



Research progress on the construction of artificial soil based on coal-based solid waste

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ABSTRACT

More than 2 billion tons of coal-based solid wastes (CBSW) are produced annually in China present not only significant environmental hazards, including air pollution from dust, soil degradation, and water contamination from heavy metals, but also direct safety risks such as spontaneous combustion and landslides. Currently, soil degradation is becoming an increasingly serious concern. Artificial soil is a crucial green construction material. However, the current resource utilization of CBSW in artificial soil is confronted with difficulties such as low efficiency, high ecological risks, and obstacles to industrialization. Therefore, there is an urgent requirement to develop a stable and eco-friendly approach for the construction of artificial soil. This paper reviews the physicochemical properties of CBSW and its adaptability to soil improvement. Considering the application directions of CBSW in ecological soil (such as remediating contaminated soil, improving poor soil quality, and promoting plant growth). It focuses on key methods for preparing artificial soil. These methods include pretreatment technology, optimizing the ratio of solid waste, additives, and soil, and evaluating ecological effects. This work provides insights into transforming coal waste into a valuable resource for ecological restoration.

1. Introduction

1.1. Research background

In recent years, the accumulation of coal-based solid waste (CBSW) has become a global issue. China produces over 2 billion tons of CBSW annually, resulting in severe land occupation and environmental hazards (Fig. 1), especially in fragile ecosystems such as mining zones, saline-alkali areas, and arid deserts [1]. The treatment and utilization of CBSW have emerged as a key research focus. Direct mixing CBSW with other solid wastes shows promise for ecological restoration applications, including mine backfilling, soil remediation, and wastewater treatment [2,3]. In the context of China's "the goals of dual carbon", there is growing demand for ecological restoration technologies that integrate resource utilization. Applying CBSW in artificial soil construction can simultaneously reduce waste stockpiles and rehabilitate degraded lands, addressing two critical challenges.

Artificial soil is an engineered substrate designed to mimic the

essential functions of natural soil (supporting plant growth, maintaining microbial communities, and regulating water and gas cycles) by adjusting the proportions of waste and natural materials. Its composition, structure, and function are customizable. As a green construction material, artificial soil serves as a key carrier for realizing the closed-loop "waste-resource-soil system". Due to its high porosity and nutrient-rich properties, CBSW is an ideal material for constructing water-retaining and nutrient-retaining artificial soil, with potential applications in multiple fields (Fig. 2). However, the current resource utilization of CBSW faces challenges such as low efficiency, high ecological risks, and industrialization barriers. To address these issues, there is an urgent need to develop a systematic approach for constructing functional, stable, and eco-friendly artificial soil.

Global research on artificial soil construction using CBSW has been extensive. Early applications, such as flue gas desulfurization gypsum (FGDG) in American agriculture, accounted for only 1 % of total FGDG usage in 2011 but increased to 5 % in 2022 [5]. Experiments conducted in Ohio (United States) demonstrated the benefits of FGDG on the

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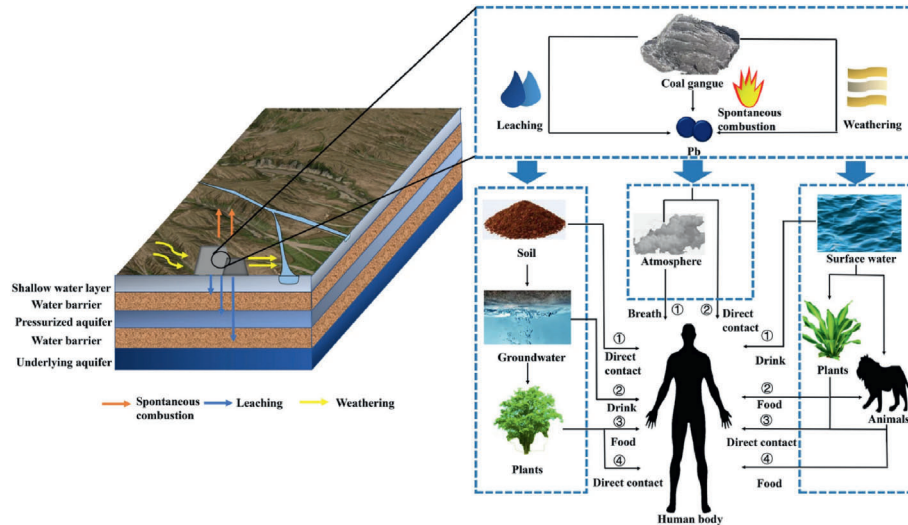


Fig. 1. Migration process and effect of heavy metal elements Pb in coal gangue [4].

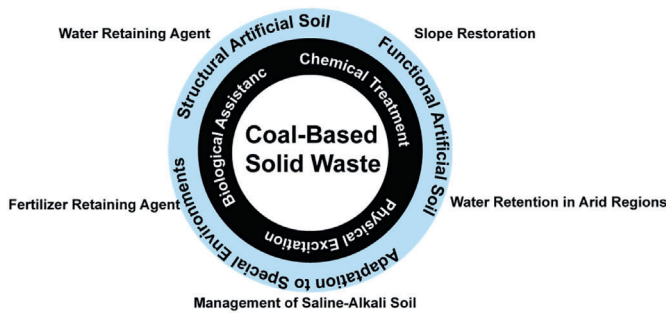


Fig. 2. Common modification methods and application fields of CBSW.

growth of crops such as corn and peanuts [5]. Zeynali et al. [6] incorporated fly ash (FA) with different particle sizes at the micrometer and nanometer scales into soil, increasing the compressive strength from 50 kPa to 410 kPa. Fly ash can be used as a substitute for a portion of cement as a binding material, reducing costs by 23 % and CO₂ emissions by 9 % [7]. It can be utilized for mine backfilling and slope stabilization. A 10-year study has shown that FGDG has beneficial effects on saline-alkali soil microorganisms [8]. The diversity of microbial communities in saline-alkali soil and the complexity of ecological co-occurrence networks increase over time. Su et al. [9] prepared a slow-release fly ash microbial fertilizer conducive to mine plant restoration to improve soil fertility. Currently, the construction of artificial soil using CBSW mainly focuses on collaborative construction with solid waste or soil function restoration. The former emphasizes cost reduction and heavy metal safety, with FA, coal gangue (CG), and biomass as application-oriented materials, highlighting material sources. The latter focuses on soil function restoration, emphasizing life cycle analysis (LCA) and microbial systems, mainly using industrial by-products, compost, and biological inoculants as mechanism-oriented materials, with a focus on ecological response pathways.

