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# 生物炭改良盐碱地研究与应用进展

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**摘要:** 盐碱地作为 21 世纪严重威胁粮食产量的农田问题土壤之一, 分布广泛, 具有极大的开发潜力. 生物炭作为高效的新型土壤改良剂, 在缓解土壤酸碱障碍、土壤污染治理、碳封存和肥料缓释等方面发挥了重要作用, 有力地推动了盐碱地农业的可持续发展. 近年来, 关于生物炭改良盐碱地的研究和应用备受关注. 但由于生物炭来源、结构和组分的复杂性和非均质性, 其对盐碱地的改良效果存在极大的不确定, 也缺乏关键机制的系统总结和深度探讨, 这限制了生物炭技术在盐碱地改良中的进一步推广和应用. 通过综合分析生物炭对盐碱地土壤理化性质、养分有效性和生物特征的影响, 归纳总结生物炭和改性生物炭对盐碱地的改良效果及其提质增效作用, 阐明生物炭在盐碱地改良中存在的可能机制, 并对未来研究方向进行了展望, 可为进一步研发绿色高效精准盐碱地生物炭改良技术及其推广应用提供参考.

**关键词:** 盐碱地; 生物炭; 改性; 理化性质; 养分

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## Research and Application Progress of Biochar in Amelioration of Saline-Alkali Soil

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**Abstract:** Saline-alkali land, as one of the farmland problems that seriously threatens grain yield in the 21st century, is widely distributed and has great potential for development. Biochar is a relatively efficient novel soil amendment, which can play an important role in alleviating the soil acid-base barrier, soil pollution control, carbon sequestration, and fertilizer slow release and has a great prospect in promoting sustainable agricultural development. In recent years, the research and application of biochar to improve saline-alkali soil have attracted much attention. However, due to the complexity and heterogeneity of the structural components of biochar, the improvement effect of biochar on saline-alkali soil is highly uncertain, and there is also a lack of systematic summary and in-depth discussion of the key mechanisms, which limits the further popularization and application of biochar technology in the improvement of saline-alkali soil. This study comprehensively analyzed the effects of biochar on physicochemical properties, nutrient availability, and biological characteristics of saline-alkali soil; summarized the improvement effects of biochar and modified biochar on saline-alkali soil and their effects on quality and efficiency; and elucidated the possible mechanism of biochar in the improvement of saline-alkali soil. The future research prospect of biochar was discussed in order to provide reference for further research and development of green, efficient, and accurate improvement technology of biochar in saline-alkali soil and its popularization and application.

**Key words:** saline-alkali soil; biochar; modification; physicochemical property; nutrient

土壤盐碱化被认为是全球范围内威胁干旱和半干旱地区农业生产、粮食安全和可持续发展的重要问题之一. 目前, 全球盐碱地面积约  $1.1 \times 10^9 \text{ hm}^2$  (占地球陆地总面积的 8.7%)<sup>[1]</sup>. 其中大多分布在亚洲、非洲和拉丁美洲的自然干旱或半干旱地带. 我国盐碱地总面积为  $3.69 \times 10^7 \text{ hm}^2$ , 主要分布在西北、华北、东北及沿海地区, 约 1/6 具有农业改良和利用潜力<sup>[2]</sup>. 盐碱地区通常淡水资源匮乏、地势低且地下水位高以及土壤脱盐困难<sup>[3]</sup>, 土壤盐碱化造成的土壤肥力下降、作物生长不良和生态环境脆弱等问题严重制约着区域农林业和城市的发展. 不同区域的土壤盐碱类型和程度受土壤演替、气候和水文地质等因素的影响较大. 盐碱地是重要的后备耕地资源, 发展经济、高效和低碳的盐碱地改良与利用技术, 积极挖掘耕地增加潜力, 推进盐碱地综合利用, 可为全球粮食

安全、严守现有耕地红线和缓解全球气候变化提供有力保障. 因此, 开发与传统物理、化学和生物等改良技术以及工程措施具有强兼容性的土壤改良剂是盐碱地绿色、高效精准改良和综合利用的关键.

