and organic amendment effects of ferric sulfate and corn straw on the aggregate variation, carbon sequestration, and ryegrass growth in bauxite residue were studied. Results showed that corn straw treatment is a promising, controllable, and effective measure for realizing soil formation and plant growth in bauxite residue, which will be beneficial for ecological remediation applications in large-area bauxite residue disposal areas.

1. Introduction

The accelerated development of industrialization and modernization has led to an increase in mining activities, resulting in the release of tailing residues into the environment.¹ Bauxite residue, a large-scale solid waste, is produced during the processing of bauxite into alumina, and its sustainable reclamation remains one of the biggest challenges faced by the global alumina industry.² The annual generation of bauxite residue

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was about 175 million tons in 2019, and it is increasing at a rate of 1.2 tons of bauxite residue for alumina generated per ton, posing substantial threat to the alumina industry and the surrounding environment.³ Therefore, it is essential to realize rapid rehabilitation and disposal of bauxite residue.

So far, there have been no reports on appropriate reuse methods for processing such a large amount of bauxite residue.⁴ Recently, ecological engineering of tailing residues has been advocated to change the physicochemical properties and accelerate pedogenic processes of tailings, thereby enabling plant growth in tailing ponds.² In this context, soil formation from bauxite residue is a promising technology for the ecological disposal and utilization of bauxite residue.⁵ Previous studies have demonstrated that bauxite residue can form soil-like growth substrate; however, it requires a long-term natural weathering process of approximately 15–20 years owing to its extremely poor soil evaluation factors, such as physicochemical properties, aggregate stability, and carbon sequestration ability.⁶ The physicochemical properties of bauxite residue, including high salinity and alkalinity similar to saline-alkali soils, are unfavorable for plant growth.⁷ The abundant aggregates in bauxite residue with weak aggregate stability renders conventional soil reclamation methods largely ineffective.^{2,4} In addition, enhancing organic carbon sequestration is crucial for improving soil fertility and quality during the soil formation process of bauxite residue.⁸

To accelerate the soil formation process of bauxite residue and improve soil evaluation factors, amendment application is an effective measure to shorten the pedogenic period of bauxite residue. This method possesses a series of advantages, such as low cost, simple operation, and remarkable remediation effect in regulating the saline-alkali properties of bauxite residue.^{9,10} According to the literature, phosphogypsum is one of the most costly amendment materials for bauxite residue remediation, but it faces a dealcalization issue.^{4,11} Ferric sulfate (FS) is a technologically important material for soil amendment application, which can effectively raise soil fertility. Ren *et al.* adopted FS material to act as an inorganic amendment and confirmed that the addition of an inorganic amendment decreased the pH and exchangeable sodium percentage (ESP) of bauxite residue.¹² Straw materials possess the advantages of low cost, abundance, and easy processing for amendment applications, which are desirable for the remediation of bauxite residue. Guo *et al.* used straw-based organic amendment materials to remediate bauxite residue, and reported that their aggregate size and stability were improved following amendment addition.¹³ Our previous research demonstrated that the addition of amendment could regulate the physicochemical properties of bauxite residues, such as pH, electrical conductivity (EC), and the concentrations of metal cations and alkaline anions.¹⁴ However, previous reports have mainly focused on the single alkalinity-salinity regulation (physicochemical properties) or aggregate variation of bauxite residue following amendment applications,^{4,13,14} and relatively few studies have conducted a systematic investigation into the relationship between aggregate stability and organic carbon sequestration in bauxite residue. In addition, in the available literature on

ecological engineering of bauxite residue, a lack of deeply understanding of the targeted remediation mechanism may limit the expected remediation effect in bauxite residue disposal areas. Therefore, a better understanding on remediation mechanism of the soil formation process of bauxite residue following amendment applications is essential.

In this study, it is hypothesized that the addition of FS and CS amendments can effectively improve aggregate stability and organic carbon sequestration in bauxite residue, further facilitating soil formation in bauxite residue. To verify this hypothesis, the effects of FS and CS treatments on the aggregate stability and organic carbon accumulation of bauxite residue were assessed by pot experiments. Briefly, the aims were (i) to explore the amendment effects of FS and CS treatments on the aggregate stability and organic carbon accumulation of bauxite residue; (ii) to understand the relationship between aggregates and organic carbon in bauxite residue following amendment application; and (iii) to reveal the mechanism of soil formation process and ecological remediation of bauxite residue following amendment application.

2. Materials and methods

2.1. Materials

The tested bauxite residue samples were collected from the surface layer (about 0–20 cm) of the bauxite residue disposal area (23°54'627" N, 108°18'200" E) in Guangxi Province, China, and their storage time was about two months. After natural air drying, the collected samples were sieved through a 2 mm mesh screen. The ferric sulfate used as the amendment was purchased from the Sinopharm Co. Ltd, China. The corn straws were collected from a factory near a bauxite residue disposal area. The physico-chemical properties of bauxite residue and amendment materials are listed in Table 1.

2.2. Experimental design

This study was conducted using pot experiments, in which the experimental samples were placed in plastic basins with an inner diameter of 100 mm and a height of 60 mm. There were 0.5 kg samples per pot, and three treatments were set as follows: (i) pure bauxite residue without amendment addition, acting as the control group (CK); (ii) bauxite residue + 5% ferric sulfate (FS); and (iii) bauxite residue + 5% corn straw (CS). Each treatment is repeated 3 times to obtain the average value (*i.e.*, 9 samples). Pot experiments were conducted at the Chemistry-Environment Building of Xiangnan University, Chenzhou, Hunan province, China. Ryegrass seeds (*Lolium perenne* L.) were used to examine the impact of amendment application on plant growth in bauxite residue. Seeds were purchased from Zhengzhou Kaiyuan Grass Industry Ltd (Henan Province, China). Ryegrass sowing was performed on September 15, 2024 (after amendment treatment for 1 year), and the seeding density was approximately 50 seeds per pot in all the treatments. Ryegrass plants were harvested after one month of growth. The plant height was then determined using a ruler, and the wet/dry weights of the plants were measured using a balance.