To address the issues of low efficiency, high ecological risk, and difficulties in industrialization in the resource recovery of CBSW. This paper discusses the feasibility of utilizing CBSW as artificial soil matrix based on its classification and physicochemical properties, elucidates how to regulate and prepare CBSW artificial soil with different functions based on engineering needs, provides typical engineering cases for the restoration of ecological environments such as saline-alkali soil and sandy wasteland, and provides route suggestions for the industrialization of CBSW.

2. Characteristics of CBSW

2.1. Classification and physicochemical properties of coal-based solid waste

CBSW, including CG, FA, and desulfurization gypsum (DG), are all by-products generated during the production, processing, and utilization of coal. Their composition and physicochemical properties vary with production location and method. These properties can affect the physicochemical properties of artificially constructed soil, ultimately influencing soil performance. For instance, CG and FA are identified as potential soil matrix materials due to their high porosity and moderate water retention and retention capacity [8]. Based on Fig. 3, He et al. [8] analyzed the impact of soil physicochemical properties on water retention capacity. They concluded that soil sand content, organic matter, and total nitrogen are negatively correlated with soil volumetric water content. They also established a prediction model for the water holding capacity of CG artificial soil based on the LSM method (Fig. 4). This model uses material ratio, soil layer thickness, and time variables as key predictive variables, identifying sand content as the main controlling factor for soil water retention. Research and induction of the physicochemical properties of common CBSW can effectively assist in constructing artificial soils with different functions.

CG is dark gray in color and coexists with coal. It is a carbonaceous rock composed of a mixture of organic and inorganic compounds, which were deposited alongside coal [10]. CG consists of both organic and inorganic components. Its main chemical components are SiO₂ and Al₂O₃, and it contains elements such as Al, Si, Fe, Ca, Mg, K, and other rare elements (Table 1). The mineral composition of CG is relatively complex, with kaolinite as the main component, and it also contains illite, montmorillonite, quartz, feldspar, pyrite, etc. It is greatly influenced by the production region, such as the CG in southern China, which is characterized by high Fe and Ti content (Table 1) [11]. Therefore, CG exhibits some physicochemical properties similar to clay minerals, with a loose structure and adsorptive capabilities [12]. This allows for ion exchange and supports the formation of soil aggregates. According to China's GB/T 29,162–2012 “Classification of CG”, CG can be classified based on four factors: total sulfur content $S_{t,d}$, calcium and magnesium content $W_{CaO+MgO}$, ash yield A_d , and silica-alumina ratio $M_{Al_2O_3} / M_{SiO_2}$. According to the Technical Specification for Saline-Alkali Land Remediation Using Coal-Based Conditioners (DB6108/T 52–2023) issued by Yulin, China, after meeting the requirements for heavy metal ions (HMs), CG can be used as a soil conditioner only when SiO₂ (mg/kg) > 50 and Al₂O₃ (mg/kg) < 30.

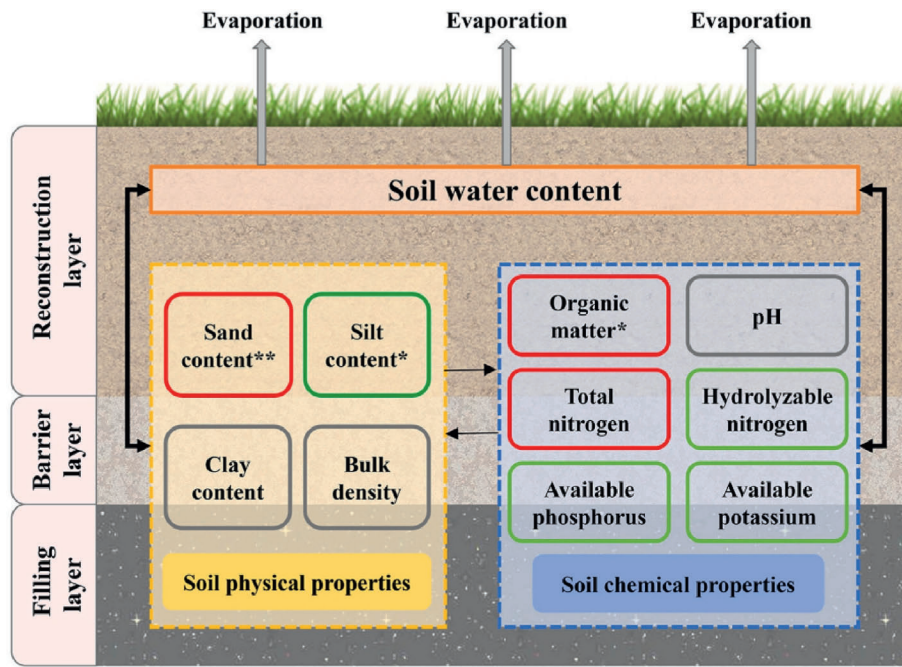


Fig. 3. The driving mechanisms of soil physicochemical properties on soil water retention [8].

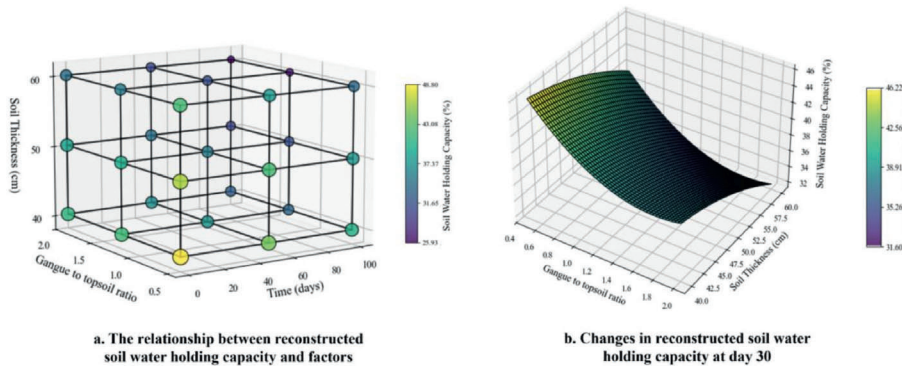


Fig. 4. Reconstructed soil water holding capacity model [8].

