applied sciences

MDPI

Review

Progress and Prospect of Saline-Alkaline Soil Management Technology: A Review

Zhengkun Li [1], Mcholomah Annalisa Kekeli [1], Yaqi Jiang [1] and Yukui Rui [1,2,3,4,5,*]

[1] College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China; tyutlizhengkun@163.com (Z.L.) annalisamcharthyholomah@gmail.com (M.A.K.); jyq9797@163.com (Y.J.)
[2] Professor Workstation in Tangshan Jinhai New Material Co., Ltd., China Agricultural University, Tangshan 063305, China
[3] Shanghe County Baiqiao Town Science and Technology Courtyard, China Agricultural University, Jinan 251600, China
[4] Hebei Wuqiang County Professor Workstation and Science and Technology Small Courtyard, China Agricultural University, Hengshui 053300, China
[5] State Key Laboratory of Nutrient Use and Management, China Agricultural University, Beijing 100193, China
* Correspondence: ruiyukui@163.com

Abstract: Saline-alkaline and alkaline land is an important potential cultivated land resource in the world. With the destruction of the ecological environment, the cultivated land area is less and less. As a potential soil conditioner, wood vinegar can adjust soil pH, increase root activity, and promote seed germination and root growth, showing its potential in improving saline-alkaline soil. This review summarizes the present situation of saline-alkaline and alkaline land, and its application to China's cultivated land policy. The traditional saline-alkaline and alkaline land management measures, and analyzes the advantages and disadvantages. Some new methods of treating saline-alkaline soil were enumerated, and the methods of treating saline-alkaline soil with wood vinegar were emphatically introduced, and the molecular mechanism of action of wood vinegar was discussed, the effects of long-term application of wood vinegar on the stability of soil ecosystem were analyzed. The prospect of comprehensive management of saline-alkaline land and how to balance economic development were proposed.

Keywords: saline-alkaline soil; wood vinegar; soil treatment; phytoremediation; salt-tolerant crops

check for updates

Academic Editor: Angeles Sanroman Braga

Received: 26 February 2025
Revised: 14 April 2025
Accepted: 17 April 2025
Published: 21 April 2025

Citation: Li, Z.; Kekeli, M.A.; Jiang, Y.; Rui, Y. Progress and Prospect of Saline-Alkaline Soil Management Technology: A Review. *Appl. Sci.* **2025**, *15*, 4567. https://doi.org/10.3390/app15084567

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Globally, the extent of saline-alkaline soils is nearly 1 billion hectares (10×10^8 hm^2), making up roughly 33.3% of the world's total land area [1]. Alarmingly, this area is expanding at a rapid pace, increasing by approximately 12 million hectares (0.12×10^8 hm^2) annually. This growth poses significant challenges for agriculture, ecosystems, and land management, highlighting the urgent need for effective strategies to combat soil degradation and ensure sustainable land use. Soils in countries like China, India, the United States, and Italy also experience varying degrees of salinization, which has become a global problem and poses an increasingly serious global challenge [2,3].

Saline-alkaline soil refers to alkaline soil containing abnormally high concentrations of soluble salt ions. These soils are notorious for being unsuitable for crop cultivation, as they often fail to support any plant growth [4,5]. The degree of salinization in China is particularly severe compared to other parts of the world. The area of saline-alkaline land in China is 3.47×10^7 hm^2, which accounts for about one third of the total global area [6].

Saline-alkaline soils are mainly distributed across China's northeast plain, northwest arid region, semi-arid area, east coastal area, and the Huanghuai plain.

1.1. The Development and Properties of Salt-Affected Lands

The development of salt-affected soils is influenced by various natural factors, such as climate conditions and topography, and the specific combination of geology and geomorphology. The development and properties of salt affected lands in China vary across different geographical regions due to diverse climatic and topographic conditions. These lands can be broadly categorized based on soil type, vegetation and environmental conditions as illustrated in Figure 1 below. Extreme climatic conditions, such as drought and low rainfall, restrict the loss of soil moisture and salt movement, leading to the accumulation of salt in the topsoil layer. The fluctuation of topography and the diversity of geomorphology also affect water flow and salt distribution, aggravating the process of salinization. Secondary Salinization is another contributing factor, such as the weathering of parent materials rich in salts or the intrusion of seawater in coastal areas. At the same time, human activities play a crucial and integral role that cannot be disregarded. These activities include long-term irrigation practices, the lack of scientifically planned drainage systems, and the over-reliance on and over-application of chemical fertilizers in agricultural production. These activities contribute to the natural imbalance of the soil, preventing the effective dilution and drainage of salts in the soil, thereby forming saline-alkaline soils [7,8].



Figure 1. Types of saline-alkaline lands in China [9]. In the figure; 1—Semi-humid semi-dry early steep meadow saline area in Northeast China, 2—Arid, semi-desert grassland saline area in Inner Mongolia Plateau, 3—Gansu and Xinjiang desert saline areas, 4—Extreme arid desert saline area in Qinghai and Xinjiang, 5—Saline area of Alpine desert in Tibet, 6—Inland local saline-alkali soil coastal saline soil, 7—Arid semi-desert saline area in the middle and upper reaches of the Yellow River and 8—Semi-humid to semi-arid dryland-meadow saline area in the Huang-Huai-Hai Alluvial Plain.

1.2. Classification of Saline-Alkaline Soil

Based on the formation period and transformation characteristics of saline-alkaline land in China, these soils can be classified into three categories. One such category is potentially salinized soils [10], which make up approximately 50% of the total land area. These soils were previously affected by salt accumulation, but the process has since halted. However, due to extreme drought conditions, the residual salts remain in the soil, as natural leaching is difficult. A notable example is salinized ash desert soil [11], which is widely distributed in arid regions with high terrain and specific bioclimatic conditions. A typical occurrence of potentially salinized soil can be observed in terraces formed in Piedmont sloping plains and old river (lake) beds. In these regions, salt accumulation was interrupted due to changes in topography, yet significant amounts of salt remained in the soil over time. Although these soils do not currently display significant salinization, they constitute about 20% of the total land area, and have the potential to transform into saline-alkaline soils under specific environmental conditions or improper land management practices [12].

Saline-alkaline soils are generally categorized into three levels based on their salinity: mild, moderate, and severe. Mild saline-alkaline soils contain less than 3% salt, and have a pH between 7.1 and 8.5. Under these conditions, the negative impact on crops is relatively low, allowing seedling emergence rates to remain between 70% and 80%. This type of land is more conducive to agricultural activities, and can be cultivated with minimal soil improvement efforts. On the other hand, severe saline-alkaline soils have a salt content exceeding 6% and a pH above 9.5, resulting in a highly alkaline environment. These conditions significantly hinder plant growth, causing seedling emergence rates to drop below 50%. Due to the extreme levels of salinity and alkalinity, direct crop cultivation is usually impractical, making soil improvement a necessary step before agricultural use. Moderate saline-alkaline soils lie between these two extremes, displaying intermediate salt concentrations and alkalinity levels. Although they still present challenges for farming, their productivity can be improved with appropriate management techniques.

There is an inverse relationship between salinity and seedling emergence, meaning that as salinity levels rise, seedling emergence declines. Over time, the spatial distribution of saline-alkaline soils shifts, causing the central points of high, moderate, and low saline-alkaline stress zones to change. In coastal areas, regions experiencing severe salinity stress often remain close to the shoreline, while moderately saline-alkaline lands gradually migrate inland, shifting from the southwest coastline toward the northwest [13,14].

1.3. The Impact of Saline-Alkaline Soils and the Challenges They Present

Saline-alkaline soils contain various salt ions, including K^+, Ga^{2+}, CO_3^{2-}, and Cl^-, which alter soil structure and contribute to salt accumulation in the surface layer. This accumulation severely limits plant growth by restricting water and nutrient availability. Additionally, soil compaction worsens the issue by reducing porosity, permeability, and water absorption, further hindering plant establishment and growth [15]. As soil salinization intensifies, it negatively affects soil microorganisms by disrupting their growth, reproduction, metabolism, and enzyme activities. This disruption hinders the breakdown and conversion of organic materials, reducing soil fertility and overall ecosystem diversity, which are crucial for plant life [16]. The persistent accumulation of salt in both the surface and deeper layers of the soil leads to a significant decline in its physical properties and functionality [17]. These effects manifest in several ways, including reduced soil cohesion, increased bulk density, diminished aeration, and severe inhibition of aerobic microbial activity. Such conditions not only promote further salt buildup in the topsoil, but also create a vicious cycle that stunts plant development, ultimately leading to plant withering and, in extreme cases, death [18]. The detrimental effects of soil salinization on plants extend be-

yond soil structure, affecting plant physiology at multiple levels. It disrupts tissue integrity, interferes with stomatal function, restricts nutrient uptake, and weakens the microbial community essential for soil health and plant growth [19]. The high osmotic pressure created by soluble salts in saline-alkaline soils leads to plant cell dehydration, triggering physiological stress responses similar to those caused by drought. In severe cases, these adverse conditions result in significant growth deformities or even plant mortality [20].

In light of the serious challenges brought about by land salinization, we must adopt diversified comprehensive management strategies, in accordance with the actual conditions of saline-alkaline areas. Researchers have developed management strategies like improving soil structure, adjusting water balance, enhancing microbial activity, screening and planting salt-tolerant crops, etc., to gradually restore soil health and improve land use efficiency, to create more favorable conditions for agricultural production.

The reduction and degradation of arable land in China pose significant challenges to the long-term growth of farming, livestock, and the building of ecological systems [21,22]. The increasing demand for resources is increasing urge for advancing the study and innovation of techniques to enhance salt-affected soils [23]. Therefore, it is necessary to use current methods to neutralize and treat saline-alkaline land.

This review will comprehensively examine both traditional and advanced techniques for managing saline-alkaline soils. It will focus on established methods such as water conservancy and phytoremediation, while also introducing innovative approaches like wood vinegar. The review will analyze the feasibility, advantages and limitations of these methods, with particular emphasis on the novel application of wood vinegar for treating saline-alkaline land.

2. Traditional Management Techniques and Methods

The traditional method of treating soil under salt alkali stress is the process of reducing the salinity and alkalinity of soil. Currently, the mature methods of treating soil under salt alkali stress include water conservancy improvement, plant restoration, traditional inorganic chemical methods, agricultural restoration, and more shown in Figure 2. Some of these methods are often used in combination under certain circumstances [24]. In the following sections, these methods will be broken down and discussed in detail exploring their effectiveness and application in different scenarios.



Figure 2. The traditional management method of saline-alkaline and alkaline land.

2.1. Water Management

Water conservation measures have long been recognized as an effective approach for improving soils affected by saline-alkaline stress. The most effective approach to managing both salinity and water saturation is by draining the salt away from the root

zone and controlling the water tale level [25]. The key to this method lies in establishing a well-structured irrigation and drainage system, including properly designed irrigation channels and an efficient drainage network. Regular and controlled irrigation and drainage practices [26] serve as a vital factor in minimizing salt accumulation in the soil, thereby creating favorable conditions for crop growth. This method is highly adaptable, requiring less time and labor while ensuring sustainable soil management.

A practical example of this approach is research by Shang Zhenfang et al., who utilized sprinkler and drip irrigation systems, either individually or in combination to target specific sensitive areas in the soil affected by inorganic salt deposition [27]. Similarly, Chen Xiaoyu et al. conducted a field experiment on salt irrigation, revealing a direct relationship linking the amount of saltwater applied and the effectiveness of soil desalination. Their findings demonstrated a significant reduction in salinity levels in the surface soil layer, confirming the visibility of this method for changing saline-alkaline soils [28].

One of the most widely used methods for managing salinity is leaching, which involves applying additional water beyond crop requirements to flush excess salts form he soil. This process helps prevent salt accumulation in the root zone, promoting better water and nutrient availability of crops [25]. However, the success of leaching depends on significantly in the soil's hydraulic properties, with soil texture influencing water movement and salt dynamics [29]. While leaching is an essential tool, it must be carefully managed, as excessive irrigation can lead to the loss of essential nutrients and agrochemicals contributing to water contamination and decreasing overall water use efficiency [30]. In areas with limited water availability, farmers must strike a balance between maximizing crop area without leaching, which may reduce yields and allocating water for leaching to improve yield per unit area. Research suggests that leaching is more cost-effective hen soil salinity levels exceed the crops salinity threshold [31].

An emerging strategy for maintaining soil salinity is rainwater harvesting, which is especially beneficial in protected and open field cultivation systems. Farmers can capture rainwater from greenhouse roofs or other sources, using it for irrigation or leaching. This method is not only cost effective, but also sustainable, as it allows for the use of good quality water in leaching operations. Cyclic irrigation, which includes intermittent leaching fractions, has been found to be more efficient than applying leaching at every irrigation event [32,33].