Table 1 Physico-chemical properties of bauxite residues and amendment materials

Contents	Bauxite residue	Ferric sulfate	Corn straw
Sand (%)	48.10	—	—
Silt (%)	51.70	—	—
Clay (%)	0.20	—	—
pH	10.43	2.93	4.57
Electrical conductivity EC ($\mu\text{S cm}^{-1}$)	197.30	135.15	57.50
Cation exchange capacity CEC (cmol kg^{-1})	339.49	43.59	20.13
Total organic carbon TOC (g kg^{-1})	1.45	0.05	3.35

2.3. Experimental analysis

The bauxite residue samples were partitioned into different aggregate-sized fractions using the drying sieving method.¹⁵ During the drying sieving process, 100 g of the air-dried bauxite residue sample (passed through 2 mm sieve) was placed on the top surface of 10, 20, 60, and 300 mesh (from top to bottom) sieve sets, then shaking at a frequency of 30 times per minute for 5 minutes. After screening, the resultant samples were divided into four aggregate-sized fractions of 2–1 mm, 1–0.25 mm, 0.25–0.05 mm, and <0.05 mm. The micro-morphology structure and particle characteristics of the bauxite residue aggregates were observed using a scanning electron microscope (SEM, ZEISS Sigma 300).¹⁶ Bauxite residue powder samples were dispersed on the surface of a copper sheet, and then small gold particles were sputtered on the top of the samples to act as a conductive coating. The average particle size of the bauxite residue aggregates after different treatments was determined by SEM observation. Based on the SEM images of particle profiles and the number of particles in bauxite residue aggregates, approximately 100 particles were counted using Nano Measurer software matched with SEM images, following which the average diameter of particles in bauxite residue aggregates was acquired from the statistical distribution histogram *via* Gauss distribution fitting.¹⁶ Moreover, we used an energy-dispersive X-ray spectrum (EDS) instrument installed on SEM equipment to analyze the elemental distribution and compositions of bauxite residue samples following different treatments. The organic carbon content of the samples was determined calorimetrically by oxidation with potassium dichromate,¹⁷ and organic functional groups associated with the bauxite residue samples were examined by Fourier-transform infrared spectra (FTIR, Thermo-Fisher Scientific Nicolet iS20). Spectra collection was ranged between 500 and 4000 cm^{-1} , along with a resolution of 4 cm^{-1} .⁷

2.4. Data analysis

The mean weight diameter (MWD) was usually used to evaluate the aggregate stability of bauxite residue samples, which was expressed as follows:¹⁵

$$\text{MWD} = \sum_{i=1}^n \bar{X}_i \times W_i \quad (1)$$

where X_i is the mean diameter for each size fraction, and W_i is the proportion of the total sample weight related to size fraction. The data analysis and graphics processing for the

experimental treatments were conducted using Microsoft Excel 2010 and Origin software version 8.5. In addition, SPSS 19.0 software was used to perform one-way ANOVA analysis for comparison of the significant differences at the 5% significance level.

3. Results and discussion

3.1. Impact of different treatments on the aggregate variation of bauxite residues

As shown in Fig. 1, for the same aggregate fraction, the amendment addition changed the distribution of bauxite residue aggregates, and significant differences ($P < 0.05$) were determined between the CK treatment and FS/CS treatments for the aggregate proportion. In the aggregate ranges of 2–1 mm and 1–0.25 mm, the distribution proportion of bauxite residue aggregates followed the order of CS > FS > CK, while this proportion followed the relationship of CS < FS < CK in the 0.25–0.05 mm and <0.05 mm ranges. The proportions of 2–1 mm aggregates in the bauxite residue after CK, FS, and CS treatments were 5.09%, 15.66%, and 19.05%, respectively. Compared with the proportion (12.67%) of 1–0.25 mm aggregates treated with CK, the FS and CS treatments increased this proportion to 17.29% and 36.37%, respectively. However, following the FS and CS

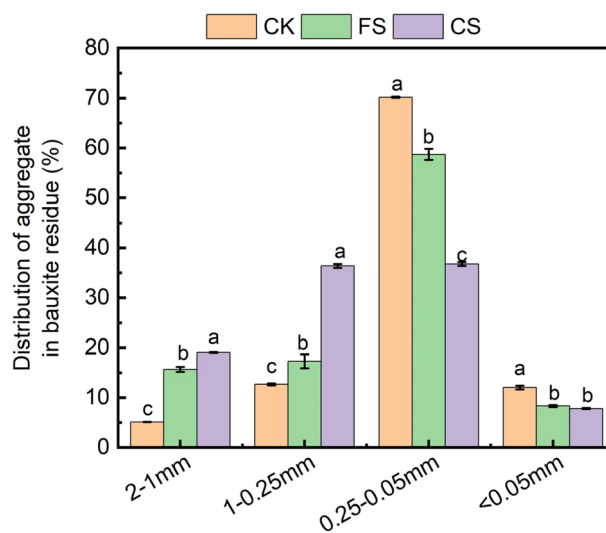


Fig. 1 Distribution of bauxite residue aggregates after different treatments.