Table 1
Composition and origin of different CBSW.

CBSW	Chemical properties (%)												Origin
	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	P ₂ O ₅	Mn ₂ O ₄	Na ₂ O	K ₂ O	MgO	SO ₃	MnO	
CG	0.99	58.44	31.01	3.57	2.23	unknown	unknown	0.43	2.09	0.50	0.467	unknown	Changzhi, China [13]
CG	0.44	38.7	16.5	5.3	0.52	unknown	unknown	0.26	0.77	0.30	3.4	unknown	Shanxi, China [14]
CG	0.23	59.59	34.24	1.87	1.34	unknown	unknown	unknown	1.58	0.58	unknown	unknown	Wuhai, China [15]
FA	4.34	48.48	24.44	8.43	1.08	0.77	0.05	1.22	1.86	2.06	0.77	unknown	Brindisi, Italy [16]
FA	13.63	40.9	22.4	13.64	unknown	unknown	unknown	0.98	2.39	2.93	0.22	unknown	Mae Moh [17]
FA	4.67	58.60	20.20	9.25	2.34	unknown	unknown	unknown	3.02	unknown	1.04	0.16	Australia [18]
FGDG	31.90	3.3	1.00	0.30	0.05	0.01	–	–	–	3.8	36.90	unknown	Brindisi, Italy [16]
FGDG	39.5	1.05	0.93	0.30	unknown	unknown	unknown	unknown	low	0.17	47.8	unknown	Taiyuan, China [19]

FA is a common industrial waste residue from mining areas and an atmospheric pollutant generated by coal combustion in thermal power plants. It is primarily composed of oxides of elements such as Si, Al, Ca, Fe, and Mn [6,20]. Studies have shown that FA particles from thermal power plants are predominantly physical sand grains, characterized by fine particle size and low bulk density. They also contain high levels of total nitrogen (N) and available phosphorus (P) [21,22]. The mineral composition of FA is mostly amorphous silica-alumina glass, including quartz, mullite, mica, feldspar, magnetite, hematite, lime, magnesium

oxide, etc. Its structure can be approximately regarded as a ternary glass of CaO-Al₂O₃-SiO₂, exhibiting high pozzolanic activity [23]. Its pozzolanic activity originates from the high content of reactive Al₂O₃ and SiO₂ (Table 1). FA is mostly spherical and possesses a mesoporous structure. It can be modified and used as an adsorbent for wastewater to remove dyes, anionic surfactants, etc. Its surface contains Si-OH groups, which undergo protonation or deprotonation upon contact with water, carrying charges, and exhibit an isoelectric point (IEP) within the pH range of 2.5–2.8 [24–26]. FA can exist as negatively charged spherical

particles in ordinary soil with significantly higher pH values, enhancing the mobility of ions in the soil [27].

In addition to CG and FA, other CBSW such as slag, DG, and biomass carbon are also commonly used as auxiliary materials for artificial soil. Slag possesses pozzolanic activity. It can be utilized in the production of Portland cement through activation treatment or used as a binder and alkali activator for artificial soil, effectively enhancing the mechanical properties of soil [28,29]. DG and biomass carbon are high-quality sources of calcium and organic matter, respectively, and can improve soil bulk density and soil porosity.

2.2. Bioactive nutrients

The inherent properties of CBSW, such as adsorptive capacity, cohesiveness, and ion-exchangeability, are conducive to improved soil structure and enhanced soil fertility. However, the current utilization of CBSW is primarily as carriers for biofertilizers or ingredients for compound fertilizers. Although CG contains soluble K, Mg, Si, and other “potential nutrient sources,” the individual nutrient contents are still relatively low and not easily absorbed by plants. Therefore, when using CBSW as a carrier or ingredient, it is necessary to convert the inactive nutrients contained therein into easily exchangeable and absorbable forms. Currently, CBSW is commonly treated through physical activation, chemical treatment, and biological assistance to promote the release of potential nutrient elements such as K, P, Si.

Physical activation primarily involves altering the physical properties of CBSW—such as particle size, specific surface area, and pore structure—through physical methods like mechanical grinding and high-temperature calcination. This is done to enhance its applicability in soil. For instance, mechanical grinding can disrupt the crystal structure of CG, increasing active reaction sites and specific surface area. As grinding fineness increases, the specific surface area and reactivity of CBSW significantly improve. After mechanical grinding (particle size < 1 mm), CG provides more interfaces for subsequent chemical or biological reactions, reduces the impact on soil aeration, and enhances soil water retention capacity [30]. The specific surface area of CG after multiple treatments has increased by 40–60 %. High-temperature calcination can transform the mineral components in CBSW, improving structural stability and pozzolanic activity. For example, high-temperature calcination of CG can convert kaolinite and illite into amorphous SiO₂ and Al₂O₃. Niu et al. [31] co-pyrolyzed CG with biomass and used it as a soil additive. It successfully released elements such as Ca, K, Ni, and F from CG, enhanced soil water retention and fertility retention capabilities, and exhibited good solidification effects on heavy metals such as Cu, Zn, and Fe. The microstructure of pyrolysis products transitions from an amorphous dispersed state to a porous agglomerated state, with the main chemical components changing being SiO₂ and C, which can enhance the ion exchange efficiency of soil.

Chemical treatment alters the chemical composition of CBSW through chemical reactions such as acid-base adjustment and oxidation-reduction. It achieves functions such as heavy metal immobilization and nutrient adsorption. Preparing CBSW composite fertilizers using chemical activation treatment methods can improve the availability of various nutrients in CBSW for crop absorption, thereby increasing crop yields. By altering the pH of the environment in which CG is located, its surface charge and ion exchange properties can be influenced. For example, treating CG with CaCl₂ solution under alkaline conditions generates calcium silicate hydrate (CSH) and ettringite (Aft), enhancing the adsorption of Pb plants [32].