Seasonal fluctuations in groundwater salinity also affect water management strategies. Higher electrical conductivity values are often observed during the summer months due to the increased evapotranspiration and lower rainfall. This suggest that crops planted early in the summer or winter crops could be more effective for managing salinity stress [25]. Additionally, preseason salt flushing (a form of salt leaching) is an effective way to lower salinity in soil before planting, but it should be followed by regular leaching throughout the growing season to prevent the soil from becoming resalinized [34].

However, the implementation of this approach comes with several challenges. One major issue is its high water consumption, which significantly raises management costs, particularly in regions facing existing water shortages. Cuevas et al. [25] stated that desalinized water is an effective solution to solving soil salinity, but its high cost (often exceeding EUR 0.50 per cubic meter) makes it unaffordable for many farmers. Additionally, frequent irrigation and drainage can lead to loss of essential nutrients, ultimately compromising soil fertility and disrupting the soils ecological balance over time [35]. Furthermore, in arid and semi-arid regions or areas facing severe water shortages applying water-based soil improvement techniques become even more challenging and expensive, often limiting both their feasibility and overall effectiveness [36].

2.2. Traditional Inorganic Chemistry Method

Saline-alkaline soils contain a variety of soluble ions, which can be classified into two main categories based on the types of salts present. One category includes saline-alkaline soils, which primarily consists of ions such as Na^+, K^+, Cl^-, and SO_4^{2-}. the other category includes alkali soils, which are characterized by high pH and primarily contain Na^+, HCO_3^-, and CO_3^{2-} [4]. To improve the soils ionic balance, ion exchange, and acid base neutralization, soil conditioners are often applied. These methods are considered chemical approaches to soil improvement [37]. Chemical improvement techniques for saline-alkaline soils include the use of chemical amendments such as gypsum, aluminum sulfate, and ferrous sulfate [38]. These agents interact with soil salts through chemical reactions, effectively reducing soil pH levels and salt concentrations, thereby enhancing soil chemical properties. For instance, experiments conducted by Feng Haojie et al. [39] demonstrated that changes in land use patterns significantly improve soil chemical attributes, including pH, electrical conductivity (EC), exchangeable sodium concentration, and its percentage. These enhancements create an optimal chemical environment that promotes the natural development of soil aggregates. Furthermore, this process promotes the accumulation of organic matter (SOC), exchangeable calcium ions (Ca^{2+}), and low-crystallinity iron/aluminum oxides inside this soil. These components combine with clay minerals to form stable metal complexes, directly facilitating soil aggregation and enhancing soil structural stability.

In a related study, Du Xuejun et al. [40] investigated the effects of nitrogen and phosphorus on soil microbial communities under saline-alkaline stress. By analyzing DNA extracted from soil samples, they found that the addition of nitrogen and phosphorus significantly increased the expression levels of microbial functional genes associated with the carbon cycle. These findings indicate that nutrient supplementation not only promotes plant growth, but also activates metabolic pathways in soil microbial communities. These pathways are involved in critical processes such as carbon sequestration, transformation, and release, thereby improving the ecological functions and long-term fertility of saline-alkaline soils.

Wang Shirui et al. [41] further demonstrated that the application of sodium ion adsorbents and desulfurization gypsum to saline-alkaline soils gradually reduces soil pH and inorganic salt content, making the soil more suitable for plant growth. Similarly, Ren Zhisheng highlighted that calcium ions in phosphogypsum exchange with sodium ions in the soil, effectively reducing soil salinity and improving soil structure [42].

The primary advantage of traditional inorganic chemical improvement techniques lies in their ability to reduce soil pH values effectively. Additionally, these methods are cost-efficient, particularly when using phosphogypsum, which is an industrial byproduct available at a low cost [43].

2.3. Phytoremediation

Phytoremediation, also referred to as vegetative bioremediation, utilizes salt-tolerant or salt-accumulating plants to mitigate soil salinity or sodicity [44]. This process involves the use of species that remove salt ions to manage salinity and sodicity, thereby supporting the long-term sustainability of agricultural lands [45]. This approach is extensively utilized in the management and restoration of saline-alkaline soils, especially in regions experiencing mild to moderate salinity stress. Compared to other salt remediation techniques, phytoremediation presents several unique benefits. For instance, while gypsum application mainly influences the upper soil layers, phytoremediation promotes a more consistent reduction of salinity across the entire soil profile, including deeper sections. Phytoremediation has also been shown to be economically viable, particularly when there is a market

demand for the crops used in the process as shown in Figure 3 or when these crops can be utilized differently at the farm level [46]. This results in more efficient and comprehensive salt removal, establishing it as a sustainable and enduring solution for soil reclamation.

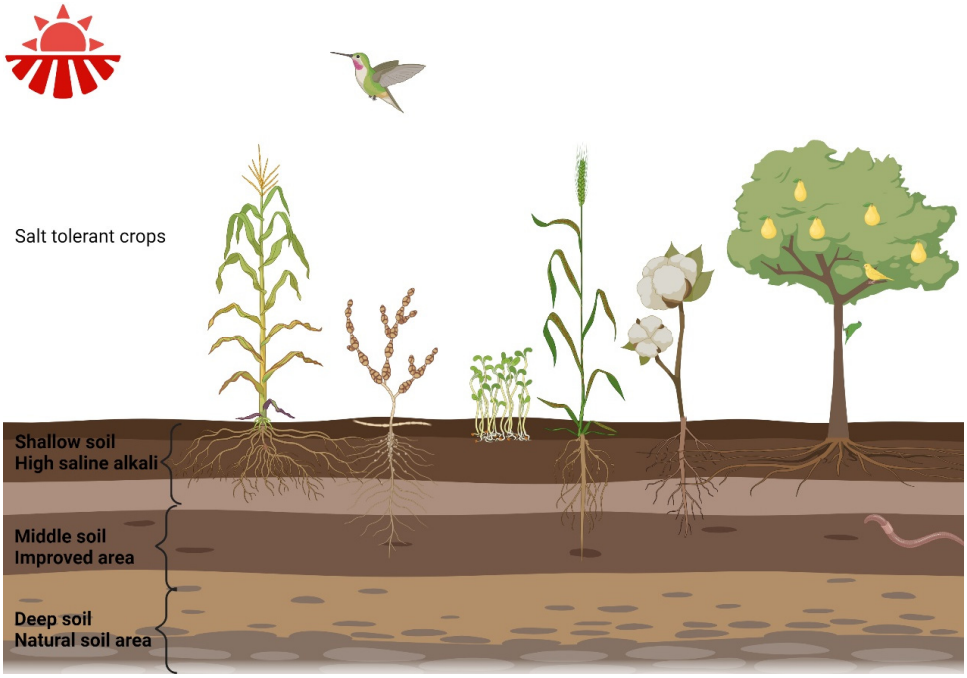


Figure 3. Planting salt-tolerant plants releases salt from the soil.

Certain plant species have adapted to saline-alkaline and alkaline environments, commonly referred to as halophytes. These plants can thrive in high salinity conditions where conventional crops struggle [47]. These plants are unique to the extent that they can compete their life cycle under salt stress, and some even perform better in saline-alkaline conditions that in fresh water [48]. Flowers and Colmer [49] reported that halophytes can even thrive and reproduce in conditions with recorded salt concentrations of 200 nM of NaCl. Several studies have explored the use of halophytes for reclaiming salt affected soils [50,51]. Phytoremediation, particularly with halophytes, has proven effective in ameliorating calcareous saline-alkaline and sodic soils, often outperforming chemical treatments [52]. In addition to improving saline-alkaline soil conditions, some halophytes show promise as a forage crop or oilseed sources [53]. For instance, *Suaeda nudiflora* was found to remove significant amounts of salt from soil, making it an efficient candidate for phytoremediation [54]. The ability of halophytes to accumulate large amounts of salt in their above-ground biomass is especially beneficial in arid and semi-arid regions, where water scarcity makes traditional methods ineffective [55]. The introduction of halophytes could provide both environmental and economic solutions for managing saline-alkaline soils, creating a more sustainable agricultural system.

Research conducted by Ashaf, M. et al. [56] has shown that cotton plant also possesses strong salt tolerance, allowing it to grow in soils with moderate salinity levels. Like Tiedge, Kira J et al. [57] identifies *melilotus ruthenic* as a highly salt tolerant forage crop that is well suited for cultivation in saline-alkaline soils. Other crops, such as sorghum, sunflower, and barley, also exhibit resilience to salinity, and can be cultivated in mildly or moderately saline-alkaline soils [58,59]. Additionally, studies by David G et al. [60] suggested that Melilotus officinalis, commonly used as green manure crop, not only survives in saline-alkaline soils, but also improves soil structure. Furthermore, certain fruit-bearing and woody species, including jujube, pear, elm, willow, and locust, demonstrate salt tolerance

while contributing to ecological restoration and improving the overall quality of saline-alkaline lands [3,61,62].

In saline-alkaline regions with access to freshwater resources, the introduction of freshwater for irrigation and rice cultivation presents a viable method for soil improvement. Rice requires substantial amounts of water during its growth cycle. Its root system not only absorbs water, but also takes up salts from the soil, which are subsequently expelled through irrigation and drainage systems. This process effectively reduces soil salinity levels [63]. A notable example is the study by Jiaying Liu et al. [64], who integrated hybrid rice cultivation with saline-alkaline land management. They cultivated the two-line hybrid rice variety "Chao you 1000" in fields with soil salinity ranging from 0.2% to 0.6%, achieving a yield of 12.04 t/ha. This demonstrates the potential of rice cultivation as a sustainable approach to saline-alkaline soil reclamation.

In areas with highly mineralized saltwater, another effective strategy involves the extraction of shallow saltwater for aquaculture, such as shrimp farming. This approach not only maximizes the utilization of groundwater resources, but also contributes to reducing salinity levels within the water body through the biological activities of aquatic organisms. Over time, this process can improve the groundwater environment, making it more suitable for agricultural and ecological purposes. Additionally, the growth and development of plants in such environments involve the absorption of soil nutrients, salts, and alkalis, which are subsequently stored in plant tissues. Harvesting these plants removes inorganic salts from the soil, further aiding in soil reclamation [23].

Phytoremediation offers multiple advantages, including cost savings compared to chemical amendments, improved soil structure and enhanced plant nutrient availability [65]. It also promoted environmental benefits such as carbon sequestration. While these methods exhibit strong environmental sustainability, it is important to note that the improvement of saline-alkaline soils is a gradual process. These approaches require sustained, long-term investments in planting, management, and infrastructure. Through careful planning of crop rotations, continuous field management, and the integration of aquaculture, soil salinity can be progressively reduced, and soil quality enhanced. This creates more favorable conditions for plant growth and long-term agricultural productivity. Consequently, these methods are particularly suitable for saline-alkaline land management projects where stakeholders are committed to long-term efforts and resource allocation.

2.4. Agricultural Restoration Method

Agricultural restoration in saline-alkaline soils involves the use of agronomic practices to rebuild soil health, structure. Physical improvement methods, such as the use of gravel barriers, deep plowing, and land exchange, have been shown to effectively mitigate soil salinity. A study by Hongjian Pan et al. [66] revealed that gravel barriers can significantly reduce soil salinity levels. Additionally, soil subsoiling technology, when combined with optimized fertilization strategies, offers a moderate yet effective approach to enhancing soil quality. This method involves increasing the application of organic fertilizers while reducing the overuse of chemical fertilizers. Over time, this not only improves soil fertility, but also enhances the physical structure of the soil by increasing porosity and promoting the formation of soil aggregates. These improvements create a healthier environment for plant root development [67].

Another effective strategy is the implementation of crop rotation systems. By systematically planting different types of crops, the rate of soil salinity accumulation can be slowed. Various plants exhibit distinct nutritional needs and differing degrees of salt tolerance, which helps balance soil nutrient consumption and replenishment. This approach reduces the risk of salt accumulation that often results from monocropping practices [68].

3. Advanced Technology of Saline-Alkaline Soil Management

Traditional methods for addressing saline-alkaline soils have proven to be limited in their efficiency, scalability, and long-term environmental sustainability. As such, there is an increasing demand for innovative solutions that offer more effective and sustainable approaches. In response, modern technologies have emerged as valuable alternatives, providing new strategies to tackle the challenges associated with saline-alkaline soils. These methods include a wide variety of techniques, ranging from information technology to Emerging Chemical Treatments, nano technology, and wood vinegar.

Physical and chemical remediation methods focus on techniques such as solidification, heat treatment, redox reaction, and electrodynamics, which directly address the soil to fix or remove harmful substances. Although technically effective, these methods face several challenges when applied on a large scale to remediation cropland soils, including high operational complexity, high costs and the potential risk of secondary environmental contamination [69]. In contrast, bioremediation technologies based on plant and microbial actions are preferred due to their lower cost and ease of operation. However, the effectiveness of bioremediation is often limited by the nature of the soil itself, and external environmental conditions, which can result in inadequate stability and predictability of remediation effects [70,71]. To a certain degree, this constrained the wide application of bioremediation in complex environments or highly polluted soil. Therefore, developing an environmentally friendly and economically feasible soil remediation method. To achieve high-efficiency, low-consumption, and safe treatment of soil pollution, it is necessary to consider the effectiveness, cost-effectiveness, and long-term environmental impact of the technology to support the sustainable use of soil resources.