生物炭技术是近年土壤学和环境科学领域的研究热点, 被认为是可一并应对气候变化<sup>[4]</sup>、农业生产安全<sup>[5]</sup>、能源危机<sup>[6]</sup>、农业废弃物资源化<sup>[7]</sup>和环境污染<sup>[8]</sup>等影响人类可持续发展重大问题的“一石多鸟”的重要技术, 在国际上引起研发热潮. 生物炭是由动植物残体在完全或部分缺氧的条件下经热解炭化产

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生的一类高度芳香化碳质材料,其具有比表面积大、吸附能力和抗分解能力强等特点<sup>[6]</sup>,在土壤改良、作物增产和环境保护等方面都具有积极功效。有研究表明,生物炭对土壤养分具有直接或间接的调控作用<sup>[9]</sup>,能够提高土壤有机质含量、阳离子交换量、通透性和微生物活性<sup>[10]</sup>,减少氮磷流失,增加土壤团聚体结构的形成<sup>[11]</sup>,也能提高土壤导水率、利于水分入渗,从而改善作物生境和提高作物产量。在短短不到20 a研究中,生物炭技术在盐碱地改良和应用中取得了一定的发展。有研究明确了施用生物炭对盐碱地土壤性质的有利影响,例如提高土壤通透性和有机质含量<sup>[10]</sup>、降低pH和盐分<sup>[12]</sup>促进微生物和作物生长<sup>[13]</sup>。然而,由于当前规模化制备的生物炭通常富含碱金属等盐离子且碱性较强,有研究也发现了施用生物炭对盐碱地土壤性质的负面影响,例如提高土壤pH和盐分含量<sup>[14]</sup>。上述研究结果展现出了当前生物炭技术在盐碱地改良方面具有矛盾性,也缺乏系统性,不利于预测和评价生物炭技术在我国不同类型盐碱地改良和治理中的科学和应用价值。同时,由于生物炭与土壤相互作用过程复杂,已有研究结果也仅停留在表面,微观机制的解释还有待于细化。因此,生物炭技术作为新型的盐碱地综合修复技术,全面系统评价其在盐碱地改良中的应用价值,明确生物炭在盐碱地改良中的相关过程及微观机制,阐明其优势和不足,才能正确引导生物炭技术在我国盐碱地改良中广泛应用,推动盐碱地生物炭改良技术健康发展。

基于此,本文总结了近20年来国内外关于生物炭在盐碱地改良方面的研究现状,分析归纳了生物炭对盐碱地土壤理化性质、养分有效性和生物学特性等方面的影响,结合生物炭的特征阐述了生物炭改良盐碱地的关键机制,强调了改性生物炭在盐碱地高效精准改良中的重要作用及其潜在应用价值,最后针对当前研究中存在的问题和不足,提出了未来的研究方向和展望。本文可为生物炭技术在盐碱地改良方面的推广与应用提供理论基础,有助于进一步探索和研发基于生物炭的绿色、低碳、环保和可持续的盐碱地高效精准改良技术。

## 1 生物炭对盐碱地土壤理化性质的影响

生物炭具有较高的比表面积、复杂的孔隙结构和丰富的官能团,这些特性造就了生物炭在盐碱地改良方面的多重作用<sup>[15]</sup>。生物炭的理化性质取决于原料类型、热解温度、制备方式、加热速率和停留时间等诸多因素<sup>[16]</sup>,并且也密切影响着生物炭对盐碱地土壤性质、水盐运移分配和农业生产力的促进效

果。综合多项研究来看,不同原料和热解方式制备的生物炭添加到不同类型盐碱地中,对可溶性盐含量、pH、团聚体、土壤容重、阳离子交换量(CEC)、有机质等土壤理化性质以及作物生长和产量的影响也不尽相同(表1),下文将详细总结讨论,这里不再赘述。