Biological assistance relies on the metabolic activities of plants or microorganisms. Through processes such as absorption, transformation, and degradation, it reduces the hazards of CBSW while improving soil ecological functions. Plants can absorb heavy metals from the soil through their roots and transport them to the aboveground parts, thereby reducing the content of heavy metals in the soil [33,34]. For example, elm and poplar trees can absorb heavy metals such as Cu, Pb,

and Ni from CG-contaminated soil, while *Typha latifolia* plants have good solidification ability for Fe in FA. Plant root exudates can also promote soil enzyme activity and enhance soil nutrient cycling [35,36]. The interaction between CBSW and microorganisms is relatively complex. The accumulation and use of materials such as CG and FA can affect the diversity and community function of soil microorganisms [37, 38]. Meanwhile, the treatment of CBSW by microorganisms can also play multiple roles, such as improving soil fertility, degrading pesticides, and sequestering CO₂ [39–41].

2.3. Ecological risk analysis

Due to the presence of components such as HMs, soluble salts, and high sulfur content, the generation and accumulation of CBSW can pollute the surrounding environment. Under simulated leaching conditions, HMs such as Cr, Mn, and Cd in CG tend to release rapidly; Pb ions in areas where CG is accumulated are prone to migration; high sulfur CG is extremely unstable in the environment and can release acidic mine water containing high concentrations of HMs; Cu, Cd, Pb ions, etc., present in FA particles generated in coal-fired areas, can damage the cellular structure of various parts of wheat seedlings [42–46]. Therefore, exploring the composition of CBSW and evaluating the toxicity of HMs holds significant research value. Common methods for assessing CBSW include leaching tests, such as the Toxicity Characteristic Leaching Procedure (TCLP), the Synthetic Precipitation Leaching Procedure (SPLP), and the European Union Leaching Test (EN 12457–2) [44]. The occurrence forms of HMs can be determined through the Community bureau of reference (BCR) Sequential Extraction Procedure and the Tessier five-step extraction method [47] (Fig. 5). According to the technical specifications for CBSW conditioners used in the remediation of saline-alkali soil (China DB6108/T 52–2023), HMs in CBSW must meet the following criteria to be used: Hg (mg/kg) < 0.5, As (mg/kg) < 20, Pb (mg/kg) < 70, Cd (mg/kg) < 0.3, Cr (mg/kg) < 150, Cu (mg/kg) < 50, Zn (mg/kg) < 200, and Ni (mg/kg) < 60. Leaching test method can predict the mobility of HMs. Its limitation lies in the significant gap between laboratory conditions and real-world environments. For soil heavy metal pollution, researchers have proposed various evaluation methods from different perspectives, such as the Potential Ecological Risk Index (PERI), the Geological Accumulation Index, and the Nemerow Pollution Index. Among them, the PERI method can effectively evaluate the risk of multiple metals in soil [48,49]. This method primarily assesses the pollution level and potential ecological risks by quantifying the content of heavy metals in soil through weighting. However, the content of HMs in soil is the result of the synergistic effects of multiple factors. This method tends to ignore these synergistic effects during evaluation [50–52]. The long-term impact of HMs in coal-based solid waste can be evaluated based on Life Cycle Assessment (LCA) [53,54]. LCA clarifies the boundaries of the life cycle assessment system for soil heavy metal pollution ecological remediation, ensuring that all influencing factors are included [55,56]. Subsequently, these data are organized and analyzed to establish a detailed life cycle inventory and form a life cycle interpretation. It is a data-intensive evaluation method.

To address the risks associated with CBSW artificial soils, a standardized performance testing and characterization protocol is proposed. The protocol begins with advanced analytical techniques—including core sample elemental scanning, micro-focus Computed tomography (CT) scanning, X-ray fluorescence (XRF), and X-ray diffraction (XRD). To investigate the chemical composition, phase constitution, and micro-morphological characteristics of coal-based solid wastes and associated minerals. This aims to identify the nature, concentration, distribution, and occurrence modes of valuable and hazardous elements present. The data will be used to evaluate the silicon-aluminum activity and glass phase content of different solid wastes, enabling the screening of CBSW materials and establishing a graded raw material classification standard tailored for specific applications. Subsequently, methods such as the

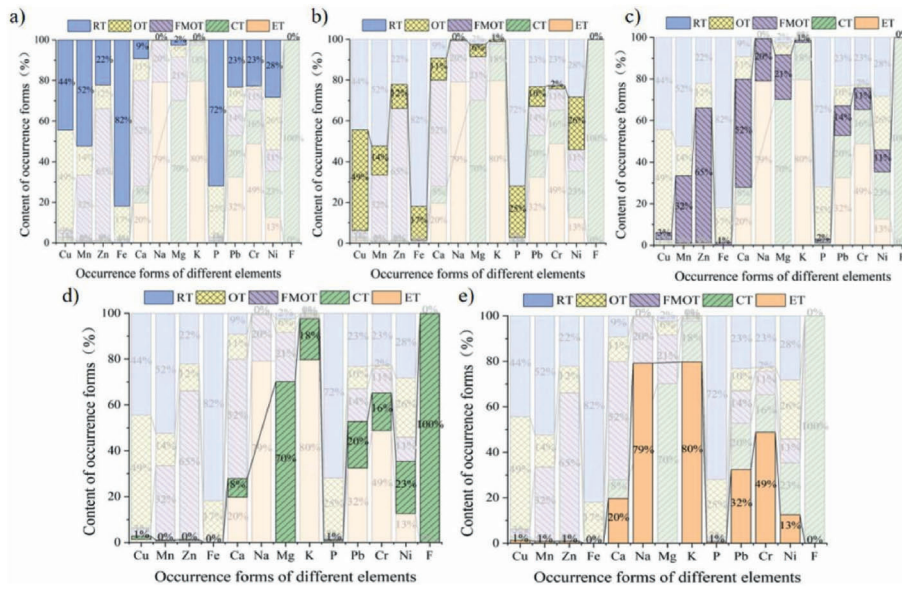


Fig. 5. Distribution of heavy metal forms (Tessier method) in CG from Fuyuan Coal Mine in Qujing, China (a) exchangeable fraction (ET); (b) carbonate-bound fraction (CT); (c) iron and manganese oxide-bound fraction (FMOT); (d) organic matter-bound fraction (OT); (e) the residual fraction (RT) [31].