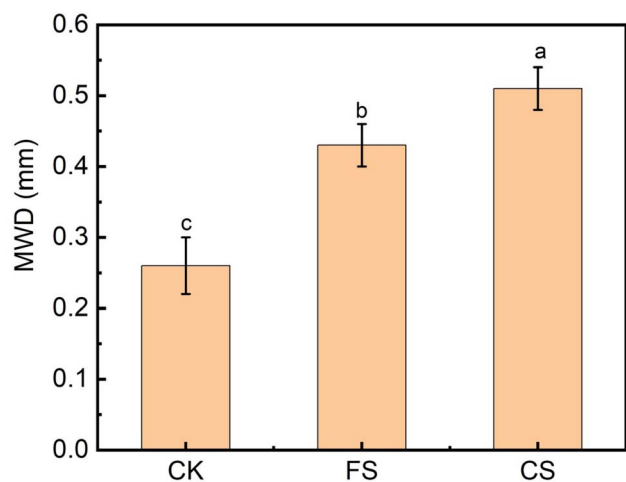


Fig. 2 Variations in MWD value of bauxite residue following different treatments.

treatments, the proportions of 0.25–0.05 mm aggregate in the bauxite residue decreased to 58.72% and 36.77%, respectively, relative to the 70.21% of CK treatment. The proportion of <0.05 mm aggregates in the bauxite residue was 12.03%, 8.33%, and 7.81% following CK, FS, and CS treatments, respectively. These results indicate that the application of the amendment increased the proportion of macroaggregates and decreased the proportion of microaggregates, suggesting the transformation from microaggregates to macroaggregates in bauxite residue.

Usually, the MWD value is used to assess the stability of aggregates in bauxite residue, which involves fertility and

storage ability of nutrients for vegetation growth.¹⁸ As illustrated in Fig. 2, the amendment applications with FS and CS treatments increased the MWD value of the bauxite residue aggregates and enhanced the aggregate stability of the bauxite residue, indicating significant differences ($P < 0.05$) among the different treatments. Compared with CK, the MWD values of the bauxite residue aggregates after FS and CS treatments increased by 1.65 and 1.96 times, respectively. In particular, the CS-treated bauxite residue exhibited the best aggregate stability. Fig. 3 displays the SEM observation results of bauxite residue aggregates after different treatments. Fig. 3(a1–a3) show the morphology characteristics of the bauxite residue aggregates after CK, FS, and CS treatments. A dispersed distribution of aggregates was observed in CK-treated bauxite residue, whereas an obvious agglomeration effect was observed in bauxite residue aggregates following FS and CS treatments. The corresponding high-resolution images of bauxite residue aggregates after different treatments are displayed in Fig. 3(b1–b3), in which amendment applications with FS and CS treatments induced aggregate structure evolution, such as particle sizes and morphologies of bauxite residue aggregates relative to the CK treatment. As shown in Fig. 3(c1–c3), in terms of the Gauss function fitting of the particle size distribution in the bauxite residue aggregates, the average particle size of the aggregates in the bauxite residue was obtained.¹⁶ The average particle sizes of aggregates following CK, FS, and CS treatments were ~102, ~167, and ~250 nm, respectively, which suggested that the particle sizes of bauxite residue aggregates were enhanced by amendment application, further improving aggregate stability in amended bauxite residue.

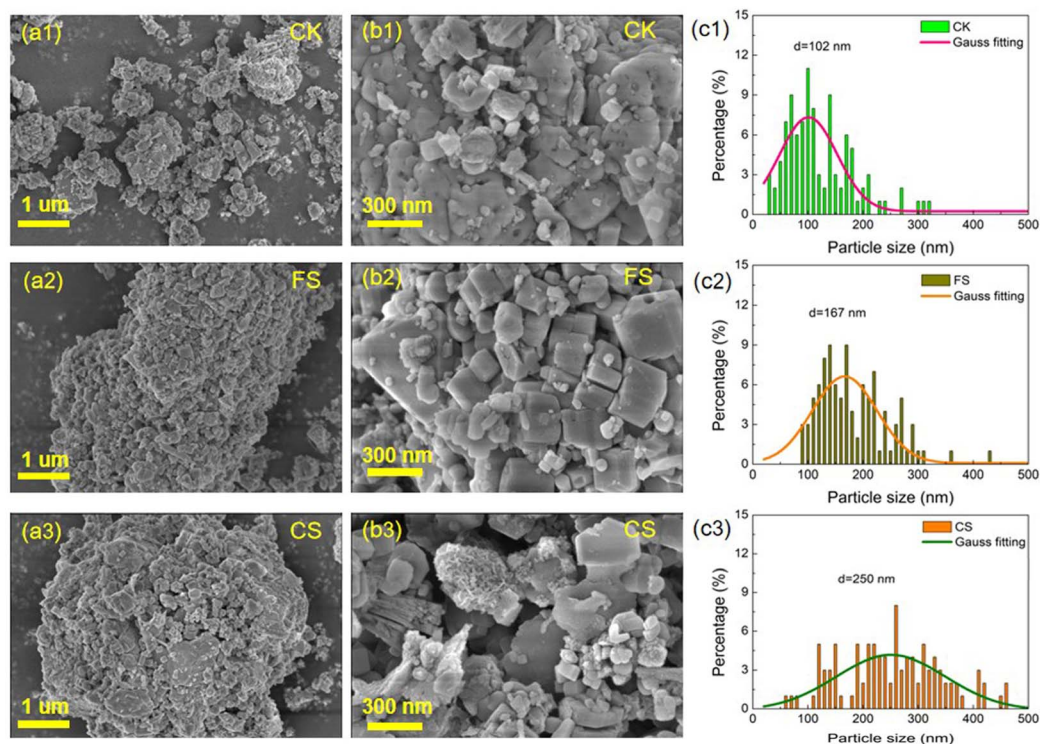


Fig. 3 Morphology characteristics and size distribution of aggregate particles in bauxite residue after different treatments.



