Carbon-based Materials for Sustainable Soil Salinity Management: Mechanisms, Modeling, and Applications in the Era of New Energy

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Abstract. The study of soil water-salt transport mechanisms is of great significance for salinity control and sustainable agricultural development. In recent years, carbon-based materials (e.g., biochar, straw-derived charcoal) have significantly enhanced the water infiltration capacity and desalination efficiency of saline-alkali soils by improving soil physical structure, regulating salt ion adsorption, and enhancing microbial activity. The porous structure and surface functional groups of biochar promote water movement and immobilize salt ions such as Na^+ and Cl_-, while straw mulching and incorporation reduce soil salinity risks by suppressing evaporation, optimizing pore structure, and driving microbial desalination processes. Meanwhile, the integration of numerical models (e.g., Green-Ampt, HYDRUS) with machine learning techniques has provided new tools for precise simulation of water-salt transport and optimization of carbon-based material application. This paper systematically reviews the mechanisms of water-salt transport regulation by carbon-based materials and advances in model applications, exploring their potential in sustainable agriculture and ecological restoration, thereby offering theoretical support for the resource utilization of saline-alkali soils in the era of new energy.

Keywords: Carbon-based materials; Water-salt transport; Salinity control; Biochar; Straw incorporation; Green-Ampt model; HYDRUS model; Sustainable agriculture; Soil remediation.

1. Introduction

The mechanisms of soil water-salt transport are central to salinity research. Strengthening the study of soil water-salt systems, understanding the transport mechanisms and dynamics of soluble salts in soil, and employing suitable mathematical models for quantitative numerical simulation can lay a solid foundation for monitoring, evaluating, and managing soil salinity [1]. In recent years, significant progress has been made in the application of carbon-based materials (e.g., biochar, straw-derived charcoal, nanocarbon) to regulate soil water-salt transport.

2. Effects of Carbon-Based Material Application on Soil Water-Salt Transport

2.1 Mechanisms of Biochar Application on Soil Water-Salt Transport

Biochar provides habitats and carbon sources for soil microorganisms, promoting the proliferation of salt-tolerant microbial communities and accelerating organic matter decomposition and salt transformation. Chen et al. (2022) found that biochar application significantly increased the abundance of Desulfovibrio and nitrifying bacteria in saline-alkali soils, driving sulfate reduction and nitrate leaching, thereby reducing salinity risks[2]. Studies indicate that biochar significantly improves the water-holding capacity and infiltration rate of saline-alkali soils by enhancing pore structure and aggregate stability [3]. Zhang et al. (2022) demonstrated that the combined application of straw-derived charcoal and biochar reduced surface salt accumulation and promoted salt leaching, particularly in arid regions[4]. Additionally, nanocarbon materials, with their high surface area and adsorption capacity, can effectively immobilize salt ions, mitigating their stress on crop roots [5].

The porous structure of biochar significantly alters soil pore distribution, increasing saturated hydraulic conductivity and promoting water infiltration and salt leaching. Li et al. (2022) reported through column experiments that adding 5% biochar (derived from wheat straw) increased the infiltration rate of saline-alkali soil by 35% and reduced surface salt accumulation by over 20% [6]. Similarly, Zhang et al. (2023) noted that biochar application (10 t/ha) reduced soil bulk density, increased macroporosity, and delayed capillary rise, thereby inhibiting surface salt accumulation [7].

Biochar surfaces are rich in oxygen-containing functional groups (e.g., carboxyl, phenolic hydroxyl), which can immobilize salt ions like Na^+ and Cl_- through ion exchange and electrostatic adsorption. Wang et al. (2021) showed that wood-derived biochar had a Na^+ adsorption capacity of 45.2 mg/g, significantly reducing soil solution electrical conductivity (EC) [8]. Furthermore, the alkaline nature of biochar can neutralize acidic saline soils, adjusting pH and reducing aluminum and sodium toxicity [9].

Despite its short-term efficacy, the long-term stability of biochar requires attention. Zhao et al. (2023) found through a 5-year field trial that biochar's ameliorative effects peaked in the first 3 years and gradually declined thereafter, recommending reapplication every 3~5 years [10]. Additionally, the feedstock (e.g., wood, straw, manure) and pyrolysis temperature (300–700°C) of biochar influence its effectiveness, necessitating tailored selection based on soil type [11].