The limitation of traditional single-treatment methods is evident in the complex soil environment under salt alkali stress, making it urgent to develop some new techniques that can adapt to the contemporary saline-alkaline and alkaline land treatment. As research advances, the technology of treating saline-alkaline and alkaline lands is being innovated and developed. New management techniques, including biotechnology, information technology, and salt-tolerant crop breeding, provide a new ideas and methods for saline-alkaline land management [72–74].

3.1. Information Technology

The application of information technology, such as remote sensing and intelligent irrigation systems, offers more accurate and efficient tools for managing saline-alkaline land. By continuously monitoring soil salt levels and moisture conditions, these technologies optimize irrigation and drainage schemes leading to improved management outcomes [75].

Numerous scholars have explored the foundational theories governing soil water and solute transport, such as Darcy's law and Fick's law, while introducing innovative perspectives to analyze the complex interactions of factors like soil texture, groundwater depth, and the dynamic processes of soil freezing and thawing on water and salt movement [75,76]. The advantages and disadvantages of these models have also been discussed, including the challenges of the Hydrus model in addressing field-scale soil spatial variability [77,78].

Currently, there are many successful cases of integrating information technology with saline-alkaline and alkaline land management. For instance, Gao Hui et al. [14] used enhanced remote sensing imaging technology to analyze the spatiotemporal changes of saline-alkaline farmland in Huanghua City between 1992 and 2011. Song Yingqiang et al. [79] developed an ecological monitoring support system for saline-alkaline land, leveraging Web GIS technology. Using the Yellow River Delta as a case study, they refined machine learning algorithms models to achieve high-precision forecasting of soil salinity levels, integrated multiple ecological monitoring functions, and effectively supported

the ecological health assessment and protection of saline-alkaline land. Qianyi Gu and colleagues [80] investigated the polarization optical properties of saline-alkaline land, integrating semi-empirical frameworks with machine learning techniques to accurately predict the surface reflectance of saline-alkaline land.

3.2. Emerging Chemical Treatments

3.2.1. Biochar Technology

Biochar, a stable carbon-rich by-product synthesized through the pyrolysis of plant and animal biomass [81], has emerged as a promising tool for improving saline-alkaline soils. Biochar is notably one of the most used soil conditioners in saline-alkaline soil. Its distinctive characteristics, featuring an extensive surface area and strong absorption capabilities, enable it to regulate soil nutrients directly or indirectly. Biochar enhances soil organic matter content, reduces nitrogen and phosphorus loss under salt-alkali stress, and promotes the formation of soil aggregate. These properties contribute to soil improvement, enhanced water retention, and increased crop resistance to salt-alkali stress. Moreover, when returned to the field, biochar increases the soil carbon pool, demonstrating superior carbon sequestration and emission reduction potential compared to other agricultural practices [82].

Biochar's high adsorption capacity and well-developed porous structure play a key role in managing saline-alkaline soils by reducing nutrient leaching and minimizing underground runoff. This helps improve the retention of essential nutrients in these challenging environments. Additionally, biochar can adsorb organic molecules, facilitating the formation of organic matter through continuous polymerization, which is vital for enhancing soil quality in saline-alkaline conditions. Its stable carbon structure enhances resists microbial degradation, allowing it to persist longer in the soil and stabilize unstable carbon. This process promotes the creation of more stable organic matter, thus increasing soil organic carbon. Furthermore, biochar's ability to enhance soil aggregate stability helps reinforce the overall stability of soil organic carbon in saline-alkaline soils, making it an effective long-term amendment for improving soil structure and fertility. Therefore, biochar presents great potential for advancing the management of saline-alkaline soils [83]. In addition to enhancing soil structure, the addition of biochar helps to replace excess exchangeable sodium in saline-alkaline soils. It also does so by increasing the levels of organic carbon and cations which, in turn, reduces both the electrical conductivity and salt content of the soil [84].

The application of biochar-based fertilizers or composite materials in saline-alkaline land improvement can delay fertilizer release, prolong soil fertility, and enhance crop adaptability to saline-alkaline conditions. Studies such as that of Du Xuejun et al. [85] have shown that an increase in labile carbon (LOC) content signals a higher carbon turnover rate, which boosts the input of carbon from plants and microbes into soil organic matter. This process promotes sustained carbon storage and aids in the restoration of salt affected soils. Similarly, research by Zhu Shengbao et al. [86] demonstrated the potential of cotton stalk biochar in alkaline soils, while Li Chunyu et al. [87] examined the impact of altered biochar on rehabilitating salt-affected soils and enhancing crop growth. The results showed that treated biochar notably enhanced soil drainage and lowered acidity and salinity levels while improving soil productivity and water-holding capacity.

The application of biochar in saline-alkaline land remediation underscores its potential not only as soil amendment, but also as a key factor in promoting agricultural sustainability and environmental stewardship. By leveraging its exceptional adsorption capacity, biochar effectively regulates soil chemistry, sequestering harmful substances and mitigating their adverse effects on crop health [88,89]. Biochar also affects physical processes in the soil,

such as reducing water evaporation at low application rates and improving water retention at higher rates, ultimately reducing surface salinity and sodium adsorption [90]. Additionally, the incorporation of bioactive biochar can significantly enhance microbial activity and biodiversity within the soil. In saline-alkaline soils, increased microbial activity accelerates the release and transformation of soil nutrients, providing more available nutrients for crops.

Despite its numerous advantages, the application of biochar alone has its limitations. For instance, it cannot directly adjust the pH of saline-alkaline soils, which may limit its effectiveness in certain conditions. This reason can be due to the influence of the organic matter from which the biochar is produced. Biochar is known to be typically alkaline, and its pH level depends on the raw materials and how it is produced. When added to neutral or slightly alkaline soils, it might raise the pH too much, which may cause harm to crops by making it harder for them to absorb essential nutrients like iron and zinc, and reduce the availability of phosphorus. In the short term, especially within the first three months, biochar can cause a significant raise in soil pH. However, over the long term, biochar can continue to raise the pH because it slowly releases alkaline substances. This ongoing increase in pH can disrupt the soils microbial community, particularly by harming acid loving bacteria [83]. Therefore, future research should focus on optimizing biochar-based treatments, such as combining biochar with other amendments or developing modified biochar formulations. It is also important to explore how biochar interacts with different soil types and climates, to overcome these limitations and maximize its potential for soil improvement [91].

3.2.2. Humic Acid

Humic acids are organic colloids with high activity, adsorption, and aggregation capabilities. These properties enable humic acid to make a crucial role in the treatment of saline-alkaline and alkaline land. Specifically, humic acid helps disperse soil particles, enabling them to agglomerate tightly [92]. This process not only improves soil architecture and the capacity to retain moisture and nutrients, but also enhance soil aeration and water permeability, providing a better environment for plant growth.

Humic acid, a macromolecular organic substance, is derived from animal and plant remains. These remains accumulate to form humic acid through a complex array of chemical reactions during microbial decomposition and metamorphosis processes [93]. In recent years, this research has advanced significantly.

Liu Mengli et al. [94] discovered that the application of earthworm castings and humic acid fertilizers significantly improved the microstructure of large aggregates in saline-alkaline and alkaline land. Humic acid fertilizers can also enhance bacterial and fungal activity, especially during harvest stage when nutrient availability and root nutrient adsorption improve in saline-alkaline soils [95]. These fertilizers also increase the yield and quality of crops like sugar beets, with reported increases in yield ranging from 11.29% to 32.54% and sugar production from 13.5% to 38.61% [4].

Zhang et al. [96] discovered that, under salt stress, humic acid boosted the photosynthetic rate, transpiration rate, and stomatal conductance of switchgrass, while lowering intercellular CO_2 concentration. This enhancement significantly promoted switchgrass growth by optimizing its photosynthetic function. In a separate study, Chen Xiaodong et al. [97] found that incorporating granular corn stover into saline-alkaline and alkaline land notably increased the soils humus content and composition.

Furthermore, humic acid can significantly improve the soil's structural and chemical properties. It can regulate soil acidity, making it more suitable for plant growth. Rich inorganic matter, minerals, and micronutrients, humic acid is essential for plant growth

and development. As a macromolecule organic matter and organic colloid, humic acid has important application value in soil, as it improves soil structure, physical and chemical quality, enhances soil fertility, and boosts productivity, thereby supporting sustainable agricultural development [98,99].

While chemical amendments provide rapid improvement in soil properties, their long-term effectiveness and potential for secondary pollution need to be carefully considered. A combined approach that includes both chemical and organic materials has been found to be more effective for improving the health of saline-alkaline soils [100]. However, it is important to evaluate the environmental impact of chemical measures, particularly considering the risk of contamination from exogenous materials like calcium containing compounds, humic acid, and furfal residue, which are commonly used in saline-alkaline soil amendments [37].

4. The New Method of Treating Saline-Alkaline Soil Mainly with Wood Vinegar

With the increasing research on saline-alkaline soil treatment, many experts and scholars are actively exploring and proposing innovative solutions. Soil improvement is regarded as a long-term and systematic process, with the core goal being to effectively reduce the risk of toxin transfer from the soil to plants and receptor organisms in the ecological environment. In this process, organic additives derived from natural bio-materials have attracted significant attention for their unique advantages, as they can be directly applied to the soil without complex pre-treatment, injecting new vitality into soil health [101]. In the search of more environmentally friendly and efficient ways to manage the growing number of organic residues, many scholars have focused on integrating the innovative preparation of organic materials with soil remediation techniques [102].

4.1. Wood Vinegar

An effective example involves the application of wood vinegar to treat salt-affected and high-pH soils. Sun et al. found that wood vinegar effectively reduced ammonia volatilization by regulating soil pH and urease activity, while maintaining a high rice yield. Wang et al. [103] also discovered that wood vinegar effectively reduced soil alkalinity by neutralizing acid and alkali, and boosted soil fertility by increasing nutrient levels (C, N, P), ultimately altering soil microbial abundance and diversity [103]. Additionally, Zhang et al. demonstrated that wood vinegar significantly boosted soil enzyme activity, lowered soil acidity and conductivity levels, while consequently enhanced soil fertility and improving the plant growth environment [104].

4.2. The Source and Application of Wood Vinegar

As a potential soil conditioner, wood vinegar is a liquid product obtained through a specific process, characterized by its unique composition and properties derived from pyrolytic biomass. Its wide range of raw material sources does provide great flexibility and sustainability for its preparation and application. The raw materials cover many aspects of agroforestry, from crop wastes such as straw, corncobs and sugarcane [105], as shown in Figure 4. These include coconut shell, pistachio shells, cashew shell, olive kernel, walnut shell, etc. [106,107], as well as forest wastes such as bark, twigs, oak, pine, and driftwood processing residues [108,109]. The specific component contents of wood vinegar prepared from different materials are shown in Table 1.



Figure 4. The source of wood vinegar.

Table 1. The characteristics related to both structure and composition of wood vinegar from various sources exhibit a diverse range of characteristics, encompassing variations in composition, acidity, and reactivity.

Materials	Materials	Nature			References
		pH	Density (g cm^{-3})	Total Acid Content (%)	
Forestry waste	*A walnut branch*	3.32	1.05	3.01	[110]
	FIR trees	2.91	1.1014	1.84	[111]
	Rubber Wood	2.9–3.8	1.009–1.027	-	[112]
	Birch Wood	1.8–2.9	-	-	[113]
	Apple tree	3.94	1.005	2.64	[114]
	FIR sawdust	2.3	1.1242	10.8	[111]
	Apricot trees	2.93	1.05	5.38	[115]
Crop waste	*Wheat straw*	2.73	1.077	2.28	[116]
	Cotton stalk	4.01	0.955	7.02	[117]
	Tomato stems	3.21	1.0104	7.64	[118]
	Straw	2.43	1.05	9.29	[119]
	Soybean straw	2.35	1.01	16.93	
	Rice straw	2.93	1.025	5.56	[120]
	Corn stalks	2.89	1.03	6.44	
Shell waste	*Bitter Apricot Shell*	2.31	1.06	6.35	[121]
	Coconut shell	3	-	-	[122]
	Durian	-	1.012	4.22	[123]
	Date shells	2.74	1.16	4.64	[124]
	Litchi shell	3.17	1.04	3.69	[125]

There are many methods for refining wood vinegar, including standing, distillation, freezing and thawing, enzymatic hydrolysis of papaya, ion-exchange resin adsorption, activated carbon adsorption, multi-layer filtration, organic solvent extraction, and electrolysis, among others. To reduce the production cost, the methods typically chosen for refining wood vinegar are standing or distillation [126]. Additionally, crude wood vinegar should be refined according to the intended use with different methods applied based on the specific purpose [127]. The preparation process can be meticulously categorized into four distinct stages: the drying stage, the pre-carbonization stage, the carbonization stage and, ultimately, the calcination stage [128].