### 1.1 土壤可溶性盐含量和碱化度

土壤总含盐量和碱化度(ESP)是衡量土壤盐碱化程度的重要指标。盐碱地土壤中由于积聚大量盐分而具有高含盐量、高电导率(EC)和高ESP等特征。降低土壤可溶性盐含量和ESP,缓解土壤生物盐胁迫,从而恢复土壤生态功能,一直是盐碱地改良的核心目标。由于生物炭技术发展之初是通过高温热解方式来制备生物炭,其通常富含碱金属等盐离子、碱性较强,导致以往研究多关注其改良酸性土壤的效果。近年来,越来越多的研究<sup>[37,38]</sup>开始关注生物炭对盐碱地的改良效果,并证实了生物炭能显著降低盐碱地土壤的含盐量和ESP。如表1所示,糠醛生物炭<sup>[35]</sup>可使盐渍化土壤的ESP降低51.0%,秸秆生物炭<sup>[39,40]</sup>可使土壤EC的降幅达到55.0%~92.1%。生物炭降低盐碱地土壤含盐量和ESP的可能机制包括以下2个方面:①由于生物炭表面富含 $\text{Ca}^{2+}$ 和 $\text{Mg}^{2+}$ 等离子可交换土壤胶体中吸附的 $\text{Na}^+$ ,降低土壤中的钠盐含量<sup>[23]</sup>;②生物炭可显著提高土壤的孔隙度和比表面积,增加了土壤持水量,促进土壤中钠盐的淋溶作用<sup>[20,41]</sup>。

然而也有研究表明<sup>[42]</sup>,生物炭的施用也会导致盐碱地土壤盐度升高,盐离子的直接输入是其负面效应的直接原因。畜禽粪便、盐生植物和核桃壳生物炭等盐分含量较高的生物炭添加会导致自身富含的可溶性 $\text{K}^+$ 、 $\text{Ca}^{2+}$ 和 $\text{Mg}^{2+}$ 等离子直接释放到土壤中,引起盐碱地土壤可溶性盐含量升高<sup>[42,43]</sup>,该类生物炭不适用于盐碱地土壤的改良<sup>[42-44]</sup>。因此,改良不同类型盐碱地时要因地制宜,尽量选用含盐量低的生物炭品种,如低温秸秆生物炭<sup>[45]</sup>。另外,生物炭吸附的盐离子可能会随着施用时间的延长,生物炭吸附能力减弱,而重新释放到土壤中,引起改良效果的反弹<sup>[46]</sup>。盐碱地土壤洗盐过程中,在生物炭作用下被交换出的 $\text{Na}^+$ 要及时从土壤中排出,避免其以游离态存在于土壤中。而且,由于水盐运移的联动性,盐碱地土壤改良也应重视生物炭与现代灌溉技术的结合,以期建立基于生物炭的盐碱地节水降盐综合技术。此外,当前大多数同类研究还停留在实验室盆栽阶段(表1),其水盐运移规律与实际农业灌溉方式有较大差别,未来针对不同地域盐碱地开展生物炭改良时需综合考虑生物炭特征、盐碱地盐渍化特征和灌溉方式等因素。