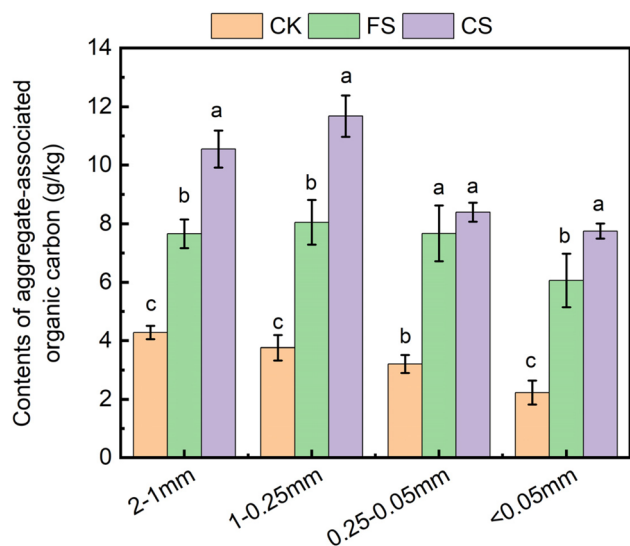


Fig. 4 Organic carbon content of aggregates with different fractions of bauxite residue after different treatments.

3.2. Organic carbon characteristics of bauxite residues after different treatments

Organic carbon content affects soil formation and ecological remediation of bauxite residue. Fig. 4 shows the variations in aggregate-associated organic carbon contents in bauxite residue after different treatments, which differed significantly between the CK and FS/CS treatments ($P < 0.05$). The content of aggregate-associated organic carbon complied with the order $CS > FS > CK$ for the same aggregate fraction. The organic carbon content of the 2–1 mm aggregates in the bauxite residue was 4.28, 7.66, and 10.55 g kg^{-1} following CK, FS, and CS treatments, respectively. Compared with the organic carbon content (3.76 g kg^{-1}) associated with 1–0.25 mm aggregates

following CK treatment, the FS and CS treatments increased the organic carbon content to 8.05 and 11.68 g kg^{-1} , respectively. However, following the FS and CS treatments, the organic carbon content of 0.25–0.05 mm aggregate in the bauxite residue decreased to 7.67 and 8.39 g kg^{-1} , respectively, relative to the 3.21 g kg^{-1} of the CK treatment. The organic carbon content associated with <0.05 mm aggregates in bauxite residue was 2.23, 6.06, and 7.75 g kg^{-1} following CK, FS, and CS treatments, respectively. These results demonstrated that amendment application raised organic carbon content of bauxite residue, and the CS treatment exhibited superiority in the sequestration and accumulation of organic carbon in bauxite residue, irrespective of any aggregate fraction, which may be due to that the CS treatment effectively enhanced the aggregate size and its stability, further promoting the formation of macroaggregates. Aggregates play an important role in the sequestration and accumulation of organic carbon, and macroaggregate formation easily promotes organic carbon accumulation relative to microaggregates.¹⁹

The effects of different treatments on the element distribution (*e.g.*, C and O) in the bauxite residue were investigated. As shown in Fig. 5(a1–a3), compared with the C element distribution in the CK-treated bauxite residue, the distribution of C element was denser in the FS-treated bauxite residue, and the densest distribution of C element was exhibited in the CS-treated bauxite residue. In addition, as shown in Fig. 5(b1–b3), the CK-treated bauxite residue exhibited a thin distribution of O element, and the amended bauxite residue with the FS and CS treatments exhibited a thick distribution of O element. These results indicate that the application of an amendment can increase the C and O contents of the bauxite residue. The quantitative analysis of the element contents in the bauxite residue is shown in Fig. 6, in which the insets show the atomic percentage of C and O contents in bauxite residue. Compared with the C element content of bauxite residue after CK

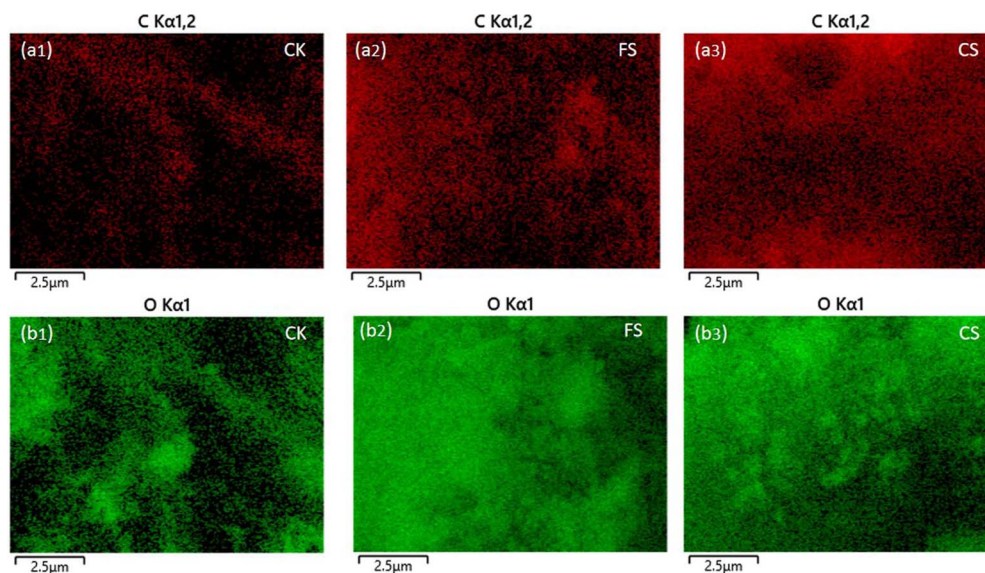


Fig. 5 Effects of different treatments on the distribution of (a1–a3) C and (b1–b3) O elements in bauxite residue.