BCR sequential extraction procedure will be employed to analyze the speciation of heavy metals in the soil/sediment matrix and assess their stabilization efficiency, thereby evaluating the impact of hazardous elements. Following the production of CBSW products, long-term heavy metal migration potential and material reliability will be demonstrated through column leaching experiments, accelerated aging tests, and freeze-thaw cycle tests, which simulate long-term environmental exposure.

3. Collaborative construction and performance regulation of CBSW artificial soil

Due to the unique physicochemical properties of CBSW, its application in the preparation of artificial soil can alleviate the pressure of solid waste disposal while protecting natural resources such as soil and peat. Based on the functions and requirements of artificial soil, the formulation of CBSW can be adjusted to better facilitate ecological functions such as vegetation growth, carbon sequestration, and biodiversity conservation.

3.1. Structural artificial soil

Structural artificial soil differs from ordinary artificial soil, which only focuses on fertility. It features a structured design and aims to achieve the synergy between structural functions (erosion resistance, collapse resistance, and deformation resistance) for engineering scenarios and ecological functions required for plant growth. Structural artificial soil is mostly used in fields such as slope ecological restoration and vertical planting in protected agriculture. CBSW is commonly used in slope restoration within Structural artificial soil. Ecological slope protection technology is an engineering protective measure that both protects slopes and considers ecological factors. It aims to combine living plants with civil engineering measures and non-living plant materials to reduce slope instability and erosion [57]. Therefore, the core of slope restoration lies in how to improve the mechanical properties of soil, such as erosion resistance and shear resistance, and enhance the soil's ability to support plant growth.

Current slope restoration often relies on optimizing material ratios. It adopts a synergistic approach with functional materials and incorporates soil spraying technology. This involves thoroughly mixing soil, organic matter, plant seeds, fiber materials, binders, etc. In specific

proportions and spraying them onto the surface of rock slopes. Among these, fiber materials can function similarly to plant roots, making them an effective measure for soil restoration in arid and semi-arid regions [58]. Cement is a commonly used binder. Gao et al. [59] explored the effects of five additives, including cement, peat soil, and wood chips, on slope restoration. Their research showed that cement contributed the most to plant biomass, pH value, and water retention, providing bonding strength and increasing soil strength, durability, and stiffness. Therefore, replacing part of the cement with CBSW with pozzolanic activity can not only enhance soil strength and provide nutrients for fertilizers but also reinforce the fiber materials. Li et al. [60] studied the interaction between basalt fiber and FA. As the hydration reaction progresses, CBSW can be transformed into hydration products such as CSH and Aft, which adhere to the fiber surface, forming a dense structure with the matrix, thereby improving crack resistance. Furthermore, studies on polypropylene fiber, coconut fiber, and soil mixed with FA have shown that FA fiber-reinforced soil can be considered a good foundation reinforcement technology. It provides additional shear strength to composite soil materials and increases the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) [61].

3.2. Functional artificial soil

In functional artificial soil, CBSW is utilized as a water-retaining agent and fertilizer due to its inherent rich nutrients and ability to regulate soil ion exchange. Among these applications, researchers are particularly interested in how CBSW can enhance the cation exchange capacity (CEC) of soil and its interaction with soil microbial communities.

The humic acid (HA) enhancement method is a common approach to increase cation exchange capacity (CEC) in artificial soils. HA is prepared through chemical or biological transformation, and its abundant functional groups, such as carboxyl and phenolic hydroxyl groups, enhance the soil's ion exchange capacity. Alternatively, stable complexes are formed between montmorillonite and HA through interlayer intercalation or surface complexation, synergistically enhancing CEC. For instance, CG can be oxidatively cracked at low temperature (160 °C, 4 h) with the assistance of urea to generate highly active HA, which increases CEC by over 40 %. Alternatively, CG and urea are mixed in a 1:4 ratio and reacted in a 0.62 mol/L NaOH solution at 70 °C for 6.18 h, generating HA through oxidative cracking-condensation reactions [62].

The oxygen-containing functional groups of HA can adsorb cations through ion exchange and complexation. The aromatic rings and alkyl chains in its molecular structure form a three-dimensional network, enhancing the soil's retention capacity for nutrients [62]. The permanent negative charges of montmorillonite and the variable charges of HA combine through electrostatic attraction. After complexation, the specific surface area and functional group density increase, thereby enhancing the adsorption capacity for cations.

CBSW can serve as a carrier material for microorganisms and also possesses the ability to screen microbial strains. This process is also related to plants, such as *Setaria viridis*, which can recruit CG-tolerant bacteria (such as Proteobacteria and Acidobacteriota) through root exudates, enhancing tolerance and accumulation of heavy metals [63]. Therefore, the microbial assembly of CBSW can be promoted by screening microbial strains with specific metabolic functions. This facilitates the leaching of nutrients from CG or FA, optimizes the soil microbial community structure, or uses FA or modified CG as a carrier to immobilize functional microorganisms through physical adsorption or chemical binding, thereby constructing a stable microbial-carrier composite system. For example, the *Stenotrophomonas bentonitica* BII-R7 strain isolated from soil can secrete low molecular weight organic acids such as acetic acid and formic acid, significantly improving the leaching efficiency of available phosphorus (AP) and available potassium (AK) from CG. Pikovskaya medium can be used to screen phosphorus-solubilizing bacteria, and the strains can be identified through 16S rRNA gene sequencing to optimize cultivation conditions and enhance their ore-dissolving ability [64]. After alkali treatment (4 mol/L NaOH), FA can be mixed with ethyl cellulose to form granules for the preparation of slow-release microspheres, which can then be loaded with various microorganisms (such as *Bacillus subtilis* and *Trichoderma reesei*) [9]. Research has shown that organic acids secreted by microorganisms can dissolve the crystal lattice of CBSW through proton exchange and complexation, releasing nutrients. They also regulate the microenvironment pH based on metabolic activity to promote the immobilization or transformation of HMs. The porous structure of CBSW as a carrier can provide sites for microbial colonization. Its surface functional groups (such as hydroxyl and carboxyl groups) can immobilize microbial cells through electrostatic interactions or hydrogen bonding, extending their survival period.