表 1 生物炭对不同类型盐碱地的改良效果比较

Table 1 Diverse effects of biochar on different types of saline-alkali land

原料	热解温度/°C	制备方式	盐碱地类型	添加方式/试验方式	推荐添加用量/%	改良效果	文献
小麦秸秆	300	热解	滨海盐渍土	单独添加/室内盆栽	2	显著降低有机碳矿化,促进土壤碳封存	[17]
小麦秸秆	500	热解	滨海盐渍土	单独添加/室内盆栽	0.5 和 1	减少土壤氮损失 11.6%~29.7%	[18]
小麦秸秆	450	热解	盐碱土	单独添加/田间试验	1 和 2	提高土壤持水能力、总有机碳和 CEC,其中速效钾最高可提高 220%	[19]
玉米秸秆	600	热解	盐渍土	单独添加/室内盆栽	2	甘草的根和叶梢生物量分别提高 80% 和 41%	[20]
稻草秸秆	450	热解	滨海盐渍土	单独添加/室内盆栽	0.4	增加土壤有效磷含量 21%~110%,水稻产量提高 9.65%	[21]
稻草秸秆和 FeCl <sub>2</sub> 、FeCl <sub>3</sub> 溶液	600	浸泡后热解	盐碱土	单独添加/田间试验	0.23	Fe 改性生物炭可使磷损失降低 86%,有效提高土壤全磷和有效磷的含量	[22]
棉花壳	350	热解	盐碱土	单独添加/室内盆栽	2	减少植物中 Na 的积累,藜麦和种子的产量提高 51%	[23]
棉花秸秆	850	热解	盐碱土	单独添加/田间试验	0.5	和有机肥相比,显著降低土壤盐度和增加作物产量	[24]
玉米秸秆	—	—	苏打盐碱地	单独添加/田间试验	1	降低 pH、盐含量和钠离子浓度,增加有机质、CEC、N、P 和 K 含量,增加产量 50.09%	[25]
棕榈属的果枝	500	热解	盐渍土	单独添加/田间试验	1	降低土壤容重,增加土壤孔隙度,显著土壤饱和和含水率和植物有效水分	[26]
葵花杆	400	热解	盐土	单独添加/田间试验	0.75	提高土壤养分有效性(尤其是 AP)和刺激根际土壤氧化还原酶活性,相比 CK 提高作物产量 300%	[27]
芦苇	500	热解	盐渍土	单独添加/田间试验	1.5	根际添加通过降低土壤硝态氮的含量和 EC,显著增长芦苇根	[28]
玉米秸秆	230	水热法	盐渍土	单独添加/田间试验	0.05	降低了土壤表层 pH、EC、土壤盐分和 ESP,显著提高了 CEC、OM、TN、AP、可溶性阳离子浓度和水分含量	[29]
玉米秸秆	—	—	滨海盐碱地	混合添加/田间试验	0.625	生物炭对 N、P 和 K 养分含量的提升效果更显著,与土壤调理剂结合施用,可防止土壤 NO <sub>3</sub> <sup>-</sup> -N 淋失	[30]
互米花草根	400	热解	滨海盐渍土	混合微生物菌剂添加/盆栽试验	3	土壤盐分降低 45.49%,土壤酶活性增加 20%,土壤有机质含量增加 40%	[31]
木屑	500	热解	盐碱土	混合堆肥添加/盆栽试验	3.75	淋滤后,土壤 SAR 降低 51% 和 ESP 降低 83%	[32]
玉米秸秆	700	热解后球磨	盐碱土	单独添加/室内盆栽	2	提高了土壤 OC、CEC、养分和微生物酶活性,降低了土壤 EC 和离子浓度,磷改性后的 BC 改良效果优于初级 BC	[33]
花生壳	600	二次热解	盐渍土	单独添加/田间试验	0.23	土壤有效磷增加 86%	[34]
糠醛	300	热解	盐碱土	单独添加/盆栽试验	5	保留氮磷等养分,土壤 ESP 降低 51.0%	[35]
稻草秸秆	300	热解	盐渍土	单独添加/盆栽试验	5	降低土壤 SAR 和 EC,土壤 EC 可降低 92.1%	[36]

## 1.2 土壤 pH

目前,有研究<sup>[11]</sup>认为生物炭并不能改善盐碱地的土壤 pH,并将其归因于生物炭富含的碱金属离子及碳酸盐等物质的浸出。但也有研究发现盐碱地土壤 pH 的变化受生物炭原材料和热解温度的影响。比如, Sun 等<sup>[47]</sup>研究发现小麦秸秆生物炭(pH = 6.9)、玉米秸秆生物炭(pH = 8.0)和花生壳生物炭(pH = 7.7)加入到滨海氯化钠盐类盐碱土壤(pH = 8.6)中,只有小麦秸秆生物炭显著提高了土壤 pH,其他两者添加后的土壤 pH 没有显著变化。进一步的研究也证实随着热解温度的升高,生物炭灰分含量增加,碱性越强<sup>[48]</sup>;而低温度(< 500°C)热解制成的生物炭呈中

性或弱碱性,更适合盐碱地改良<sup>[49]</sup>。此外,有研究发现采用水热法制成的生物炭呈酸性,可有效地降低土壤 pH<sup>[50]</sup>。但该制备工艺对设备要求高、技术难度大、安全性能差,难以实现规模化生产。综上,生物炭对盐碱地土壤 pH 的改良效果受制于土壤类型和生物炭的原料、热解温度、性质及使用方式等多方面因素。