Wood vinegar is used in various applications, including as a fertilizer, insecticide, feed additive, anti-hair loss treatment, and herbicide [129]. It is widely utilized across several sectors, including animal husbandry, agriculture, industry, environmental conservation, food production, and medicine, demonstrating its versatility and significance in multiple facets of our daily life [130,131]. Some scholars have pointed out that wood vinegar primarily changes the structure of adsorption of heavy metals [132]. The combination of wood vinegar and plant ash or mushroom residue can significantly improve soil nutrient status, promote crop growth, improve root activity, and increase dry matter accumulation [133]. Zheng, J. et al., proposed the feasibility of applying wood vinegar through the life cycle of *Eucommia ulmoides* stem wood vinegar production [134]. Yeon Lee has suggested that wood vinegar originates from a variety of applications and contexts [135]. Wang et al. innovatively developed an efficient, environmentally friendly and economical heavy metal contaminated soil remediation material by combining biochar with humic acid produced through the interaction of sodium humic acid sodium and wood vinegar [136]. Sun et al. further investigated the desorption process, which involves the removal of Cd(II), Pb(II), and As(III) ions from the surface of adsorbents, and successfully determined the optimal concentration of wood vinegar in different adsorption systems [132]. The study revealed that acetic acid, being the primary active element in wood vinegar, significantly contributed to improving the adsorbent's performance in capturing substances, as seen in Figure 5 below.

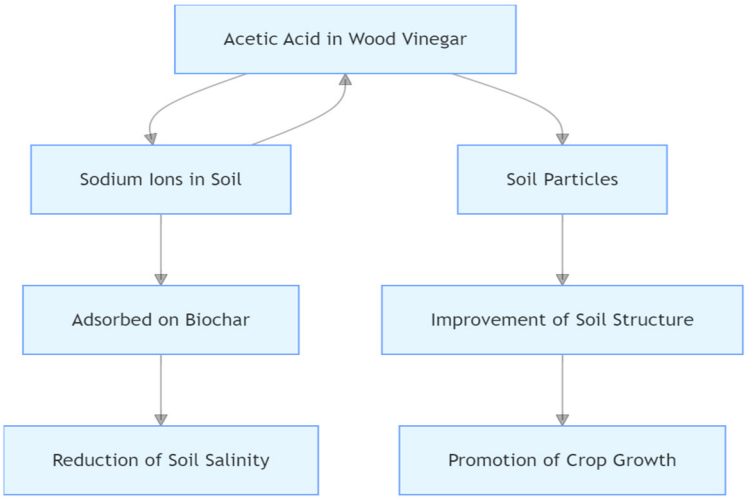


Figure 5. Schematic diagram of the exchange process between acetic acid in wood vinegar and sodium ions in soil and their synergistic effects: This figure illustrates the exchange process between acetic acid in wood vinegar and sodium ions in the soil. After the exchange, some of the sodium ions are adsorbed by biochar, reducing the soil salinity. Meanwhile, acetic acid participates in improving the soil structure, ultimately promoting crop growth. This process reflects the synergistic mechanism of wood vinegar and biochar in the management of saline-alkaline soils.

4.3. The Operational Principles of Wood Vinegar on Saline-Alkaline Soil

Because wood vinegar contains numerous types of organic compounds, including phenols, alcohols, esters, and other small organic molecular substances [137,138], it can regulate soil pH, increase root activity, promote seed germination and root growth, and shows potential for improving saline-alkaline soils [139]. A Study by Zhou Wenzhi et al. suggested that moderate use of wood vinegar could promote soil leaching [140]. This idea was also confirmed in the study by Willow et al. [141], which showed that the combination of wood vinegar solution and biochar significantly improved the properties of saline-alkaline soil, increased soil nutrient content, and enhanced stress resistance and photosynthetic capacity of cotton. In addition, wood vinegar can promote an increase in

the soil microbial population, improve soil microbial structure, and has a positive effect on saline-alkaline land improvement [142].

It is also necessary to maintain a suitable concentration range for wood vinegar to improve saline-alkaline land. The appropriate dilution concentration is very important for improving saline-alkaline soil. Wood vinegar with too low a concentration cannot effectively improve the soil, while wood vinegar with too high a concentration may lead to salt accumulation and root toxicity. The results in a study by Deng et al. [143] showed that different concentrations of wood vinegar notably influenced the acidity levels and electrical conductivity, and wood vinegar diluted 20 times could significantly decrease the soil's alkalinity, enhance its conductivity, and improving its enzyme activity. Xinyou Liu et al. also studied the effects of wood vinegar solution on soil properties and microbial activity at different concentrations. They found that wood vinegar solution diluted 10–100 times could be used for soil treatment, effectively enhancing soil conditions and promoting biological activity. At the same time, the specific dilution ratio needs to be adjusted according to soil conditions, crop species, growth needs, and other factors [114].

Wood vinegar is frequently utilized in conjunction with biochar to enhance soil properties. For instance, its co-application with biochar has been shown to augment blueberry yield in cropland soil and foster an increase in the population of fungi, Actinomycetes, and bacteria within the soil [144]. When applied in suitable concentrations, wood vinegar has been shown to markedly improve the physical and chemical properties of soils affected by high levels of salt and alkali as seen in Figure 6 below. This application boosts microbial populations and enhances enzymatic functions within the soil, leading to improved fertility and productivity in saline-alkaline soil conditions. In particular, wood vinegar can promote the number of fungi, Actinomycetes, and bacteria present inside the soil, enhance soil enzyme activity, and exert a beneficial influence on enzyme activity in soil under salt alkali stress [145]. For example, in northwestern Liaoning province, wood vinegar at 0.30% and 0.15% concentrations had the best effects on enzyme activity in low and medium fertility soils, respectively [146]. However, the concentration at which wood vinegar is applied needs to be carefully controlled to avoid excessive concentrations that inhibit microbial growth or cause competition between plants and microbes for nutrients in the soil [147].

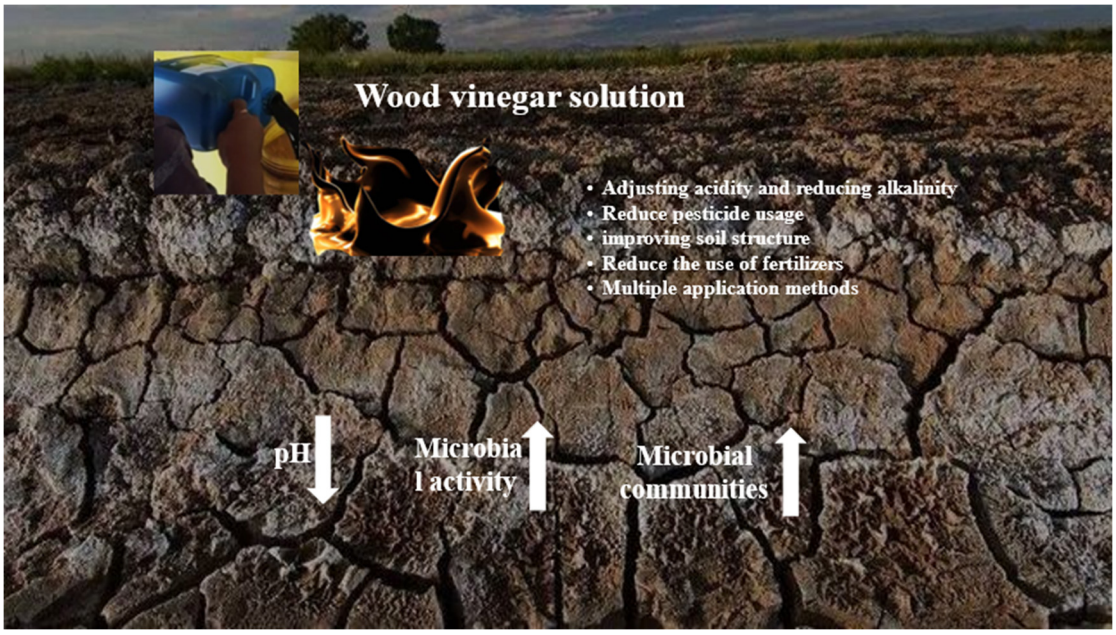


Figure 6. Mechanism of using wood vinegar to improve saline-alkaline and alkaline land.

4.4. The Advantages and Disadvantages of Wood Vinegar, and Its Prospects

As a method of treating saline-alkaline soil, wood vinegar is also feasible, but there are some aspects that need to be paid attention to. For example, in green environmental protection, wood vinegar is a natural organic fertilizer and soil conditioning agent, is non-toxic, harmless, and environmentally friendly. Costs are low, and wood vinegar is made from widely available ingredients at a relatively low cost. Research findings demonstrated that applying wood vinegar led to substantial improvements in saline-alkaline soils, effectively decreasing both acidity and salinity levels. Additionally, it improved soil structure and enhanced crop growth, demonstrating its potential as an effective solution for rehabilitating degraded lands and boosting agricultural productivity. Wood vinegar has certain bactericidal and antibacterial functions, which can reduce the occurrence of crop diseases and insect pests, thus minimizing pesticide application and lowering expenses in farming operations. The wood vinegar can be applied in many ways, such as irrigation, foliage spraying, etc. It is convenient and flexible. The wood vinegar can be mixed with farm manure, chemical fertilizers, etc.

The synergistic use of wood vinegar in combination with other techniques has also proven to be highly effective in managing saline-alkaline soils. According to research by Wang et al. [103], the combined application of wood vinegar for pH regulation, biochar for salt adsorption, and salt tolerant crops such as *Suaeda salsa* has significantly improved the soil environment and boosted land productivity. In experimental fields located in the yellow river basin, where the wood vinegar and biochar were applied together and *Suaeda salsa* was planted, the results indicated that soil pH was effectively neutralized. Biochar adsorbed and stabilized a substantial number of salts, while the well-developed root system of *Suaeda salsa* not only enhanced soil structure, but also promoted microbial activity. Over the course of the experiment, soil fertility increased, microbial diversity expanded, and crop yields were notably higher than those in plots treated with single methods. This integrated approach leverages the strengths of each method, offering a more efficient and sustainable solution to managing saline-alkaline soils.

However, the application of wood vinegar faces certain challenges. Its use requires careful adjustment based on the soil's pH levels and salt content to maximize its effectiveness. This process demands a high level of expertise and precision, making it a specialized practice that may limit its widespread adoption without proper guidance or professional involvement. In addition, regular monitoring of soil pH and salt content, as well as flexible adjustment of wood vinegar according to changes in the use of the program, is also essential.

5. Method Comparison and Comprehensive Application

In order to fully understand the effectiveness, feasibility and scalability of both traditional an advanced technologies for managing saline-alkaline soils, the following table summarizes the key differences between these approaches. Table 2 compares aspects such as the cost, effectiveness, and environmental impact, providing a clear overview of their respective advantages and limitations.

Table 2. Comparative analysis of traditional and advanced technologies for saline-alkaline soil management.

Method	Effectiveness	Cost (Per Hectare)	Scalability	Environmental Risks	References
Water Conservancy	pH reduction: Moderate (0.5–1.5) Salt removal: High (60–80%)	High (USD 800–USD 1500)	Moderate	High water consumption; nutrient leaching; soil structure degradation	[26,28,35]
Phytoremediation	pH reduction: Low (0.3–0.8) Salt removal: Slow but cumulative (40–60% in 5–10 years)	Low (USD 200–USD 500)	High (suitable for large areas)	Minimal risks; enhances biodiversity	[64]
Traditional Inorganic Chemistry	pH reduction: High (1.5–3.0) Salt removal: Rapid (70–90%)	Low–Moderate (USD 300–USD 800)	Moderate (weather-dependent)	Secondary contamination (e.g., gypsum residues); nutrient imbalance	[38,42]
Agricultural Restoration	pH reduction: Low (0.2–0.7) Salt removal: Gradual (30–50%)	Moderate (USD 400–USD 700)	High (low-tech requirements)	Minimal risks; improves soil fertility	[66–68]
Humic Acid	pH reduction: Moderate (1.0–2.0) Salt removal: Moderate (50–70%)	Moderate (USD 500–USD 900)	Moderate (requires organic inputs)	Low; improves soil organic matter	[96,98]
Biochar	pH reduction: Low (0.5–1.0) Salt removal: Moderate (50–70%)	High (USD 800–USD 1200)	Moderate (production constraints)	Risk of heavy metal contamination if feedstock is polluted	[81,86,88]
Wood Vinegar	pH reduction: High (1.5–2.5) Salt removal: High (70–85%)	Low–Moderate (USD 300–USD 600)	High (easy application)	Overuse may inhibit microbes; requires precise dosing	[103,140,143]

6. Conclusions

There is a long way to go for the treatment of and research on saline-alkaline land. In northeast China, such as the Heilongjiang, Jilin, and Liaoning provinces, the sustainable utilization of water resources should be fully considered when improving saline-alkaline land. This will ensure a win-win situation for saline-alkaline land improvement and water conservation through the rational deployment of external fresh water resources, optimization of irrigation systems, and promotion of water-saving irrigation techniques [148,149]. In northwest China, including Qinghai, Gansu, Ningxia, and other areas, there is a water shortage, and these regions have faced the problem of overexploitation. The ecological environment is extremely fragile. In these areas, the improvement and utilization of saline-alkaline and alkaline land must be approached more prudent [150]. Priority should be given to the protection of the region's fragile natural saline-alkaline eco-environmental systems and the prevention of wider ecological catastrophes caused by short-term, small-scale improvement and utilization, which is a current priority [151,152].