2.2 Effects of Straw Application on Soil Water-Salt Transport

Straw incorporation and mulching, as key agricultural practices, significantly regulate soil water-salt transport. Straw mulching reduces soil evaporation and surface salt accumulation. Sun et al. (2022) found that 5 cm straw mulching in arid farmland increased topsoil (0–20 cm) moisture by 15–30% while reducing salt accumulation by over 40% [12]. Straw incorporation also improves soil structure, enhances pore connectivity, and increases water infiltration. Li et al. (2023) reported that deep straw incorporation (20–40 cm) increased the saturated hydraulic conductivity of saline-alkali soil by 25%, promoting salt leaching to deeper layers [13].

Organic acids (e.g., humic acid, fulvic acid) released during straw decomposition can chelate salt ions like Na^+ and $Ca_2{}^+$, reducing their activity. Wang et al. (2023) observed in microplot trials that straw incorporation reduced the exchangeable sodium percentage (ESP) by 20~35%, alleviating sodium toxicity [14]. Additionally, straw-derived carbon promotes soil colloid formation, enhancing salt ion adsorption [15].

Straw provides carbon for soil microorganisms, stimulating salt-tolerant microbial growth and accelerating organic mineralization and salt transformation [16]. Chen et al. (2023) demonstrated through metagenomic analysis that straw incorporation increased the abundance of halophiles (e.g., Halomonas) and Desulfovibrio in saline soils, facilitating sulfide and nitrate transformation and reducing salinity risks [16].

However, the application rate and ratio of carbon-based materials still need optimization to avoid soil structure damage or increased costs due to excessive use. Li et al. (2012) set up different straw interlayer materials to analyze the mechanism of straw interlayer treatments in inhibiting soil salinity [17]. Their research showed that straw interlayers enhanced the leaching effect of salts. Liu et al. (2011) demonstrated through experiments that straw mulching promotes soil desalination [18]. Yu et al. (2015) found that straw returning could enhance winter wheat growth, increase yield, and improve water use efficiency [19]. Straw mulching and returning effectively block direct sunlight from reaching the ground, reduce ineffective evaporation between plants, increase soil moisture content, and inhibit the upward movement of deep soil salts. At the same time, straw mulching and returning prolong the infiltration time of irrigation or rainwater, improving the leaching effect on salts in the tillage layer. Returning straw below the tillage layer can increase soil porosity, suppress capillary water evaporation, and achieve water retention and salt suppression [20]. It can also serve as a "water storage layer" to improve soil moisture content. Additionally, studies have shown that biochar increases the infiltration rate of saline-alkali soil by enhancing porosity and aggregate formation, improving soil colloid cementation substances and microbial populations [21], thereby achieving remediation. However, most of these remediation materials involve complex processes and large application rates, leading to high costs.

3. Advances in Water-Salt Transport Modeling

3.1 Green-Ampt Model in Water-Salt Transport Simulation

Quantitative numerical simulation using suitable mathematical models is also indispensable for studying water-salt transport laws. Among these, the Green-Ampt model is commonly used in simulating water-salt transport characteristics. Proposed in 1911 by Green and Ampt based on soil capillary theory [22], the Green-Ampt model is widely applied due to its high computational accuracy. With its solid theoretical foundation and precision, the Green-Ampt model remains extensively used in simulating water-salt transport in saline-alkali soils. Zhou et al. (2021) modified the Green-Ampt model by introducing dynamic hydraulic conductivity parameters, making it more suitable for infiltration simulation in heterogeneous saline-alkali soils [23]. Moreover, machine learning methods are gradually being introduced into water-salt transport research. For example, Liu et al. (2022) combined support vector machines (SVM) with the Green-Ampt model, significantly improving the accuracy of salt transport predictions [24]. Li et al. (2024) enhanced the model's applicability to straw-improved soil infiltration by modifying the wetting front matrix suction parameters, achieving a 12% increase in accuracy [25].