## 1.3 土壤胶体和团聚体

从微观层面来说,盐碱地中的胶体主要是由 2:1 型黏土矿物(如蒙脱石和蛭石)组成的,拥有大量的恒负电荷<sup>[51]</sup>。大量的负电荷导致黏粒间排斥力强,呈高度分散的状态。同时,由于盐碱地中缺少凝聚力强

的变价金属阳离子(如  $Fe^{3+}$ 、 $Al^{3+}$ )<sup>[52]</sup>和腐殖质,更加导致了胶体无法凝聚.生物炭的加入会改变这种状态,它可以提供凝聚力较强的变价金属阳离子和有机质,从物理化学的角度增加生物炭和黏粒间的相互吸引,使得胶体彼此联结凝聚,形成具有水稳性的复合结构.

从宏观层面来说,盐碱地的大团聚体数量和稳定性远不如正常土壤.如图1所示,一方面是由于盐碱土中有大量的钠离子,不利于胶体凝聚.而生物炭含有的  $Ca^{2+}$ 和  $Mg^{2+}$ ,可以阻止胶体分散,提高土壤团聚体的数量和稳定性;另一方面,盐碱地中微生物和作物根系等不发达,致使土壤缺乏团聚体形成的架桥<sup>[53]</sup>.例如,Han等<sup>[54]</sup>研究发现生物炭可以促进植物根系的生长,由于根系活动产生的缠绕作用、根系分泌物均可对土壤团聚体的形成起到促进作用.另外,生物炭会提高土壤微生物和酶的活性,其代谢产物和有机质一起也可作为架桥<sup>[32]</sup>,连接粘土颗粒和多价阳离子形成微团聚体<sup>[55]</sup>.然而,生物炭作用下微生物和作物根系对团聚体结构和稳定性的影响尚需更多的研究去证实.今后的研究应采用原位成像和检测技术分析生物炭调控盐碱地土壤团聚体的变化过程,准确辨识其中的微观机制.

#### 1.4 土壤孔隙度和容重

盐碱地土壤孔隙度普遍较低<sup>[1]</sup>,不利于植物生长.有研究证明生物炭可以显著增加盐碱地的孔隙度<sup>[26,56]</sup>,尤其是0~30 cm的表层土壤,可提高4.8%~30.1%.其直接原因是生物炭本身孔隙度比较高,加入土壤后可以直接增加土壤的总体孔隙度<sup>[57]</sup>.同时,盐碱地因其孔隙度低等极差的物理条件导致土壤容重高,但生物炭具有较大的比表面积,远低于盐碱地

土壤的密度、容重和稳定的多孔结构<sup>[58]</sup>,可以直接降低土壤的容重.同时,生物炭不仅能够改善土壤团聚体结构,增强团聚体稳定性,提高土壤孔隙度,还含有大量的有机质,可稀释土壤矿物组分<sup>[26]</sup>,间接地降低土壤容重.因此,在改良盐碱地土壤孔隙度和容重方面,生物炭应优先选择容重低、孔隙度高、灰分含量低的品种,如高热解温度( $>600^{\circ}C$ )制备的秸秆类生物炭<sup>[59,60]</sup>.

#### 1.5 土壤保水能力

土壤水分含量是维持土壤生物生理和生态过程的关键.盐碱地本身土壤水分保持能力和透水性差<sup>[61]</sup>.生物炭孔隙结构和表面亲水性极性官能团(如  $-OH$ 和  $-COOH$ 等)丰富,可以有效改善盐碱地土壤的水力条件,增加土壤保水能力和导水率<sup>[62,63]</sup>,有助于盐碱地生产和生态功能的恢复(见图1).但是,生物炭类型不同,其保水效果也存在显著差异.例如,花生壳生物炭比秸秆生物炭更适合改良盐碱地的水力条件,这可能与生物炭的微孔结构、排列方式密切相关<sup>[64]</sup>.花生壳生物炭的微孔呈柱状、大小相似且排列紧密,更易于储存水分.大量施用高温生物炭( $\geq 500^{\circ}C$ )对土壤水力特性有不利影响<sup>[65,66]</sup>.因高温生物炭的疏水性可能会阻止水分渗入到生物炭的孔隙,并且生物炭粒径越小,其疏水性就越大,持水能力也随之降低,这种疏水性在生物炭用量较大时会显著降低土壤含水量.因此,生物炭表面的亲疏水性和孔隙结构是调控土壤保水能力的关键因素.而且,生物炭在土壤中的老化过程可以改善其亲疏水性.高温生物炭在土壤中老化后亲水性极性官能团增加,表面或孔隙中残留的焦油组分分解或浸出,亲水性增强,孔隙度增加,从而增强对水分的保持效果<sup>[46,67]</sup>.但