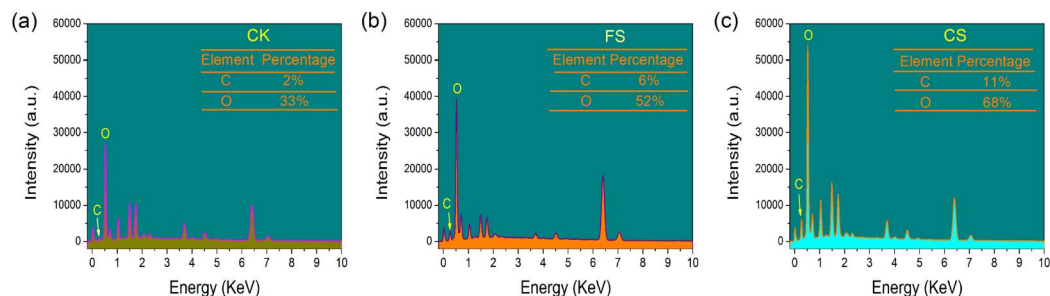


Fig. 6 Effects of different treatments on element contents in bauxite residue.

treatment, the FS and CS treatments increased the C content in bauxite residue by 3.0 and 5.5 times, respectively, indicating that amendment application can enhance the carbon sequestration effect of bauxite residue. In addition, the FS and CS treatments increased the O contents in the bauxite residue by 1.6 and 2.1 times relative to the O content of the CK-treated bauxite residue, respectively. Therefore, FS and CS treatments can raise the C and O contents of bauxite residue, which is conducive to improving nutrient composition and enhancing fertility properties during the soil formation process of bauxite residue.

3.3. FTIR analysis

Fig. 7 illustrates the FTIR spectral characteristics of bauxite residue after different treatments. An obvious adsorption peak located at 3528 cm^{-1} was found in bauxite residue after CK treatment, while this adsorption peak in bauxite residue following FS and CS treatments was red-shifted to 3417 and 3420 cm^{-1} , respectively, which suggested a variation in the corresponding functional group of $-\text{OH}$.^{20–22} Following that, an adsorption peak centered at 2974 cm^{-1} was observed in FS-treated bauxite residue, which may be due to that ferric sulfate changed the intensities in stretching vibrations, and a similar spectrum shape was found in previous literature.²³ Furthermore, the adsorption band at 2514 cm^{-1} results from C–H stretching vibration,⁷ and the distinctive peak at 1631 cm^{-1} is ascribed to the $\text{C}=\text{O}$ stretching vibration.^{7,20} The adsorption peak was located at 1476 cm^{-1} in CK-treated bauxite residue, while this peak in the bauxite residue after FS and CS treatments was red-shifted to 1421 and 1419 cm^{-1} , respectively, which may be due to the variation in the mineral phase structure in bauxite residue following amendment application.^{21,22} The adsorption band at 1113 cm^{-1} in CK-treated bauxite residue was red-shifted to 1091 cm^{-1} in FS-treated bauxite residue, which suggested that ferric sulfate induced the variation of the Si–O–Al group in the bauxite residue.^{20,24} In the low-frequency region, the adsorption band ranges of 998 – 571 cm^{-1} are attributed to the Si–O bond,^{7,20,22,24,25} and the peak located at 461 cm^{-1} is ascribed to the hematite phase in bauxite residue, due to the vibrational stretching mode of the Fe–O band.^{20,22,23,25,26} The variation of absorption bands reflected the change in soil-associated organic functional group characteristics (*i.e.*, amounts and quantities), organic matter contents, and soil quality.⁷ The results of FTIR analysis indicated that amendment

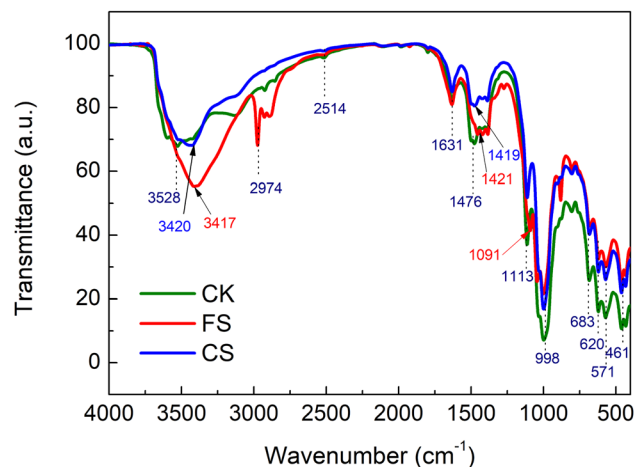


Fig. 7 FTIR spectra of bauxite residue after different treatments.

applications (FS and CS) induced the variations of infrared spectra shape or peak positions, which suggested that the organic matter, such as organic carbon and soil formation quality of bauxite residue, can be regulated by the FS and CS treatments.