With the deepening of research on saline-alkaline soil treatment, an increasing number of technologies are being integrated across disciplines, including gene editing, nanotechnology, and biotechnology. By utilizing gene editing technology, crop varieties with exceptional salt and alkali tolerance have been cultivated, enabling these crops to thrive in high saline-alkaline environments, thereby significantly enhancing agricultural output in saline-alkaline land [153,154].

Regarding new materials and nanotechnology, research by Rui Yukui [153] discovered that nanomaterials are capable of adsorbing and immobilizing salt in soil. By applying nanomaterials to saline-alkaline land, soil salinity can be effectively reduced. The viability

of nanomaterials has been supported by numerous studies. For example, Yan et al. [155] found that pretreating rice seeds with silver nanoparticles (Ag NPs) triggers metabolic and transcriptional reprogramming within the seeds. This process significantly improves germination rates, seedling vigor, biomass, and root length, especially under salt stress conditions. Additionally, it enhances the plants resistance to rice blast. These findings highlight the potential of nanoparticles to strengthen crops resilience to stress by activating key defense pathways. Tang et al. [156] also demonstrated the effectiveness of nickel ferrite ($NiFe_2O_4$) nanoparticles in improving maize's tolerance to both drought and salt stress. The research showed that different concentrations of $NiFe_2O_4$ nanoparticles enhanced maize seed germination, boosted seedling vigor, and improved the plants water retention capabilities. Figure 7 clearly illustrates the impact of nanomaterials on plant growth, yield and quality, while also demonstrating their potential to improve soil properties and mitigate soil alkalinity issues. Nano-fertilizers thus present a practical and viable approach for crop improvement and soil restoration, holding great promise as a pivotal technological instrument in propelling the advancement of sustainable agriculture.

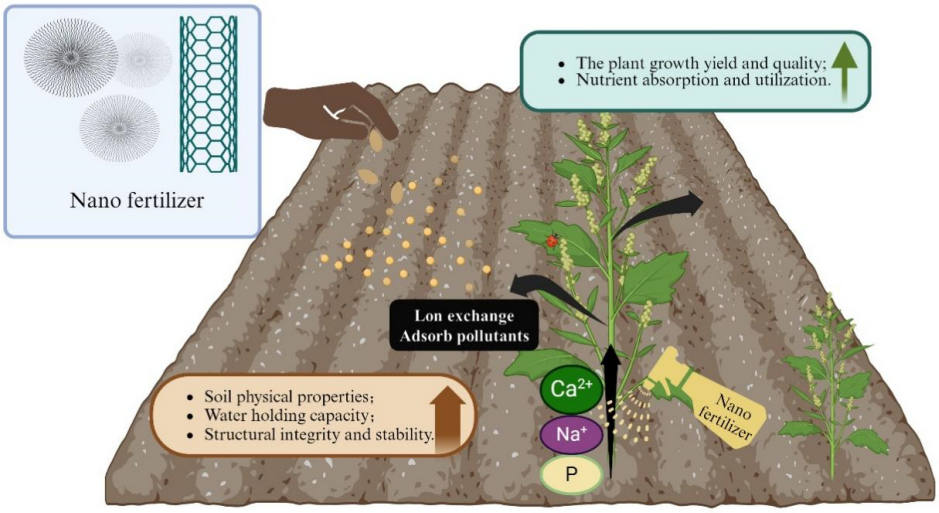


Figure 7. The benefits of nanomaterial accessories for soil and plants.

Furthermore, new energy sources are being developed for saline-alkaline land, leveraging its unique environment to establish renewable energy initiatives, including solar and wind power projects, providing clean energy support for saline-alkaline soil treatment while simultaneously boosting local economic development.

The production of wood vinegar is faced with the double challenges of scale and standardization, which greatly limits its wide application. At the same time, in the practical application process, determining the appropriate amount of wood vinegar has become a complex issue. Additionally, several key questions that need to be further explored are whether the introduction of wood vinegar will have a suppressive effect on the beneficial microbial population in the environment, potentially introducing unforeseen threats to ecosystems. Meanwhile, wood vinegar for inhibition is still unclear, and these are urgent issues that require scientific research to address.

Author Contributions: Conceptualization, Z.L.; writing—original draft preparation, Z.L.; writing—review and editing, Z.L., M.A.K., Y.J.; visualization, Z.L.; supervision, Y.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Shang, X.; Geng, L.; Yang, J.; Zhang, Y.; Xu, W. Transcriptome analysis reveals the mechanism of alkalinity exposure on spleen oxidative stress, inflammation and immune function of Luciobarbus capito. *Ecotoxicol. Environ. Saf.* **2021**, *225*, 112748. [CrossRef] [PubMed]
2. Mongelli, G.; Monni, S.; Oggiano, G.; Paternoster, M.; Sinisi, R. Tracing groundwater salinization processes in coastal aquifers: A hydrogeochemical and isotopic approach in the Na-Cl brackish waters of northwestern Sardinia, Italy. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 2917–2928. [CrossRef]
3. Sishu, N.K.; Das, U.; Selvaraj, C.I. Indian jujube a potential fruit tree to improve the livelihood. *Saudi J. Biol. Sci.* **2023**, *30*, 103769.
4. Zhu, W.; Gu, S.; Jiang, R.; Zhang, X.; Hatano, R. Saline-alkali Soil Reclamation Contributes to Soil Health Improvement in China. *Agriculture* **2024**, *14*, 1210. [CrossRef]
5. Wang, S.; Chen, Q.; Li, Y.; Zhuo, Y.; Xu, L. Research on saline-alkali soil amelioration with FGD gypsum. *Resour. Conserv. Recycl.* **2017**, *121*, 82–92. [CrossRef]
6. Wei, Z.; Han, Y.; Bu, Y. Research Progress in Adversity Stress of Woody Plants. *Mol. Plant Breed.* **2020**, *18*, 2382–2387.
7. Xia, W.T.; Niu, C.C.; Yu, Q.B.; Wang, Q.; Wang, J.Q.; Sun, X.; Wang, Z.; Shan, X. Experimental investigation of the erodibility of soda saline-alkali soil under freeze-thaw cycle from a microscopic view. *CATENA* **2023**, *232*, 107430. [CrossRef]
8. Wang, X.; Ding, J.; Wang, J.; Han, L.; Tan, J.; Ge, X. Ameliorating saline-sodic soils: A global meta-analysis of field studies on the influence of exogenous amendments on crop yield. *Land Degrad. Dev.* **2024**, *35*, 3330–3343. [CrossRef]
9. Dai, X. Preliminary study on adaptability of forage grass planting in saline-alkali land of Jiangsu coastal beach. *Agron. Seed Ind* **2017**, *7*, 42.
10. Zhang, B.; Song, X.F.; Zhang, Y.H.; Han, D.M.; Tang, C.Y.; Yu, Y.L.; Ma, Y. Hydrochemical characteristics and water quality assessment of surface water and groundwater in Songnen plain, Northeast China. *Water Res.* **2012**, *46*, 2737–2748. [CrossRef]
11. Qi, J.; Fu, D.; Wang, X.; Zhang, F.; Ma, C. The effect of alfalfa cultivation on improving physicochemical properties soil microorganisms community structure of grey desert soil. *Sci. Rep.* **2023**, *13*, 13747. [CrossRef] [PubMed]
12. Shokri, N.; Hassani, A.; Sahimi, M. Multi-Scale Soil Salinization Dynamics From Global to Pore Scale: A Review. *Rev. Geophys.* **2024**, *62*, e2023RG000804. [CrossRef]
13. Gu, L.J.; Ren, R.Z.; Cao, J.S.; Sun, J. (Eds.) Saline alkali land classification using MODIS data in Western Jilin Province, China. In Proceedings of the Conference on Satellite Data Compression, Communications, and Processing IX, San Diego, CA, USA, 26–27 August 2013; SPIE: Bellingham, WA, USA, 2013.
14. Gao, H.; Liu, J.T.; Eneji, A.E.; Han, L.P.; Tan, L.M. Using Modified Remote Sensing Imagery to Interpret Changes in Cultivated Land under Saline-Alkali Conditions. *Sustainability* **2016**, *8*, 619. [CrossRef]
15. Hendricks, S.; Zechmeister-Boltenstern, S.; Kandeler, E.; Sandén, T.; Diaz-Pines, E.; Schnecker, J.; Alber, O.; Miloczki, J.; Spiegel, H. Agricultural management affects active carbon and nitrogen mineralisation potential in soils. *J. Plant Nutr. Soil Sci.* **2022**, *185*, 513–528. [CrossRef]
16. Luo, X.J.; Zhang, X.; Zhang, L.; Guo, L.L.; Nie, Z.Y.; Zhou, J.; Wang, R.Z.; Zhang, T.Y.; Miao, Y.; Ma, L.; et al. Characteristics of clay dispersion and its influencing factors in saline-sodic soils of Songnen Plain, China. *Agric. Water Manag.* **2024**, *303*, 109033. [CrossRef]
17. An, Y.; Yang, X.-X.; Zhang, L.; Zhang, J.; Du, B.; Yao, L.; Li, X.T.; Guo, C. Alfalfa *MsCBL4* enhances calcium metabolism but not sodium transport in transgenic tobacco under salt and saline-alkali stress. *Plant Cell Rep.* **2020**, *39*, 997–1011. [CrossRef] [PubMed]
18. Wang, Y.; Gao, M.; Chen, H.; Chen, Y.; Wang, L.; Wang, R. Organic Amendments promote saline-alkali soil desalinization and enhance maize growth. *Front. Plant Sci.* **2023**, *14*, 1177209. [CrossRef]
19. Xing, J.; Li, X.; Li, Z.; Wang, X.; Hou, N.; Li, D. Remediation of soda-saline-alkali soil through soil amendments: Microbially mediated carbon and nitrogen cycles and remediation mechanisms. *Sci. Total Environ.* **2024**, *924*, 171641. [CrossRef]
20. Bagheri, R.; Nosrati, A.; Jafari, H.; Eggenkamp, H.G.M.; Mozafari, M. Overexploitation hazards and salinization risks in crucial declining aquifers, chemo-isotopic approaches. *J. Hazard. Mater.* **2019**, *369*, 150–163. [CrossRef]
21. Cao, D.; Shi, F.; Koike, T.; Lu, Z.; Sun, J. Halophyte Plant Communities Affecting Enzyme Activity and Microbes in Saline Soils of the Yellow River Delta in China. *CLEAN-Soil Air Water* **2014**, *42*, 1433–1440. [CrossRef]
22. Zhao, K.; Song, J.; Feng, G.; Zhao, M.; Liu, J. Species, types, distribution, and economic potential of halophytes in China. *Plant Soil* **2011**, *342*, 495–509. [CrossRef]
23. Gupta, B.; Huang, B.R. Mechanism of Salinity Tolerance in Plants: Physiological, Biochemical, and Molecular Characterization. *Int. J. Genom.* **2014**, *2014*, 701596. [CrossRef] [PubMed]