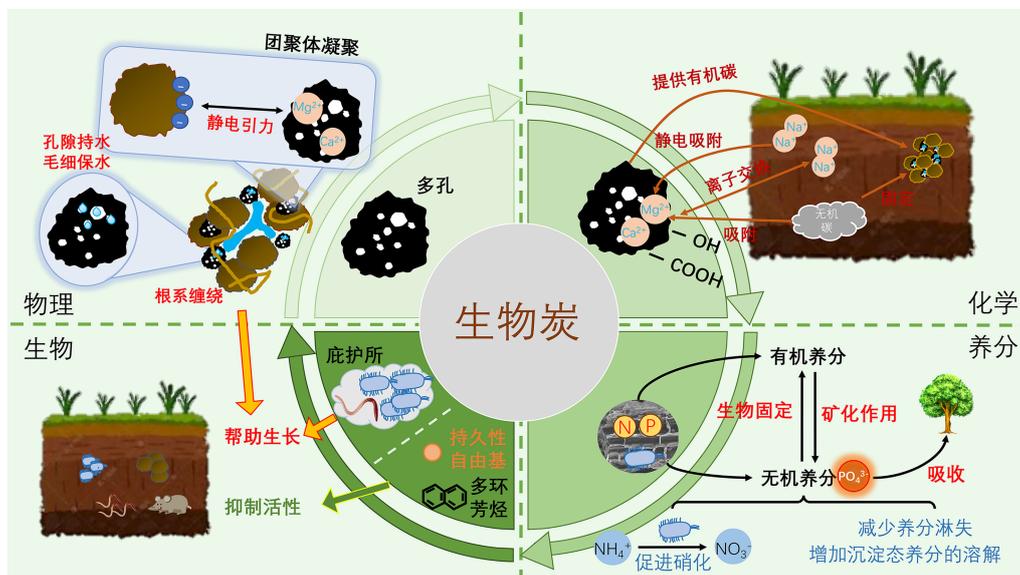


图1 生物炭对盐碱地的改良机制

Fig. 1 Amelioration mechanism of biochar on saline-alkali soil

是,耕作、生物活动和风化等可导致生物炭破碎为小颗粒,甚至土壤有机质及粘土矿物等组分可迁移到生物炭表面,占据亲水性吸附位点,阻塞孔隙结构,阻碍水分传导,进而降低生物炭对土壤的保水效果<sup>[68,69]</sup>。另外,土壤质地也是影响生物炭改善土壤保水能力的重要因素。生物炭往往更易增强分布于干旱或半干旱地区的盐碱地土壤(砂粒含量高,粒间孔隙大)的保水能力,而不易增强滨海盐碱地土壤(黏粒含量高、土壤压实板结)的导水率和水分入渗能力<sup>[70]</sup>。需要注意的是,生物炭对于盐碱地土壤保水能力和导水率的研究尚十分有限,生物炭的亲疏水性、孔隙结构和粒径大小与不同类型盐碱地改良效果的关联规律尚需更多的研究去证实。

### 1.6 土壤 CEC

盐碱地本身因其有机质含量低,且土壤交换点位被  $\text{Na}^+$  等盐离子占据,限制土壤保留其他阳离子的能力,导致土壤阳离子交换量小,因此 CEC 是评价盐碱地改良效果的指标之一。目前有研究证实,生物炭因其丰富的官能团( $-\text{OH}$  和  $-\text{COOH}$  等),增加了其对土壤阳离子的吸附能力,盐碱地的 CEC 能有效提升 22.5%~82.0%<sup>[19,29]</sup>。生物炭增加盐碱地 CEC 的机制可能包括以下两个方面:①生物炭具有较高的比表面积、丰富的羧基、羟基等含氧官能团和金属矿物,可直接增加土壤的交换点位<sup>[23]</sup>;②由生物炭引起的土壤 pH 升高会导致土壤胶体去质子化,促进土壤 CEC 的增加<sup>[71]</sup>。