3.4. Ryegrass growth

To examine the effects of different treatments on soil formation of bauxite residue, ryegrass growth was evaluated in bauxite residue following amendment application for 1 year. Ryegrass (*Lolium perenne* L.) is an agriculturally tolerant plant.²⁷ Fig. 8 shows the ryegrass growth in bauxite residue following different treatments. No significant growth of ryegrass was observed in CK-treated bauxite residue, whereas ryegrass growth was obvious in bauxite residue following FS and CS treatments, only sowing for 10 days. Compared with the CK treatment, the dense growth of ryegrass was covered in bauxite residue after 30 days of sowing following the FS and CS treatments. The densest convergence of ryegrass growth was observed in bauxite residues treated with CS treatment. To further explore the effect of amendment on the soil formation of bauxite residue, the biomass of ryegrass growth for 30 days after sowing in bauxite residue was analyzed (Table 2). Compared with ryegrass growth in FS-treated bauxite residue, ryegrass grown in CS-treated bauxite residue exhibited better leaf length and plant height, although both treatments possessed the same root length of



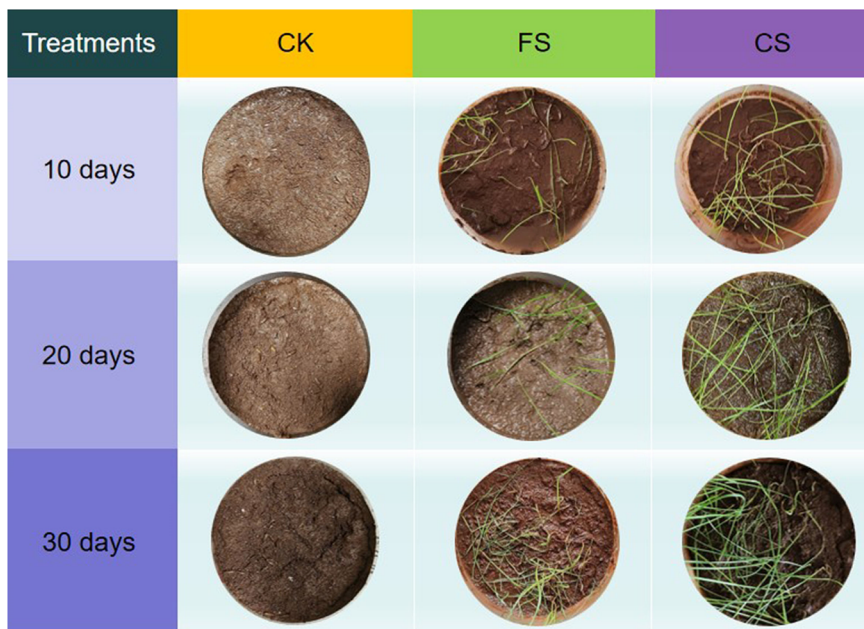


Fig. 8 Comparison of ryegrass growth in bauxite residue after different treatments.

Table 2 Summary of biomass of ryegrass growth in bauxite residues after different treatments

Treatments	Root (cm)	Leaf (cm)	Height (cm)	Fresh weight (g per pot)	Dry weight (g per pot)
CK	0	0	0	0	0
FS	3.50 ± 0.00	8.40 ± 0.98	11.90 ± 0.66	0.53 ± 0.19	0.13 ± 0.06
CS	3.50 ± 0.41	9.15 ± 0.32	12.65 ± 0.74	0.99 ± 0.90	0.18 ± 0.01

ryegrass. In addition, ryegrass growth in CS-treated bauxite residue achieved higher fresh weight and dry weight relative to FS treatment (approximately 0.99 and 0.18 g per pot, respectively), suggesting that the use of CS treatment to remediate is a feasible approach.

3.5. Mechanisms of aggregate variation and organic carbon sequestration

Based on the above analysis and discussion of variations in aggregate distribution, organic carbon regulation, FTIR

characteristics, and ryegrass biomass in bauxite residue following different treatments, the mechanisms of aggregate variation and organic carbon sequestration for reclamation of bauxite residue were proposed, as shown in Fig. 9. For pure bauxite residue without amendment applications (CK), bauxite residue possesses fine particles with poor aggregate stability and low organic carbon content.⁵ Compared with CK treatment, for the FS-treated bauxite residue, ferric sulfate increased the surface area and active sites in bauxite residue, as well as providing functional groups to accelerate degradation of protein and polysaccharide,²⁸ which induced

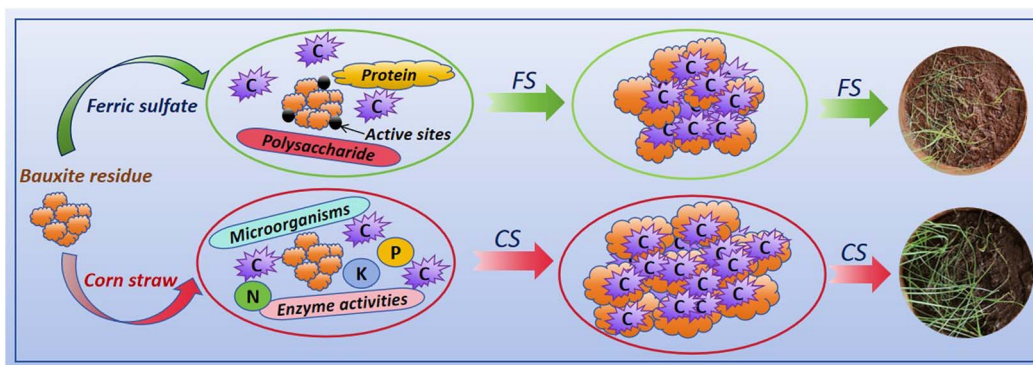


Fig. 9 Schematic showing aggregate variation and organic carbon regulation in bauxite residue after different treatments.



formation and accumulation of organic carbon. Moreover, the introduction of ferric sulfate into the bauxite residue increased the aggregate size, further enhancing aggregate stability in bauxite residue. Therefore, improvements in organic carbon content and aggregate stability are beneficial for ryegrass growth. For the CS-treated bauxite residue, the introduction of corn straw into the bauxite residue can provide organic matter for microorganism proliferation and increase the number of microorganisms and enzyme activity, which promotes organic carbon accumulation.²⁹ Furthermore, the mineralization effect of organic matter in corn straw releases nutrients and increases nitrogen (N), phosphorus (P), and potassium (K) contents, which accelerates ryegrass growth.²⁹ Similarly, the CS treatment increased the aggregate size of bauxite residue and enhanced aggregate stability. In comparison, the CS treatment is more desirable for ryegrass growth relative to the FS treatment, which may be due to the CS treatment being more conducive to the enhancement of aggregate size and aggregate stability through the analysis of aggregate distribution, MWD, and SEM observation in bauxite residue. Previous studies have demonstrated that organic carbon is mainly concentrated and accumulates in macroaggregates.³⁰ In this study, CS treatment easily induces the formation of macroaggregates from microaggregates compared with FS treatment, which can result in CS treatment obtaining better organic carbon sequestration relative to FS treatment. Thus, CS treatment exhibited superiority in aggregate stability enhancement, organic carbon accumulation, and ryegrass growth in bauxite residue.