3.3. Adaptation to Special environments

Saline-alkali soil is a general term for saline soil and alkaline soil with varying degrees of salinization. Both contain large amounts of soluble salts, such as Na^+ , K^+ , Ca^{2+} , Cl^- , SO_4^{2-} , and CO_3^{2-} , making them unsuitable for plant growth. Currently, the area of saline-alkali soil worldwide exceeds 833 million hectares, making it difficult to utilize a large area of land resources [65]. Bi et al. [66] used a combination of halophilic *Bacillus* BH-8 and CG, significantly reducing the pH of saline-alkali soil. After 21 days, the nitrate-nitrogen content was nearly twice that of the control group. Wang et al. [67] used FGDG, and due to the effect of calcium, the dispersion of soil particles was reduced, and the aggregation rate of high-salt soil increased by 97 % to 32.5. An et al. [68] used FA as the matrix material, supplemented with nutrient additives, organic matter, acidic organic matter, and water-retaining agents, reducing the pH value of saline soil from 10.51 to 8.89. The high salt content in saline-alkali soil is mainly caused by high groundwater levels and overly dense capillary pores. CBSW has a rich specific surface area and pores. After being applied to soil, it increases the microporosity and non-capillary porosity of the soil, allowing soil salts to migrate deeper into the soil. The main components, SiO_2 and Al_2O_3 , can undergo hydration, playing a role in water retention. Exchangeable Ca ions and CaSO_4 can react with Mg^{2+} , Na^+ , CO_3^{2-} , and HCO_3^- in saline-alkali soil, generating carbonates and sulfates [67]. Existing studies have demonstrated that utilizing fly ash as a supplementary stabilizer can effectively mitigate salt-induced expansion, enhance soil structure, and improve

the durability and stability of treated soils [69]. Nan et al. [70] incorporated ionic soil stabilizers, lime, and fly ash in combination to enhance the freeze-thaw durability of saline soils. During the initial freeze-thaw cycles, the thaw-state stiffness values (G_0 and E_0) initially decreased and subsequently increased with the progression of cycles, attributable to microstructural repair via hydration reactions. After 20 cycles, both stiffness and structural integrity were improved, G_0 and E_0 reaching 1055–1325 MPa and 2973–3644 MPa. In addition to saline-alkali soil, CBSW is often used in areas such as water retention in arid regions and passivators in acidic mining areas.

4. Typical engineering application cases and evaluation methods

4.1. Typical cases of saline-alkali soil remediation

Zhao et al. [71] used FA, DG, furnace bottom slag, and coal washing sludge as the main raw materials to remediate the saline-alkali soil in Emao River, Huairan County. They evaluated the remediation effect and safety of solid waste-based artificial soil. The main mechanism behind the remediation was based on the chelation, adsorption, and ion exchange of humic acid in CBSW with saline-alkali ions. This led to the formation of large agglomerate structures in soil particles, reducing the salt transported to the soil surface due to water evaporation (Fig. 6). The results showed that after remediation, the soil pH decreased from 9.98 to 7.60, the total water-soluble salt content decreased from 8.30 to 4.80 g/kg, and organic matter increased from 6.5 to 39.1 g/kg. Furthermore, the heavy metal content in the soil did not increase after remediation. This is due to the low heavy metal content in the CBSW used, which further decreased after mixing with the original saline-alkali soil. Corn planting experiments indicated that the average yield of corn in the restored field was 16.56 % higher than the local average yield level. And the residual content of heavy metals and organic toxic substances in corn and potatoes was far below the standard values.

Dong et al. [72] conducted research on the land of the Helan Mountain agricultural and pastoral area in the northern part of Yinchuan, Ningxia. This was based on integrated technology involving targeted modification of FA combined with soil structure reconstruction. The aim was to reduce soil salinization and promote plant growth by using FA as a soil conditioner. The aim was to reduce soil salinization and promote plant growth by using FA as a soil conditioner. The results showed that after applying the conditioner for soil improvement, new crystal phases of calcite were formed in the soil minerals, the pH value decreased from 9.01 to 7.66, and porosity gradually increased. The heavy metals in CBSW are in a passively encapsulated state. For instance, FA is formed through high-temperature combustion, a process that encapsulates all metals within glass microspheres, making them resistant to leaching. When saline-alkali soil, FA-based soil conditioner, and groundwater coexist in an ecological environment, the main alkali-inducing ions in the soil solution, HCO_3^- , can undergo both ionization and hydrolysis reactions simultaneously. After adding the FA-based soil conditioner, due to the abundant active Ca^{2+} contained in the conditioner, the active Ca^{2+} easily reacts with CO_3^{2-} ionized from HCO_3^- , generating calcium carbonate precipitate while promoting the ionization reaction of HCO_3^- , producing more H^+ and thus reducing soil pH. After three consecutive years of test planting rice on the improved land covering thousands of acres, the yield per acre increased from 248 kg to 720 kg. The heavy metal content in the soil met the standard (GB 15618–2018).