24. Wang, W.; Ren, L.; Deng, C.; Wang, Q.; Yu, J. The Water-Saving Management Contract in China: Current Status, Existing Problems, and Countermeasure Suggestions. *Water* **2022**, *14*, 3116. [CrossRef]
25. Cuevas, J.; Daliakopoulos, I.N.; del Moral, F.; Hueso, J.J.; Tsanis, I.K. A review of soil-improving cropping systems for soil salinization. *Agronomy* **2019**, *9*, 295. [CrossRef]
26. Howe, C.W.; Goemans, C. Water transfers and their impacts: Lessons from three Colorado water markets. *J. Am. Water Resour. Assoc.* **2003**, *39*, 1055–1065. [CrossRef]
27. Zhang, B.-Q.; Wang, N. Study on the harm of saline alkali land and its improvement technology in China. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *692*, 042053. [CrossRef]
28. Chen, X.Y. *Changes of Main Properties in Carbonate Meadow Soil Under the Condition of Plastic Mulching Drip Irrigation*; Northeast Agricultural University: Harbin, China, 2010.
29. Li, J.-G.; Pu, L.-J.; Zhu, M.; Zhang, R. The present situation and hot issues in the salt-affected soil research. *Acta Geogr. Sin.* **2012**, *67*, 1233–1245.
30. Gabriel, J.L.; Vanclooster, M.; Quemada, M. Integrating water, nitrogen, and salinity in sustainable irrigated systems: Cover crops versus fallow. *J. Irrig. Drain. Eng.* **2014**, *140*, A4014002. [CrossRef]
31. Matthews, N.; Grové, B.; Barnard, J.; Van Rensburg, L. Modelling the economic tradeoffs between allocating water for crop production or leaching for salinity management. *Water SA* **2010**, *36*, 37–43. [CrossRef]
32. Ashraf, M.; Saeed, M.M. Effect of improved cultural practices on crop yield and soil salinity under relatively saline groundwater applications. *Irrig. Drain. Syst.* **2006**, *20*, 111–124. [CrossRef]
33. Panagea, I.; Daliakopoulos, I.N.; Tsanis, I.K.; Schwilch, G. Evaluation of promising technologies for soil salinity amelioration in Timpaki (Crete): A participatory approach. *Solid Earth* **2016**, *7*, 177–190. [CrossRef]
34. Forkutsa, I.; Sommer, R.; Shirokova, Y.; Lamers, J.; Kienzler, K.; Tischbein, B.; Martius, C.; Vlek, P.L.G. Modeling irrigated cotton with shallow groundwater in the Aral Sea Basin of Uzbekistan: II. Soil salinity dynamics. *Irrig. Sci.* **2009**, *27*, 319–330. [CrossRef]
35. Haddeland, I.; Heinke, J.; Biemans, H.; Eisner, S.; Flörke, M.; Hanasaki, N.; Konzmann, M.; Ludwig, F.; Masaki, Y.; Schewe, J.; et al. Global water resources affected by human interventions and climate change. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 3251–3256. [CrossRef]
36. Alcon, F.; Tapsuwan, S.; Brouwer, R.; de Miguel, M.D. Adoption of irrigation water policies to guarantee water supply: A choice experiment. *Environ. Sci. Policy* **2014**, *44*, 226–236. [CrossRef]
37. Yang, J.; Yao, R.; Wang, X.; Xie, W.; Zhang, X.; Zhu, W.; Zhang, L.; Sun, R. Research on salt-affected soils in China: History, status quo and prospect. *Acta Pedol. Sin.* **2022**, *59*, 10–27.
38. Zhao, J.S.; Chen, S.; Hu, R.G.; Li, Y.Y. Aggregate stability and size distribution of red soils under different land uses integrally regulated by soil organic matter, and iron and aluminum oxides. *Soil Tillage Res.* **2017**, *167*, 73–79. [CrossRef]
39. Feng, H.; Wang, S.; Gao, Z.; Pan, H.; Zhuge, Y.; Ren, X.; Hu, S.; Li, C. Aggregate stability and organic carbon stock under different land uses integrally regulated by binding agents and chemical properties in saline-sodic soils. *Land Degrad. Dev.* **2021**, *32*, 4151–4161. [CrossRef]
40. Du, X.J.; Ge, Y.N.; Zhang, Y.; Hu, H.; Zhang, Y.Y.; Yang, Z.Y.; Ren, X.; Hu, S.; Feng, H.; Song, Y. Responses of soil carbon cycling microbial functional genes to nitrogen and phosphorus addition in saline-sodic soils. *Plant Soil* **2023**, *490*, 261–277. [CrossRef]
41. Liu, X.; Ding, J.; Li, J.; Zhu, D.; Li, B.; Yan, B.; Sun, G.; Sun, L.; Li, X. The Response of Soil Bacterial Communities to Cropping Systems in Saline-Alkaline Soil in the Songnen Plain. *Agronomy* **2023**, *13*, 2984. [CrossRef]
42. Ren, Z.; Wang, L.; Wang, H.; Liu, S.; Liu, M. Solidification/stabilization of lead-contaminated soils by phosphogypsum slag-based cementitious materials. *Sci. Total Environ.* **2023**, *857*, 159552. [CrossRef]
43. Sun, Q.; Xu, W.; Huang, Q.; Ma, R.; Zhang, J.; Ji, H.; Yao, S.; Hui, Y.; Lin, J.; Ren, Q.; et al. Recovery and reuse of phosphogypsum: Effect of ternary cementitious materials on the performance of phosphogypsum pavement base layers. *Constr. Build. Mater.* **2024**, *433*, 136702. [CrossRef]
44. Arora, S.; Singh, A.K.; Sahni, D. Bioremediation of salt-affected soils: Challenges and opportunities. In *Bioremediation of Salt Affected Soils: An Indian Perspective*; Springer: Cham, Switzerland, 2017; pp. 275–301.
45. Rabhi, M.; Talbi, O.; Atia, A.; Abdelly, C.; Smaoui, A. Selection of a halophyte that could be used in the bioreclamation of salt-affected soils in arid and semi-arid regions. In *Biosaline Agriculture and High Salinity Tolerance*; Springer: Berlin/Heidelberg, Germany, 2008; pp. 241–246.
46. Sandhu, G.; Qureshi, R. *Salt Affected Soils of Pakistan and Their Utilization*; Elsevier: Amsterdam, The Netherlands, 1986.
47. Zhu, J.K. Plant salt tolerance. *Trends Plant Sci.* **2001**, *6*, 66–71. [CrossRef] [PubMed]
48. Yensen, N.P. Halophyte uses for the twenty-first century. In *Ecophysiology of High Salinity Tolerant Plants*; Springer: Dordrecht, The Netherlands, 2006; pp. 367–396.
49. Flowers, T.J.; Colmer, T.D. Salinity tolerance in halophytes. *New Phytol.* **2008**, *179*, 945–963. [CrossRef] [PubMed]
50. Gul, B.; Weber, D.J.; Khan, M.A. Effect of salinity and planting density on physiological responses of Allenrolfea occidentals. *West. N. Am. Nat.* **2000**, *60*, 188–197.

51. Jithesh, M.; Prashanth, S.; Sivaprakash, K.; Parida, A.K. Antioxidative response mechanisms in halophytes: Their role in stress defence. *J. Genet.* **2006**, *85*, 237–254. [CrossRef]
52. Ahmad, N.; Qureshi, R.; Qadir, M. Amelioration of a calcareous saline-sodic soil by gypsum and forage plants. *Land Degrad. Dev.* **1990**, *2*, 277–284. [CrossRef]
53. Glenn, E.P.; Brown, J.J.; Blumwald, E. Salt tolerance and crop potential of halophytes. *Crit. Rev. Plant Sci.* **1999**, *18*, 227–255. [CrossRef]
54. Arora, S.; Trivedi, R.; Rao, G. Bioremediation of coastal and inland salt affected soils using halophyte plants and halophilic soil microbes. *CSSRI Annu. Rep.* **2012**, *13*, 94–100.
55. Shiyab, S.M.; Shibli, R.A.; Mohammad, M.M. Influence of sodium chloride salt stress on growth and nutrient acquisition of sour orange in vitro. *J. Plant Nutr.* **2003**, *26*, 985–996. [CrossRef]
56. Ashraf, M. Salt tolerance of cotton: Some new advances. *Crit. Rev. Plant Sci.* **2002**, *21*, 1–30. [CrossRef]
57. Liu, X.; Elzenga, J.T.M.; Venema, J.H.; Tiedge, K.J. Thriving in a salty future: Morpho-anatomical, physiological and molecular adaptations to salt stress in alfalfa (*Medicago sativa* L.) and other crops. *Ann. Bot.* **2024**, *134*, 1113–1130. [CrossRef] [PubMed]
58. Huang, R.D. Research progress on plant tolerance to soil salinity and alkalinity in sorghum. *J. Integr. Agric.* **2018**, *17*, 739–746. [CrossRef]
59. Chen, Z.W.; Guo, Z.Z.; Zhou, L.H.; Xu, H.W.; Liu, C.H.; Yan, X. Advances in Identifying the Mechanisms by Which Microorganisms Improve Barley Salt Tolerance. *Life* **2023**, *14*, 6. [CrossRef] [PubMed]
60. Masters, D.G.; Benes, S.E.; Norman, H.C. Biosaline agriculture for forage and livestock production. *Agric. Ecosyst. Environ.* **2007**, *119*, 234–248. [CrossRef]
61. Ahmad, R.; Anjum, M.A. Mineral Nutrition Management in Fruit Trees Under Salt Stress: A Review. *Erwerbs-Obstbau* **2023**, *65*, 397–405. [CrossRef]
62. Mirck, J.; Zalesny, R.S. Mini-Review of Knowledge Gaps in Salt Tolerance of Plants Applied to Willows and Poplars. *Int. J. Phytoremediat.* **2015**, *17*, 640–650. [CrossRef]
63. Liu, B.; Huang, L.; Jiang, X.; Liu, Y.; Huang, G.; Yang, C.; Liang, Y.; Cai, J.; Zhu, G.; Kong, Q. Quantitative evaluation and mechanism analysis of soil chemical factors affecting rice yield in saline-sodic paddy fields. *Sci. Total Environ.* **2024**, *929*, 172584. [CrossRef]
64. Liu, J.Y.; Wan, J.L.; Yin, X.J.; Gu, X.Z.; Yin, H.D.; Yu, M.; Luan, Y.; Li, R.; Mi, T.; Li, J. Progress and prospect of developing salt and alkali tolerant rice using hybrid rice technology in China. *Plant Breed.* **2024**, *143*, 86–95. [CrossRef]
65. Qadir, M.; Oster, J.; Schubert, S.; Noble, A.; Sahrawat, K. Phytoremediation of sodic and saline-sodic soils. *Adv. Agron.* **2007**, *96*, 197–247.
66. Zhu, J.; Cui, Z.; Wu, C.; Deng, C.; Chen, J.; Zhang, H. Research advances and prospect of saline and alkali land greening in China. *World For. Res.* **2018**, *31*, 70–75.
67. Yuan, J.; Feng, W.Z.; Jiang, X.M.; Wang, J.L. Saline-alkali migration in soda saline soil based on sub-soiling technology. *Desalination Water Treat.* **2019**, *149*, 352–362. [CrossRef]
68. Zheng, H.; Huang, H.; Zhang, C.; Li, J. National-scale paddy-upland rotation in Northern China promotes sustainable development of cultivated land. *Agric. Water Manag.* **2016**, *170*, 20–25. [CrossRef]
69. Houben, D.; Evrard, L.; Sonnet, P. Mobility, bioavailability and pH-dependent leaching of cadmium, zinc and lead in a contaminated soil amended with biochar. *Chemosphere* **2013**, *92*, 1450–1457. [CrossRef]
70. Xia, S.; Song, Z.; Jeyakumar, P.; Shaheen, S.M.; Rinklebe, J.; Ok, Y.S.; Bolan, N.; Wang, H. A critical review on bioremediation technologies for Cr(VI)-contaminated soils and wastewater. *Crit. Rev. Environ. Sci. Technol.* **2019**, *49*, 1027–1078. [CrossRef]
71. Verma, S.; Kuila, A. Bioremediation of heavy metals by microbial process. *Environ. Technol. Innov.* **2019**, *14*, 100369. [CrossRef]
72. Zhang, G.L.; Dong, J.W.; Xiao, X.M.; Hu, Z.M.; Sheldon, S. Effectiveness of ecological restoration projects in Horqin Sandy Land, China based on SPOT-VGT NDVI data. *Ecol. Eng.* **2012**, *38*, 20–29. [CrossRef]
73. Qadir, M.; Qureshi, R.H.; Ahmad, N. Amelioration of calcareous saline sodic soils through phytoremediation and chemical strategies. *Soil Use Manag.* **2002**, *18*, 381–385. [CrossRef]
74. Yazdanpanah, N.; Pazira, E.; Neshat, A.; Mahmoodabadi, M.; Sinobas, L.R. Reclamation of calcareous saline sodic soil with different amendments (II): Impact on nitrogen, phosphorous and potassium redistribution and on microbial respiration. *Agric. Water Manag.* **2013**, *120*, 39–45. [CrossRef]
75. Abliz, A.; Tiyip, T.; Ghulam, A.; Halik, U.; Ding, J.-L.; Sawut, M.; Zhang, F.; Nurmemet, I.; Abliz, A. Effects of shallow groundwater table and salinity on soil salt dynamics in the Keriya Oasis, Northwestern China. *Environ. Earth Sci.* **2016**, *75*, 260. [CrossRef]
76. Bresler, E. SIMULTANEOUS TRANSPORT OF SOLUTES AND WATER UNDER TRANSIENT UNSATURATED FLOW CONDITIONS. *Water Resour. Res.* **1973**, *9*, 975–986. [CrossRef]
77. Yao, R.-J.; Yang, J.-S.; Zhang, T.-J.; Hong, L.-Z.; Wang, M.-W.; Yu, S.-P.; Wang, X.P. Studies on soil water and salt balances and scenarios simulation using SaltMod in a coastal reclaimed farming area of eastern China. *Agric. Water Manag.* **2014**, *131*, 115–123. [CrossRef]