决定生物炭 CEC 值的关键是其表面含氧官能团和金属矿物组分,因此不同原料在不同温度下制备的生物炭具有不同的 CEC 值<sup>[72]</sup>。当制备温度从  $450^\circ\text{C}$  提高到  $700^\circ\text{C}$  时,秸秆生物炭的 CEC 从  $26.36 \text{ cmol}\cdot\text{kg}^{-1}$  降低到  $10.28 \text{ cmol}\cdot\text{kg}^{-1}$ ,这是因为较低热解温度下纤维素的不完全分解,可产生更多的含氧官能团<sup>[73,74]</sup>。同时,由污泥或畜禽粪便等制备的生物炭通常含有比秸秆类生物炭更加丰富的含氧官能团和金属矿物。因此,低温污泥或畜禽粪便生物炭可能更适合用于增强盐碱地的土壤 CEC。另外,随着施用时间的推移,生物炭的老化可能会导致羧基和羟基等含氧官能团的增加,并提高生物炭的 CEC,提升对盐碱地的改良效果<sup>[17]</sup>。综合来看,生物炭对 CEC 较低的盐碱地确有改善作用,并且生物炭对土壤 CEC 的影响与生物炭和土壤类型以及在土壤中的老化时间密切相关。但是,生物炭对盐碱地土壤 CEC 的影响机制研究较少,尤其是淹水、干旱等环境因素以及土壤质地等如何影响生物炭性质与盐碱地改良效果的关联规律尚需更多长期的田间试验去证实。

### 1.7 土壤有机质和碳库

土壤碳是陆地生态系统最大的碳库,其微小变动往往会大气  $\text{CO}_2$  浓度以及碳循环产生重要影响。生物炭作为富含有机碳的土壤改良剂,对盐碱土壤碳封存<sup>[75]</sup>和减少温室气体排放<sup>[76]</sup>的作用已在许多研究中得到了证实。生物炭进入土壤后存在固碳(增加碳汇)和增强碳排放两种机制,这两种机制通过增加或减少 3 种温室气体( $\text{CO}_2$ 、 $\text{CH}_4$  和  $\text{N}_2\text{O}$ )<sup>[77]</sup>在农田系统与大气之间的交换而实现,是否具有碳汇效果取决于上述两种机制何种占优。可能的固碳机制主要包括:①生物炭自身具有较高比例的难降解碳,因而可长期封存于土壤中,形成固碳基础<sup>[78]</sup>;②生物炭利用自身比表面积大的特点吸附土壤中含 C、N 的有机和无机物质,生成更稳定的有机-无机复合体等形式,以降低碳的分解释放<sup>[79]</sup>;③通过调节土壤性质、抑制微生物活性和降低酶活性,进而影响土壤碳氮循环,通过调控土壤呼吸、硝化及反硝化反应,降低 3 种温室气体的排放<sup>[75]</sup>。

生物炭对盐碱土壤有机碳的矿化(增强碳排放)激发效应的研究也受到广泛关注,主要机制包括:①提高盐基离子,特别是钾的含量,促进土壤有机质及生物炭的矿化,促进可溶性有机质的释放;②提高土壤含水量和 pH,促进可溶性有机质释放,促进矿化作用;③增加微生物活性及生物量,提高酶活性,从而促进有机质矿化<sup>[17]</sup>。上述效应在生物炭添加初期因为提升微生物的活性<sup>[80]</sup>等作用较为明显,同时受生物炭的原料、制作温度、施用量、土壤理化性质、作物生长阶段和耕作方式等影响<sup>[80,81]</sup>,而长期来看这种作用会随时间的增加而减弱甚至呈现负效应<sup>[82]</sup>。另外,针对盐碱地土壤无机碳的研究也证明荒漠盐碱地可以吸收大量的  $\text{CO}_2$ ,尤其是碳酸盐型的盐碱土<sup>[83]</sup>,这可能是因为土壤碳酸盐溶解过程会消耗  $\text{CO}_2$ <sup>[84]</sup>。但在添加生物炭之后,该类型的盐碱土是否会因为土壤质量改善而减弱这种固碳能力,植物和土壤的固碳能力是否会出现此消彼长的现象等等都尚未可知。总的来说,生物炭是一种非常适宜用来提高盐碱地土壤有机碳和碳汇水平的改良剂,未来研究需重点关注生物炭对盐碱地土壤固碳和碳排放的调控机制,进一步发掘生物炭在土壤碳封存方面的潜力,为未来精准调控盐碱地的土壤碳循环提供理论和技术支撑。