As research progresses, the Green-Ampt model has been continuously modified and applied to infiltration studies in soils with uneven initial moisture content [26], layered soils [27-28], muddy water infiltration [29], and rainfall infiltration [30], demonstrating its broad applicability. Zhao et al. (2010) developed a Green-Ampt model suitable for constant-head well infiltration, derived expressions for infiltration rate and cumulative infiltration, inversely solved soil hydraulic conductivity and wetting front matrix suction, and found that the soil wetting body under constant-head well infiltration assumes an ellipsoidal shape [31]. Ma et al. conducted large-scale experiments on layered soil columns and modified the Green-Ampt model using Bouwer's method, with the revised model showing good simulation results [32]. Modifications to the Green-Ampt model primarily focus on transforming and solving parameters such as soil hydraulic conductivity and wetting front matrix suction, which present significant challenges. To date, numerous studies have used this infiltration model to simulate saline-alkali soil infiltration processes. Zhou et al. (2018) applied Bacillus subtilis to improve saline-alkali soil and fitted infiltration data using both the Philip and Green-Ampt models [33]. The results showed that the Green-Ampt model had smaller errors than the Philip model [33]. This aligns with the findings of Wang Quanjiu et al., confirming that the Green-Ampt model offers higher simulation accuracy for longer infiltration durations [34]. Due to the presence of salt ions, saline-alkali soils exhibit reduced infiltration performance and longer infiltration times compared to ordinary soils [35], making the Green-Ampt model more suitable for describing water transport laws in such soils.

3.2 HYDRUS Model in Water-Salt Transport Simulation

For water-salt transport problems with complex boundary conditions, the HYDRUS model has also achieved new advancements. Li et al. (2023) used HYDRUS-2D to simulate salt distribution patterns in soil profiles under different irrigation methods, providing theoretical support for precision irrigation [36]. Meanwhile, the development of coupled models (e.g., Green-Ampt and solute transport models) has further enhanced the simulation capability of coordinated water-salt transport [37].

The HYDRUS model is widely used in water-salt transport simulations due to its robust numerical computation capabilities and adaptability to complex boundary conditions. Based on the

Richards equation and solute transport equation, the model can simulate dynamic changes in water and salt under various irrigation methods, climatic conditions, and soil management practices [38].

Research indicates that the HYDRUS-1D/2D/3D models have significant advantages in evaluating the effects of different irrigation methods (e.g., drip irrigation, subsurface irrigation, and flood irrigation) on salt distribution. For example, Li et al. (2022) used HYDRUS-2D to simulate salt accumulation patterns in root zones under drip irrigation, finding that high-frequency, low-volume irrigation effectively reduces surface salt accumulation [39]. Additionally, Wang et al. (2023) combined HYDRUS-3D to simulate the improvement effects of mulched drip irrigation on saline-alkali soils, revealing that mulching combined with drip irrigation significantly reduces surface salt concentration and improves water use efficiency [40].

In recent years, researchers have begun integrating the remediation effects of carbon-based materials (e.g., biochar, straw-derived biochar) with the HYDRUS model to optimize saline-alkali soil management strategies. For instance, Zhang et al. (2021) used HYDRUS-1D to simulate the effects of biochar application, showing that it significantly improves soil water retention and delays salt rise [41]. Chen et al. (2023) further combined field experiments with HYDRUS simulations, proving that the combined application of biochar and straw enhances salt leaching and reduces salinization risks [42]. The mechanisms of water-salt regulation by biochar have gradually been incorporated into numerical models. For example, Zhou et al. (2023) added a biochar module to HYDRUS-1D to simulate salt leaching dynamics under different application rates, with results closely matching field data (R^2=0.85)[43]. Furthermore, the modified Green-Ampt model, by introducing biochar correction parameters (e.g., porosity change coefficients), can more accurately predict infiltration processes in biochar-improved soils [36]. Zhang et al. (2023) introduced a straw mulching module in HYDRUS-1D to simulate the effects of different mulching thicknesses on soil water-salt dynamics. The results showed that a 10 cm mulching layer provided the best salt suppression effect (R^2=0.89) [41].

With the advancement of artificial intelligence, some studies have attempted to combine machine learning (e.g., random forests, neural networks) with the HYDRUS model to improve simulation efficiency and accuracy. Liu et al. (2023) proposed a deep learning-based parameter optimization method for HYDRUS, significantly reducing the time cost of traditional inversion calculations and enhancing the accuracy of salt transport predictions [44].

4. Summary

Current research on water-salt transport focuses on single or multiple factors, showing positive effects of carbon-based materials. However, studies on composite applications are limited. Field experiments are time-consuming and face numerous variables, necessitating combined lab studies and advanced modeling (e.g., modified Green-Ampt, HYDRUS, machine learning) to uncover deeper mechanisms.

Acknowledgment

This work was supported by Open Research Fund Program of State Key Laboratory of Eco-hydraulics in Northwest Arid Region, Xi’an University of Technology, (Grant No. 2023KFKT-7). The authors also wish to acknowledge the Chinese Academy of Sciences "Light of the West" Young Scholar Program for providing financial support for this paper.

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