4. Conclusions

In summary, the amendment effects of different treatments (CK, FS, and CS) on aggregate variation, carbon sequestration, and ryegrass growth in bauxite residue were systematically studied. The results demonstrated that FS and CS treatments increased the proportion of macroaggregates, decreased the proportion of microaggregates, and facilitated the transformation from microaggregate to macroaggregate in bauxite residue. In addition, the FS and CS treatments increased the MWD value and the average particle size of bauxite residue aggregates, thereby effectively improving the aggregate stability of bauxite residue. With the application of FS and CS treatments, the aggregate-associated organic carbon contents in bauxite residue increased in the 2–1 mm and 1–0.25 mm aggregates and decreased in 0.25–0.05 mm aggregates and <0.05 mm aggregates, respectively, relative to the CK treatment. Compared with the CK treatment, the FS and CS treatments significantly enhanced the carbon sequestration effect of the bauxite residue, such as that the C content increased by 3.0 and 5.5 times and the O content increased by 1.6 and 2.1 times, respectively. In addition, FS and CS treatments regulated organic functional group content and improved ryegrass growth. Among the different treatments, the CS treatment exhibited superior performance in enhancing aggregate stability and organic carbon sequestration in bauxite residue with improved ryegrass growth, and the related mechanism was proposed. These findings provide a promising strategy for enabling plant growth and promoting the ecological disposal of bauxite residue.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author contributions

Tao Tian: preparation, presentation of the published work, writing of the initial manuscript, data curation, and funding acquisition. Ruixin Feng: data curation and result validation. Chuangye Yao: ideas, formulation of overarching research goals and aims, reviewing, guidance, and funding acquisition. Shao-hua Feng: result validation. Xinrui Li: data curation. Le Yu: data curation. Liya Yang: formulation of the overarching research goals and aims, reviewing, guidance, and funding acquisition.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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References

- 1 L. Jiang, H. Sun, T. Peng, W. Ding, B. Liu and Q. Liu, Comprehensive evaluation of environmental availability, pollution level and leaching heavy metals behavior in non-ferrous metal tailings, *J. Environ. Manage.*, 2021, **290**, 112639.
- 2 S. Wu, F. Wang, M. Komarek and L. Huang, Ecological rehabilitation of mine tailings, *Plant Soil*, 2024, **497**, 1–5.
- 3 M. K. Kar, M. A. R. Onal and C. R. Borra, Alumina recovery from bauxite residue: A concise review, *Resour. Conserv. Recycl.*, 2023, **198**, 107158.
- 4 T. Tian, C. Zhang, F. Zhu, S. Yuan, Y. Guo and S. Xue, Effect of phosphogypsum on saline-alkalinity and aggregate stability of bauxite residue, *Trans. Nonferrous Met. Soc. China*, 2021, **31**, 1484–1495.
- 5 S. Xue, Soil formation in bauxite residue: The most promising way to large-scale and ecological disposal, *J. Cent. South Univ.*, 2019, **26**, 265–267.