To address the challenges of ameliorating saline-alkali soils in arid regions, the recycling of low-cost waste materials (FA and sewage sludge) was explored [73]. This study evaluated the effects of varying application rates of a waste mixture on three soils with different salinity levels through indoor leaching experiments. The soil samples were collected from Turkey. A mixture of sewage sludge and FA at a 1:1 wt

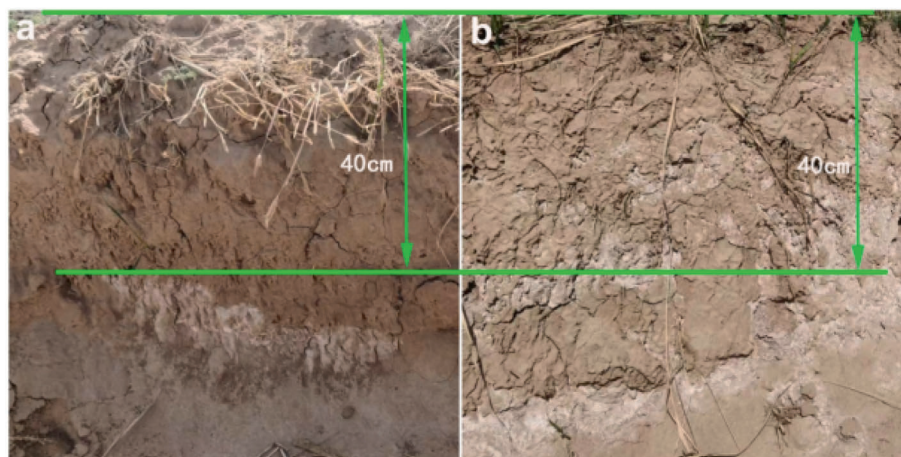


Fig. 6. Distribution of saline in soil layer: after (a) and before (b) restoration of saline alkali soil [71].

ratio was used. Following the application of the waste mixture, the Exchangeable Sodium Percentage (ESP) significantly decreased ($p < 0.01$) in all soils, with sodium ions being leached downward. This reduction is attributed to calcium ions provided by the FA displacing sodium ions. Meanwhile, the organic matter from the sewage sludge improved soil structure, increasing porosity and saturated hydraulic conductivity. The synergistic effect of the waste mixture buffered pH fluctuations and promoted the leaching of salts.

4.2. Typical cases of sand wasteland restoration

Li et al. [74] proposed a novel approach for activating and improving desert soil. This involves using sulfuric acid on FA with a large stockpile in the Ximeng region of Inner Mongolia, where soil desertification is severe. In this study, cheap and readily available sulfuric acid (1.5 mol/L) was used to modify FA. The modified FA was compounded with sandy soil at a mass ratio of 1:9 to investigate its effect on the stability of sandy soil. After pre-modification with sulfuric acid solution, the number of hydroxyl groups on the surface of FA particles increased by fourfold. The cohesion of the FA-sand soil composite increased from 0.29 kPa for the original sandy soil to 3.51 kPa after modification. Experiments showed that after acid etching, amorphous silica on the surface and inside of FA dissolved out. It could combine with H^+ at room temperature to form silica gel. The silica gel surface contains a large number of siloxane bonds (-Si-O-Si-) and silanol groups (-Si-OH-), which significantly increase the interparticle forces dominated by hydrogen bonding. And it significantly enhances the bonding between FA and sandy soil and forming a suitable soil structure. The original soil samples from the Ximeng region of Inner Mongolia have a high pH value. After adding acid-modified FA, the pH of sandy soil was improved to weakly alkaline, with a significant decrease in pH value. Therefore, adding acid-modified FA can effectively reduce the pH of sandy soil, improve soil cohesion, and reduce the risk of soil salinization and alkalization.

To explore solutions to desertification and sandification caused by mining, Li et al. [75] conducted an ecological experiment on CG wastelands in the Yulin sand area of Shaanxi Province. They used the method of “soil cushioning with sand, drought resistance and water retention, and the combination of shrubs and grasses”. The experimental site was located at the Fangjiapan Coal Mine in Yulin City, Shaanxi Province, and the test site was an open-pit coal mine dump with both platform and slope systems. The experimental soil conditioner was formed by using FA and CG, accounting for 75 %–85 % of the total, as an activator. The total thickness of sand covering and loess cushioning was 50 cm, with an additional 10–15 cm of loess cushioning. Subsequently, six types of experimental plants, including *Avena sativa* L, *astragalus laxmannii* Jacquin, *Leymus chinensis*, and *Salsola collina* Pall, were

planted at a seeding rate of 4500 t/km² to study the changes in plant biomass after applying the soil conditioner. After two years, the organic matter in the soil increased from 5.10 to 6.12 g/kg, and the available nitrogen increased from 18.07 to 33.62 mg/kg. Both available phosphorus and potassium also increased, with an average increase in aboveground biomass of 39.9 %. Thus, the use of CBSW helps to enhance soil fertility and increase aboveground biomass. Plant roots secrete substances such as organic acids, sugars, and amino acids, which stimulate the growth of microbial populations. Then influences soil enzyme activity. Microbial communities, in turn, enhance their adaptability to the environment by altering their structure, specific functions, and interaction networks. Under the combined influence of plants and coal gangue, salt-tolerant, acidophilic, and iron-sulfur-related bacteria proliferate extensively and occupy dominant ecological niches, thereby contributing to resistance against multiple heavy metals [76].

4.3. Effect evaluation method

Currently, numerous studies from around the world have proposed diverse, multi-faceted evaluation methods for natural environments and soils. These methods primarily focus on assessing soil physicochemical properties, carbon sequestration capacity, economic costs, and environmental risks. For instance, the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model is commonly used to evaluate the carbon sequestration function of ecosystem services (ESs) and the degree of soil erosion [77–81]. The Denitrification Decomposition mode (DNDC model) can be used to simulate soil carbon sequestration capacity and root respiration based on changes in carbon (C) and nitrogen (N) in the soil [82–85], or can be modified to simulate water-salt balance in the soil. The Integrated Exposure Uptake Biokinetic (IEUBK) model is often used to determine the impact of lead (Pb) pollution in soil on residents [85–87]. Additionally, models such as RothC, DayCent, and STICS are also commonly used for soil evaluation [88,89]. However, there is currently no specific evaluation method for assessing the effectiveness of CBSW in artificial soil. Therefore, based on economic benefit accounting and comprehensive evaluation, this paper discusses how to evaluate the application effect of CBSW in artificial soil. It is hoped to assist in the industrialization and implementation of CBSW.