78. Bailey, R.T.; Tavakoli-Kivi, S.; Wei, X.L. A salinity module for SWAT to simulate salt ion fate and transport at the watershed scale. *Hydrol. Earth Syst. Sci.* **2019**, *23*, 3155–3174. [CrossRef]
79. Song, Y.Q.; Pan, Y.X.; Xiang, M.Y.; Yang, W.H.; Zhan, D.X.; Wang, X.R.; Lu, M.A. A WebGIS-Based System for Supporting Saline-Alkali Soil Ecological Monitoring: A Case Study in Yellow River Delta, China. *Remote Sens.* **2024**, *16*, 1948. [CrossRef]
80. Gu, Q.Y.; Han, Y.; Xu, Y.P.; Yao, H.Y.; Niu, H.F.; Huang, F. Laboratory Research on Polarized Optical Properties of Saline-Alkaline Soil Based on Semi-Empirical Models and Machine Learning Methods. *Remote Sens.* **2022**, *14*, 226. [CrossRef]
81. Ahmad, M.; Rajapaksha, A.U.; Lim, J.E.; Zhang, M.; Bolan, N.; Mohan, D.; Vithanage, M.; Lee, S.S.; Ok, Y.S. Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere* **2014**, *99*, 19–33. [CrossRef] [PubMed]
82. Du, X.J.; Hu, H.; Wang, T.H.; Zou, L.; Zhou, W.F.; Gao, H.X.; Ren, X.; Wang, J.; Hu, S. Long-term rice cultivation increases contributions of plant and microbial-derived carbon to soil organic carbon in saline-sodic soils. *Sci. Total Environ.* **2023**, *904*, 166713. [CrossRef]
83. Zhu, Z.; Zhang, Y.; Tao, W.; Zhang, X.; Xu, Z.; Xu, C. The Biological Effects of Biochar on Soil's Physical and Chemical Characteristics: A Review. *Sustainability* **2025**, *17*, 2214. [CrossRef]
84. Yue, Y.; Guo, W.; Lin, Q.; Li, G.; Zhao, X. Improving salt leaching in a simulated saline soil column by three biochars derived from rice straw (*Oryza sativa* L.), sunflower straw (*Helianthus annuus*), and cow manure. *J. Soil Water Conserv.* **2016**, *71*, 467–475. [CrossRef]
85. Du, X.; Xu, Z.; Lv, Q.; Meng, Y.; Wang, Z.; Feng, H.; Ren, X.; Hu, S.; Gao, Z. Fractions, stability, and influencing factors of soil organic carbon under different land-use in sodic soils. *Geoderma Reg.* **2022**, *31*, e00590. [CrossRef]
86. Zhu, S.; Liu, J.; Tang, G.; Sun, T.; Jia, H.; Zhao, H.; Zhang, Y.; Lin, L.; Xu, W. Evaluating the Application Potential of Acid-Modified Cotton Straw Biochars in Alkaline Soils Based on Entropy Weight TOPSIS. *Agronomy* **2023**, *13*, 2807. [CrossRef]
87. Li, C.Y.; Wang, Z.C.; Xu, Y.T.; Sun, J.F.; Ruan, X.Y.; Mao, X.W.; Hu, X.; Liu, P. Analysis of the Effect of Modified Biochar on Saline-Alkali Soil Remediation and Crop Growth. *Sustainability* **2023**, *15*, 5593. [CrossRef]
88. Sun, J.N.; He, F.H.; Shao, H.B.; Zhang, Z.H.; Xu, G. Effects of biochar application on *Suaeda salsa* growth and saline soil properties. *Environ. Earth Sci.* **2016**, *75*, 630. [CrossRef]
89. Liu, G.; Zheng, H.; Jiang, Z.; Zhao, J.; Wang, Z.; Pan, B.; Xing, B. Formation and Physicochemical Characteristics of Nano Biochar: Insight into Chemical and Colloidal Stability. *Environ. Sci. Technol.* **2018**, *52*, 10369–10379. [CrossRef] [PubMed]
90. Yang, R.; Zhou, C.; Zhu, J.; Pan, Y.; Sun, J.; Zhang, Z. Effects of biochar application on phreatic water evaporation and water-salt distribution in coastal saline soil. *J. Plant Nutr.* **2019**, *42*, 1243–1253. [CrossRef]
91. Nath, H.; Sarkar, B.; Mitra, S.; Bhaladhare, S. Biochar from Biomass: A Review on Biochar Preparation Its Modification and Impact on Soil Including Soil Microbiology. *Geomicrobiol. J.* **2022**, *39*, 373–388. [CrossRef]
92. Wang, Y.; Zhu, Y.; Liu, Y.; Mu, B.; Wang, A. Research on preparation and properties of a multifunctional superabsorbent based on semicoke and humic acid. *Eur. Polym. J.* **2021**, *159*, 110750. [CrossRef]
93. Tang, W.W.; Zeng, G.M.; Gong, J.L.; Liang, J.; Xu, P.; Zhang, C.; Huang, B.B. Impact of humic/fulvic acid on the removal of heavy metals from aqueous solutions using nanomaterials: A review. *Sci. Total Environ.* **2014**, *468*, 1014–1027. [CrossRef]
94. Liu, M.L.; Wang, C.; Liu, X.L.; Lu, Y.C.; Wang, Y.F. Saline-alkali soil applied with vermicompost and humic acid fertilizer improved macroaggregate microstructure to enhance salt leaching and inhibit nitrogen losses. *Appl. Soil Ecol.* **2020**, *156*, 103705. [CrossRef]
95. Liu, M.; Wang, C.; Wang, F.; Xie, Y. Maize (*Zea mays*) growth and nutrient uptake following integrated improvement of vermicompost and humic acid fertilizer on coastal saline soil. *Appl. Soil Ecol.* **2019**, *142*, 147–154. [CrossRef]
96. Zhang, J.X.; Meng, Q.X.; Yang, Z.P.; Zhang, Q.; Yan, M.; Hou, X.C.; Zhang, X. Humic Acid Promotes the Growth of Switchgrass under Salt Stress by Improving Photosynthetic Function. *Agronomy* **2024**, *14*, 1079. [CrossRef]
97. Chen, X.D.; Wu, J.G.; Opoku-Kwanowaa, Y. Effects of Returning Granular Corn Straw on Soil Humus Composition and Humic Acid Structure Characteristics in Saline-Alkali Soil. *Sustainability* **2020**, *12*, 1005. [CrossRef]
98. Bacilio, M.; Moreno, M.; Bashan, Y. Mitigation of negative effects of progressive soil salinity gradients by application of humic acids and inoculation with *Pseudomonas stutzeri* in a salt-tolerant and a salt-susceptible pepper. *Appl. Soil Ecol.* **2016**, *107*, 394–404. [CrossRef]
99. Yang, F.; Sui, L.; Tang, C.; Li, J.; Cheng, K.; Xue, Q. Sustainable advances on phosphorus utilization in soil via addition of biochar and humic substances. *Sci. Total Environ.* **2021**, *768*, 145106. [CrossRef] [PubMed]
100. Rezapour, S.; Nouri, A.; Asadzadeh, F.; Barin, M.; Erpul, G.; Jagadamma, S.; Qin, R. Combining chemical and organic treatments enhances remediation performance and soil health in saline-sodic soils. *Commun. Earth Environ.* **2023**, *4*, 285. [CrossRef]
101. Knicker, H.; Staunton, S. Editorial for the special issue on "Understanding soil interfacial reactions for sustainable soil management and climatic change mitigation" (ISMOM 2019). *Eur. J. Soil Sci.* **2021**, *72*, 1079–1082. [CrossRef]
102. Gregory, S.J.; Anderson, C.W.N.; Arbestain, M.C.; McManus, M.T. Response of plant and soil microbes to biochar amendment of an arsenic-contaminated soil. *Agric. Ecosyst. Environ.* **2014**, *191*, 133–141. [CrossRef]

103. Wang, Z.; Pan, X.; Kuang, S.; Chen, C.; Wang, X.; Xu, J.; Li, X.; Li, H.; Zhuang, Q.; Zhang, F.; et al. Amelioration of Coastal Salt-Affected Soils with Biochar, Acid Modified Biochar and Wood Vinegar: Enhanced Nutrient Availability and Bacterial Community Modulation. *Int. J. Environ. Res. Public Health* **2022**, *19*, 7282. [CrossRef]
104. Zhang, Y.; Wang, X.; Liu, B.; Liu, Q.; Zheng, H.; You, X.; Sun, K.; Luo, X.; Li, F. Comparative study of individual and Co-Application of biochar and wood vinegar on blueberry fruit yield and nutritional quality. *Chemosphere* **2020**, *246*, 125699. [CrossRef]
105. Marumoto, S.; Yamamoto, S.P.; Nishimura, H.; Onomoto, K.; Yatagai, M.; Yazaki, K.; Fujita, T.; Watanabe, T. Identification of a Germicidal Compound against Picornavirus in Bamboo Pyroligneous Acid. *J. Agric. Food Chem.* **2012**, *60*, 9106–9111. [CrossRef]
106. Mathew, S.; Zakaria, Z.A. Pyroligneous acid-the smoky acidic liquid from plant biomass. *Appl. Microbiol. Biotechnol.* **2015**, *99*, 611–622. [CrossRef]
107. Cai, K.; Jiang, S.; Ren, C.; He, Y. Significant damage-rescuing effects of wood vinegar extract in living Caenorhabditis elegans under oxidative stress. *J. Sci. Food Agric.* **2012**, *92*, 29–36. [CrossRef] [PubMed]
108. Loo, A.Y.; Jain, K.; Darah, I. Antioxidant and radical scavenging activities of the pyroligneous acid from a mangrove plant, *Rhizophora apiculata*. *Food Chem.* **2007**, *104*, 300–307. [CrossRef]
109. Chen, Y.-X.; Huang, X.-D.; Han, Z.-Y.; Huang, X.; Hu, B.; Shi, D.-Z.; Wu, W.X. Effects of bamboo charcoal and bamboo vinegar on nitrogen conservation and heavy metals immobility during pig manure composting. *Chemosphere* **2010**, *78*, 1177–1181. [CrossRef]
110. Wei, Q.; Ma, X.; Dong, J. Preparation, chemical constituents and antimicrobial activity of pyroligneous acids from walnut tree branches. *J. Anal. Appl. Pyrolysis* **2010**, *87*, 24–28. [CrossRef]
111. Xu, J.; Zhang, S.; Zhou, Y.; Liu, S.; Lang, S.; Yang, J.; Wu, Y. Comparative study on the properties of wood vinegar prepared from the pretreated Chinese fir: Effect of hydrothermal parameters and hydrogen peroxide. *J. Anal. Appl. Pyrolysis* **2022**, *167*, 105674. [CrossRef]
112. Wang, C.; Zhang, S.; Wu, S.; Sun, M.; Lyu, J. Multi-purpose production with valorization of wood vinegar and briquette fuels from wood sawdust by hydrothermal process. *Fuel* **2020**, *282*, 118775. [CrossRef]
113. Fagernas, L.; Kuoppala, E.; Tiilikkala, K.; Oasmaa, A. Chemical Composition of Birch Wood Slow Pyrolysis Products. *Energy Fuels* **2012**, *26*, 1275–1283. [CrossRef]
114. Liu, X.; Wang, J.; Feng, X.; Yu, J. Wood vinegar resulting from the pyrolysis of apple tree branches for annual bluegrass control. *Ind. Crops Prod.* **2021**, *174*, 114193. [CrossRef]
115. Gama, G.S.P.; Pimenta, A.S.; Feijo, F.M.C.; Santos, C.S.; Fernandes, B.C.C.; de Oliveira, M.F.; De Souza, E.C.; Monteiro, T.V.; Fasciotti, M.; De Azevedo, T.K.; et al. Antimicrobial activity and chemical profile of wood vinegar from eucalyptus (*Eucalyptus urophylla x Eucalyptus grandis* – clone I144) and bamboo (*Bambusa vulgaris*). *World J. Microbiol. Biotechnol.* **2023**, *39*, 186. [CrossRef]
116. Gao, T.; Bian, R.; Joseph, S.; Taherymoosavi, S.; Mitchell, D.R.G.; Munroe, P.; Xu, J.; Shi, J. Wheat straw vinegar: A more cost-effective solution than chemical fungicides for sustainable wheat plant protection. *Sci. Total Environ.* **2020**, *725*, 138359. [CrossRef]
117. Wu, Q.M.; Zhang, S.Y.; Hou, B.X.; Zheng, H.J.; Deng, W.X.; Liu, D.H.; Tang, W. Study on the preparation of wood vinegar from biomass residues by carbonization process. *Bioresour. Technol.* **2015**, *179*, 98–103. [CrossRef]
118. Wang, C.; Zhang, S.; Huang, S.; Cao, Z.; Xu, J.; Lyu, J. Effect of hydrothermal treatment on biomass structure with evaluation of post-pyrolysis process for wood vinegar preparation. *Fuel* **2021**, *305*, 121513. [CrossRef]
119. Zhang, F.; Shao, J.; Yang, H.; Guo, D.; Chen, Z.; Zhang, S.; Chen, H. Effects of biomass pyrolysis derived wood vinegar on microbial activity and communities of activated sludge. *Bioresour. Technol.* **2019**, *279*, 252–261. [CrossRef] [PubMed]
120. Li, Z.C.; Zhang, Z.Q.; Wu, L.J.; Zhang, H.Q.; Wang, Z.M. Characterization of Five Kinds of Wood Vinegar Obtained from Agricultural and Forestry Wastes and Identification of Major Antioxidants in Wood Vinegar. *Chem. Res. Chin. Univ.* **2019**, *35*, 12–20. [CrossRef]
121. Raza, M.; Abu-Jdayil, B.; Al-Marzouqi, A.H.; Inayat, A. Kinetic and thermodynamic analyses of date palm surface fibers pyrolysis using Coats-Redfern method. *Renew. Energy* **2022**, *183*, 67–77. [CrossRef]
122. Sari, R.M.; Wahono, S.K.; Anwar, M.; Rizal, W.A.; Suryani, R.; Suwanto, A. Wet scrubbing pre-condensation purification of wood vinegar from pyrolysis coconut shell: Physicochemical parameters, antioxidant capacity and biological properties. *J. Wood Chem. Technol.* **2024**, *44*, 351–362. [CrossRef]
123. Theapparat, Y.; Khongthong, S.; Rodjan, P.; Lertwittayanon, K.; Faroongsarng, D. Physicochemical properties and in vitro antioxidant activities of pyroligneous acid prepared from brushwood biomass waste of Mangosteen, Durian, Rambutan, and Langsat. *J. For. Res.* **2019**, *30*, 1139–1148. [CrossRef]
124. Afsharipour, S.; Mirzaalian Dastjerdi, A.; Seyedi, A. Optimizing *Cucumis sativus* seedling vigor: The role of pistachio wood vinegar and date palm compost in nutrient mobilization. *BMC Plant Biol.* **2024**, *24*, 407. [CrossRef]
125. Yang, J.-F.; Yang, C.-H.; Liang, M.-T.; Gao, Z.-J.; Wu, Y.-W.; Chuang, L.-Y. Chemical Composition, Antioxidant, and Antibacterial Activity of Wood Vinegar from *Litchi chinensis*. *Molecules* **2016**, *21*, 1150. [CrossRef]
126. Feng, T.-H.; Xue, R.; Zhu, L.; Zhu, Y.-H. Comparison of antioxidant and antibacterial effects of the Eucommia wood vinegar under the refining methods of atmospheric distillation and vacuum distillation. *Ind. Crops Prod.* **2023**, *192*, 116013. [CrossRef]