- 6 Z. Zhong, S. Wu, X. Lu, Z. Ren, Q. Wu, M. Xu, C. Ren, G. Yang and X. Han, Organic carbon, nitrogen accumulation, and soil aggregate dynamics as affected by vegetation restoration patterns in the Loess Plateau of China, *Catena*, 2021, **196**, 104867.
- 7 T. Tian, L. Yu, R. Feng, C. Yao, L. Gong, H. Xiao, L. Liu and F. Li, Unveiling the combined effects of water management and lime on remediation of Cd-contaminated soils with improved soil quality, *J. Environ. Chem. Eng.*, 2024, **12**, 114778.
- 8 Y. Li, Y. Duan, G. Wang, A. Wang, G. Shao, X. Meng, H. Hu and D. Zhang, Straw alters the soil organic carbon composition and microbial community under different tillage practices in a meadow soil in Northeast China, *Soil Tillage Res.*, 2021, **208**, 104879.
- 9 M. Sol-Magdaleno, J. I. Aguilar-Aguilar, E. Beltrán-Naturi, L. D. Valencia-Ordoñez, A. Díaz-González, P. Trejo-Flores, C. A. Camas-Flores, G. Palacios-Pola, Z. Ali-Sahito and M. González-Moscoso, Carbon nanomaterials as an environmental technology in the remediation of agricultural soils contaminated with heavy metals: a review, *Discov. Soil*, 2025, **2**, 26.
- 10 Y. S. Miura, J. Mulder, V. Zivanovic, R. Courtney and G. Okkenhaug, Enhancing bauxite residue properties for plant growth: Gypsum and organic amendment effects on chemical properties of soil and leachate, *J. Environ. Manag.*, 2023, **337**, 117721.
- 11 Y. Wu, Y. Jiang, J. Jiang, L. Chen, X. Qin, H. William and S. Xue, Conversion of alkaline characteristics of bauxite residue by mechanical activated pretreatment: Implications for its dealkalization, *J. Environ. Manag.*, 2022, **305**, 114446.
- 12 X. Ren, X. Zhang, P. Tuo, B. Yang, J. Chen, W. Guo and J. Ren, Neutralization of bauxite residue with high calcium content in abating pH rebound by using ferrous sulfate, *Environ. Sci. Pollut. Res.*, 2022, **29**, 13167–13176.
- 13 Y. Guo, Y. Ye, F. Zhu, R. Xue, X. Zhang, M. Zhu, W. Hartley, L. Guo and S. Xue, Improvements on physical conditions of bauxite residue following application of organic materials, *J. Environ. Sci.*, 2022, **116**, 198–208.
- 14 T. Tian, J. Zhou, F. Zhu, Y. Ye, Y. Guo, W. Hartley and S. Xue, Effect of amendments on the leaching behavior of alkaline anions and metal ions in bauxite residue, *J. Environ. Sci.*, 2019, **85**, 74–81.
- 15 T. Tian, W. Ke, F. Zhu, Q. Wang, Y. Ye, Y. Guo and S. Xue, Effect of substrate amendment on alkaline minerals and aggregate stability in bauxite residue, *J. Cent. South Univ.*, 2019, **26**, 393–403.
- 16 C. Yao, C. Wu, L. Gong, Q. Wu and T. Tian, Coexistence of digital and analog resistive switching behaviors in nanocrystalline yttrium-iron-garnet thin films achieved by electrode engineering, *Appl. Surf. Sci.*, 2025, **680**, 161329.
- 17 T. Tian, H. Zhou, J. Gu, R. Jia, H. Li, Q. Wang, M. Zeng and B. Liao, Cadmium accumulation and bioavailability in paddy soil under different water regimes for different growth stages of rice (*Oryza sativa* L.), *Plant Soil*, 2019, **440**, 327–339.
- 18 A. Mustafa, M. Xu, S. A. A. Shah, M. M. Abrar, S. Nan, W. Baoren, Z. Cai, Q. Saeed, M. Naveed, K. Mehmood and A. Núñez-Delgado, Soil aggregation and soil aggregate stability regulate organic carbon and nitrogen storage in a red soil of southern China, *J. Environ. Manag.*, 2020, **270**, 110894.
- 19 J. Li, P. Chen, Z. Li, L. Li, R. Zhang, W. Hu and Y. Liu, Soil aggregate-associated organic carbon mineralization and its driving factors in rhizosphere soil, *Soil Biol. Biochem.*, 2023, **186**, 109182.
- 20 K. Sharma, K. Kohansal, A. J. Azuara, L. A. Rosendahl, V. Benedetti, D. Yu and T. H. Pedersen, Green and facile recycling of bauxite residue to biochar-supported iron-based composite material for hydrothermal liquefaction of municipal solid waste, *Waste Manage.*, 2023, **171**, 259–270.
- 21 M. M. Almeida, N. P. F. Goncalves, T. Gameiro, Z. Alves, J. A. Labrincha and R. M. Novais, 3D-printing bauxite residue/fly ash-containing geopolymers as promising metals sorbents for water treatment, *Waste Manage.*, 2024, **190**, 35–44.
- 22 A. I. Arogundade, P. S. M. Megat-Yusoff, F. Ahmad, A. H. Bhat and L. O. Afolabi, Modification of bauxite residue with oxalic acid for improved performance in intumescent coatings, *J. Mater. Res. Technol.*, 2021, **12**, 679–687.
- 23 A. X. Vesga, M. F. Cuentas and A. R. A. Arrieta, The effect of ZnSO₄ and Fe₂(SO₄)₃ on the pyrolysis of cocoa shells: A tg-FTIR study, *Heliyon*, 2024, **10**, e33117.
- 24 D. L. Bollinger, J. Erickson, N. Stone-Weiss, A. J. Lere-Adams, S. Karcher, I. D. Akin and J. S. McCloy, Structure of amorphous aluminosilicates obtained from mineral transformation: Potential path for partial remediation of alkaline bauxite residues, *Environ. Adv.*, 2021, **6**, 100136.
- 25 D. Dodoo, G. Appiah, G. Acquaaah and T. D. Junior, Fixed-bed column study for the remediation of the bauxite-liquid residue using acid-activated clays and natural clays, *Heliyon*, 2023, **9**, e14310.
- 26 D. Dodoo, G. E. Fynn, E. S. C. Yawson, G. Appiah, N. Suleiman and A. Yaya, Eco-efficient treatment of hazardous bauxite liquid-residue using acid-activated clays, *Cleaner Chem. Eng.*, 2022, **3**, 100040.
- 27 A. Bothe, P. Westermeier, A. Wosnitza, E. Willner, A. Schum, K. J. Dehmer and S. Hartmann, Drought tolerance in perennial ryegrass (*Lolium perenne* L.) as assessed by two contrasting phenotyping systems, *J. Agron. Crop Sci.*, 2018, **204**, 375–389.
- 28 L. Xu, L. Li, W. Lu, Y. Gu, H. Zhuang, Q. He and L. Zhu, The modified properties of sludge-based biochar with ferric sulfate and its effectiveness in promoting carbon release from particulate organic matter in rural household wastewater, *Environ. Res.*, 2023, **231**, 116109.
- 29 T. Huang, N. Yang, C. Lu, X. Qin and K. H. M. Siddique, Soil organic carbon, total nitrogen, available nutrients, and yield under different straw returning methods, *Soil Tillage Res.*, 2021, **214**, 105171.
- 30 C. Li, Y. Li, J. Xie, Y. Liu, Y. Wang and X. Liu, Accumulation of organic carbon and its association with macro-aggregates during 100 years of oasis formation, *Catena*, 2019, **172**, 770–780.