The commonly used method in economic benefit accounting is Cost-Benefit Analysis (CBA). It was first employed in the 19th century to measure the costs and benefits of public works projects. As illustrated in Fig. 7, the CBA process compels decision-makers to consider or ascertain all pertinent costs and benefits associated with a project, policy, or decision [90]. This encompasses potential impacts on human life and the environment. Since CBSW should be considered indivisible in various projects of soil improvement, financial analysis can be conducted based

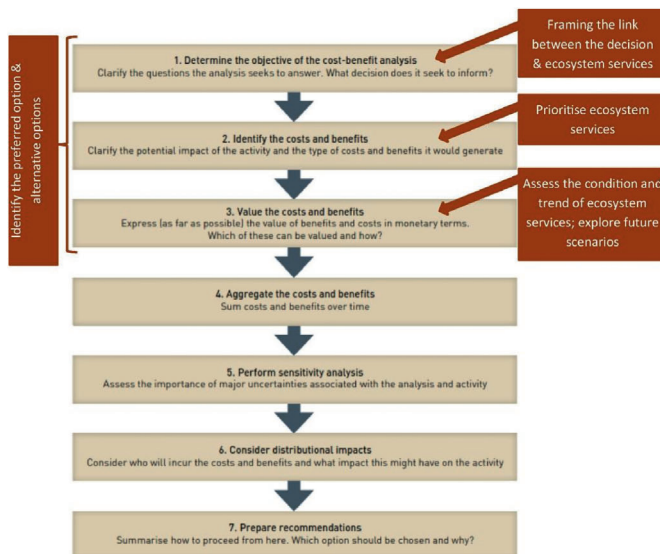


Fig. 7. CBA stages with links to an ecosystem services framework [90].

on the Net-Present Value (NPV) method, as shown in Formula 1. The calculation is conducted based on repair costs (raw material costs, construction costs) and benefits (increased agricultural production, carbon trading income). Subsequently, further precise calculations can be performed on various parts of the soil covering stage, including raw material extraction, processing and activation, construction application, and later maintenance costs, by combining methods such as Analytic Hierarchy Process (AHP), Data Envelopment Analysis (DEA), LCA, Life Cycle Costing (LCC), and Life Cycle Cost Analysis (LCCA). Some scholars have pointed out that since both LCA and CBA are used as inputs in Environmental Impact Assessment (EIA), and LCA can be used in parallel with LCC, they can be integrated to form a new sustainability assessment tool [91]. For the repaired land, the Hedonic Price Model (HPM), which is commonly used for land, housing, etc., can be based to assess the appreciation of land value [92–94].

Based on the “Technical Guidelines for Gross Ecosystem Product (GEP) Accounting of Terrestrial Ecosystems” issued by the Ministry of Ecology and Environment of China, the ecosystem service value (ESV) can be comprehensively assessed. For CBSW-remediated artificial soil, this method is calculated through Formula 2, where GEP represents the gross ecosystem product and *EPV* stands for the ecosystem material product value; *ERV* represents the value of ecosystem regulation services; *ECV* represents the value of ecosystem cultural services [95]. This evaluation method can simultaneously account for the supporting services (soil improvement, water conservation), regulating services (climate regulation, pollution purification), and cultural services (landscape aesthetics, educational value) of the project.

$$NPV = \sum_{t=0}^n \frac{B_t - C_t}{(1+r)^t} \quad (1)$$

t denotes the t -th year since the project was constructed and put into use, with B_t being the income generated by the project in the t -th year; C_t represents the cost incurred by the project in the t -th year; $1/(1+r)$ signifies the discount factor when the interest rate is r ; and n stands for the duration of the analyzed project

$$GEP = EPV + ERV + ECV \quad (2)$$

5. Conclusion

Research shows that CBSW-based artificial soil has excellent properties such as water retention, carbon sequestration, and plant growth promotion. After being regulated using different methods, it can be

widely applied in areas like water-retaining agents, fertilizers, saline-alkali soil management, and mine management. This paper summarizes the classification and physicochemical properties of CBSW, discusses the feasibility of using CBSW as a matrix for artificial soil. It also explains how to regulate and prepare artificial soil with various functions based on engineering needs. Typical engineering cases for restoring ecological environments, such as saline-alkali land and sandy wastelands, are included. CBSW occupies a large area and poses environmental threats when stockpiled. Using CBSW in artificial soil construction helps solve the problem of solid waste accumulation. It also reduces potential environmental issues and lowers the cost of artificial soil. This approach opens new possibilities for combining ecological restoration technology with resource use. It is significant for the safe treatment of solid waste.

Currently, many deficiencies exist in the research on constructing artificial soil using CBSW: 1. The application of CBSW in soil exhibits boundary effects, and research on how to maximize its use is still ongoing. 2. The synergistic mechanism between CBSW, plants, and microorganisms in soil is complex, and there is still no unified conclusion in academia. 3. The use of CBSW in soil construction and ecological environment management can have long-lasting and profound impacts, and research in this area requires long-term tracking, making it impossible to completely rule out the possibility of new environmental issues arising from the large-scale application of CBSW. 4. There is no specific method to evaluate the effectiveness of CBSW in artificial soil, hindering its large-scale engineering application.

Further research on the construction of artificial soil from CBSW can focus on the following areas: 1. Integrating modern computer technology to simulate the synergistic effects of CBSW with plants and microorganisms over time. 2. Employing computational materials science and computer simulation methods, particularly molecular dynamics, aims to investigate the interaction mechanisms between CBSW components and soil minerals, organic matter, and water at the atomic/molecular level. It will provide a theoretical foundation for the preparation of novel materials. 3. Furthermore, tailored to specific environmental needs, functional gradient composites using CBSW as the raw material can be developed. These composites can be engineered to meet the requirements of different soil layers. 4. Developing new evaluation methods to assess the effectiveness of CBSW in artificial soil, aiding its industrialization and implementation.

CRedit authorship contribution statement

Hui Deng: Writing – original draft. **Lijuan Wang:** Writing – review & editing. **Kunqian Zhu:** Data curation. **Libing Liao:** Project administration. **Guocheng Lv:** Writing – review & editing, Project administration.

Declaration of competing interest

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

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