127. Aguirre, J.L.; Baena, J.; Martin, M.T.; Nozal, L.; Gonzalez, S.; Manjon, J.L.; Peinado, M. Composition, Ageing and Herbicidal Properties of Wood Vinegar Obtained through Fast Biomass Pyrolysis. *Energies* **2020**, *13*, 2418. [CrossRef]
128. Li, Z.; Zhang, L.; Chen, G.; Wu, L.; Liu, B.; Li, Y.; Sun, S.; Zhang, H.; Zhang, Z.; Wang, Z. A new method for comprehensive utilization of wood vinegar by distillation and liquid–liquid extraction. *Process Biochem.* **2018**, *75*, 194–201. [CrossRef]
129. Aguirre, J.L.; Baena, J.; Martin, M.T.; Gonzalez, S.; Manjon, J.L.; Peinado, M. Herbicidal effects of wood vinegar on nitrophilous plant communities. *Food Energy Secur.* **2020**, *9*, e253. [CrossRef] [PubMed]
130. Lei, M.; Liu, B.; Wang, X. Effect of adding wood vinegar on cucumber (*Cucumis sativus* L.) seed germination. In Proceedings of the 3rd International Conference on Energy Equipment Science and Engineering (ICEESE), Beijing, China, 28–31 December 2017; IOP Publishing Ltd.: Bristol, UK, 2017.
131. Shehata, S.A.; Abouziena, H.F.; Abdelgawad, K.F.; Elkhawaga, F.A. Weed Control Efficacy, Growth and Yield of Potato (*Solanum tuberosum* L.) as Affected by Alternative Weed Control Methods. *Potato Res.* **2019**, *62*, 139–155. [CrossRef]
132. Sun, S.; Gao, Z.-T.; Li, Z.-C.; Li, Y.; Gao, J.-L.; Chen, Y.-J.; Li, H.; Liu, X.-Y.; Wang, Z.-M. Effect of Wood Vinegar on Adsorption and Desorption of Four Kinds of Heavy (loid) Metals Adsorbents. *Chin. J. Anal. Chem.* **2020**, *48*, E20013–E20020. [CrossRef]
133. Yang, Y.; Ahmed, W.; Ye, C.; Yang, L.; Wu, L.; Dai, Z.; Khan, K.A.; Hu, X.; Zhu, X.; Zhao, Z. Exploring the effect of different application rates of biochar on the accumulation of nutrients and growth of flue-cured tobacco (*Nicotiana tabacum*). *Front. Plant Sci.* **2024**, *15*, 1225031. [CrossRef]
134. Zheng, J.L.; Zhu, Y.H.; Dong, Y.Y.; Zhu, M.Q. Life-cycle assessment and techno-economic analysis of the production of wood vinegar from stem: A case study. *Front. Chem. Sci. Eng.* **2023**, *17*, 1109–1121. [CrossRef]
135. Cho, Y.H.; Lee, J.Y.; Lee, J.H.; Cho, J.S.; Lee, G.W. Evaluation of Stability in the Purified Wood Vinegar and Its Hair Growth Effect. *J. Life Sci.* **2009**, *19*, 1389–1395.
136. Wang, J.; Gao, W.; Zhu, J.; Yang, Y.; Niu, Y. Remediation of Cd and Cu Contaminated Agricultural Soils near Oilfields by Biochar Combined with Sodium Humate-Wood Vinegar. *Agronomy* **2023**, *13*, 1009. [CrossRef]
137. Zhang, F.; Yang, H.; Guo, D.; Zhang, S.; Chen, H.; Shao, J. Effects of biomass pyrolysis derived wood vinegar (WVG) on extracellular polymeric substances and performances of activated sludge. *Bioresour. Technol.* **2019**, *274*, 25–32. [CrossRef]
138. Grewal, A.; Abbey, L.; Gunupuru, L.R. Production, prospects and potential application of pyroligneous acid in agriculture. *J. Anal. Appl. Pyrolysis* **2018**, *135*, 152–159. [CrossRef]
139. Zhou, X.; Shi, A.; Rensing, C.; Yang, J.; Ni, W.; Xing, S.; Yang, W. Wood vinegar facilitated growth and Cd/Zn phytoextraction of *Sedum alfredii* Hance by improving rhizosphere chemical properties and regulating bacterial community. *Environ. Pollut.* **2022**, *305*, 119266. [CrossRef] [PubMed]
140. Xu, J.-W.; Abbas, S.; Xiu, H.-F.; Ma, K.; Pan, Y.-T.; Lan, W.-K.-N.; Mao, Z.S.; Liu, D. Effects of Different Materials on Desalting and Fertility of Coastal Saline Soil in Zhejiang Province, China. *Water Air Soil Pollut.* **2023**, *234*, 407. [CrossRef]
141. Yang, L.; Tang, G.M.; Xu, W.L.; Zhang, Y.S.; Ning, S.R.; Yu, P.J.; Zhu, J.; Wu, Q.; Yu, P. Effect of Combined Application of Wood Vinegar Solution and Biochar on Saline Soil Properties and Cotton Stress Tolerance. *Plants* **2024**, *13*, 2427. [CrossRef]
142. Jeong, K.W.; Kim, B.S.; Ultra, V.U., Jr.; Chul, S. Effects of Rhizosphere Microorganisms and Wood Vinegar Mixtures on Rice Growth and Soil Properties. *Korean J. Crop Sci.* **2015**, *60*, 355–365. [CrossRef]
143. Deng, H.; Zhang, Y.Y.; Liu, K.P.; Mao, Q.Z.; Agathokleous, E. Allelopathic effects of *Eucalyptus* extract and wood vinegar on germination and sprouting of rapeseed (*Brassica rapa* L.). *Environ. Sci. Pollut. Res.* **2024**, *31*, 4280–4289. [CrossRef]
144. Zhang, P.; Bing, X.; Jiao, L.; Xiao, H.; Li, B.; Sun, H. Amelioration effects of coastal saline-alkali soil by ball-milled red phosphorus-loaded biochar. *Chem. Eng. J.* **2022**, *431*, 133904. [CrossRef]
145. Zhu, K.; Liu, J.; Luo, T.; Zhang, K.; Khan, Z.; Zhou, Y.; Cheng, T.; Yuan, B.; Peng, X.; Hu, L. Wood Vinegar Impact on the Growth and Low-Temperature Tolerance of Rapeseed Seedlings. *Agronomy* **2022**, *12*, 2453. [CrossRef]
146. Liu, X.; Cui, R.; Shi, J.; Jiang, Q.; Gao, J.; Wang, Z.; Li, X. Separation and microencapsulation of antibacterial compounds from wood vinegar. *Process Biochem.* **2021**, *110*, 275–281. [CrossRef]
147. He, K.; Xu, Y.; He, G.; Zhao, X.; Wang, C.; Li, S.; Zhou, G.; Hu, R. Combined application of acidic biochar and fertilizer synergistically enhances Miscanthus productivity in coastal saline-alkaline soil. *Sci. Total Environ.* **2023**, *893*, 164811. [CrossRef]
148. Wang, J.; Jing, H.; Xu, T.; Li, C.; Zhao, C.; Feng, W. Application Effect of Straw Returning and Biochar in the Improvement of Saline-Alkali Land in Northeast China. *Biol. Bull.* **2023**, *50*, 825–836. [CrossRef]
149. Hu, J.; Huang, Y.; Zhou, D. Phosphorus fractions affect fungal compositions and functions under land use conversions in saline-alkali soil in northeastern China. *Chem. Biol. Technol. Agric.* **2024**, *11*, 56. [CrossRef]
150. Zhang, L.; Jia, X.; Zhao, Y.; Wang, H.; Peng, B.; Zhang, P.; Zhao, M. Spatio-temporal characteristics and driving mechanism of land degradation sensitivity in Northwest China. *Sci. Total Environ.* **2024**, *918*, 170403. [CrossRef] [PubMed]
151. Dong, S.; Wan, S.; Kang, Y.; Miao, J.; Li, X. Different mulching materials influence the reclamation of saline soil and growth of the *Lycium barbarum* L. under drip-irrigation in saline wasteland in northwest China. *Agric. Water Manag.* **2021**, *247*, 106730. [CrossRef]

152. Chen, Y.; Zhang, J.; Wang, Z.; Li, H.; Chen, R.; Zhao, Y.; Huang, T.; Luo, P. Influence of Long-Term Mulched Drip Irrigation on Upward Capillary Water Movement Characteristics in the Saline-Sodic Region of Northwest China. *Agronomy* **2024**, *14*, 1300. [CrossRef]
153. Han, X.L.; Chen, Z.J.; Li, P.D.; Xu, H.S.; Liu, K.; Zha, W.J.; Li, S.; Chen, J.; Yang, G.; Huang, J.; et al. Development of Novel Rice Germplasm for Salt-Tolerance at Seedling Stage Using CRISPR-Cas9. *Sustainability* **2022**, *14*, 2621. [CrossRef]
154. Luo, T.T.; Ma, C.X.; Fan, Y.H.; Qiu, Z.D.; Li, M.; Tian, Y.S.; Shang, Y.; Liu, C.; Cao, Q.; Peng, Y.; et al. CRISPR-Cas9-mediated editing of GmARM improves resistance to multiple stresses in soybean. *Plant Sci.* **2024**, *346*, 112147. [CrossRef]
155. Yan, X.; Chen, S.; Pan, Z.Y.; Zhao, W.C.; Rui, Y.K.; Zhao, L.J. AgNPs-Triggered Seed Metabolic and Transcriptional Reprogramming Enhanced Rice Salt Tolerance and Blast Resistance. *ACS Nano* **2023**, *17*, 492–504. [CrossRef]
156. Tang, Y.Y.; Ding, Y.R.; Nadeem, M.; Li, Y.B.; Zhao, W.C.; Guo, Z.L.; Zhang, P.; Rui, Y. Enhancing maize stress tolerance with nickel ferrite nanoparticles: A sustainable approach to combat abiotic stresses. *Environ. Sci. Nano* **2025**, *12*, 302–314. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.