## 2 生物炭对盐碱地养分含量有效性的影响

由于盐碱地土壤结构差,土壤中  $\text{Cl}^-$ 、 $\text{SO}_4^{2-}$  和  $\text{OH}^-$  等阴离子可与氮、磷等养分竞争土壤颗粒表面的吸附位点<sup>[85]</sup>,导致土壤养分容易随水流走或渗入地下。

同时,盐碱地有效养分匮乏导致植物养分利用率极低<sup>[86]</sup>. 生物炭自身含有丰富的N、P、K及矿物质等营养元素,可显著增加盐碱地的养分含量,其主要途径如下:①用自身养分直接提高土壤养分<sup>[87]</sup>. 比如畜禽粪便类生物炭的氮含量相对较高<sup>[88]</sup>;生物炭中水溶性氮和磷含量也会随着生物炭热解温度的升高而逐渐降低<sup>[45,49,89]</sup>. 并且 Christel等<sup>[90]</sup>认为随着热解温度的升高,无机正磷酸盐( $\text{PO}_4^{3-}$ )在500℃时成为粪肥生物炭中唯一存在的形式,而在高温( $\geq 700^\circ\text{C}$ )下水溶性磷几乎不存在. 因此,低温畜禽粪便类生物炭是提高盐碱地养分含量的较好选择. ②生物炭增强土壤团聚体稳定性<sup>[18]</sup>,提高土壤对养分的固持能力,减少养分的淋溶<sup>[9]</sup>;③生物炭还可以缓解作物盐胁迫,促进作物吸收土壤中游离的养分<sup>[91]</sup>,利于作物生长.

同时,生物炭还能够通过提升微生物和土壤酶活性来影响土壤N、P和K元素循环(见图1),减少土壤养分的流失<sup>[86]</sup>. 例如,生物炭可以减少 $\text{NH}_3$ 和 $\text{N}_2\text{O}$ 的排放<sup>[92]</sup>、减少 $\text{NO}_3^-$ 的淋溶<sup>[18]</sup>、促进硝化作用<sup>[81]</sup>和提高固氮能力<sup>[93]</sup>,进而增加土壤中流向植物的N素比例. 生物炭可提高磷酸酶<sup>[9]</sup>和根际微生物的数量及活性<sup>[28]</sup>,促进有机磷的矿化,将有机磷转化为有效磷来进一步提高磷的可利用率. 钾在土壤中存在的机制和氮磷并不相同,钾的行为不受微生物的影响,它主要受土壤阳离子交换特性的影响<sup>[51]</sup>. 目前关于生物炭影响盐碱地中钾元素作用机制的研究缺乏,仅有少量研究证明生物炭施用后土壤阳离子交换量和速效钾含量显著增加<sup>[94]</sup>.

### 3 生物炭对盐碱地土壤生物特性的影响

盐碱地能够承载的动植物数量、微生物丰度和酶活性都远不及正常土壤<sup>[95]</sup>. 目前关于生物炭添加对盐碱地土壤微生物群落结构和丰度影响的研究很多. 有研究表明,由于生物炭较高的比表面积、多孔的结构和丰富的有机质N、P和K等营养元素,生物炭可提高土壤中可溶性有机物和无机养分,降低盐分含量,缓解盐胁迫,从而提高微生物丰度和酶活性<sup>[96,97]</sup>. 但是,由于原材料和制备过程的不同,生物炭的pH和营养元素含量差异较大. Tang等<sup>[48]</sup>认为高温生物炭( $>550^\circ\text{C}$ )具有较少的羧酸、酚类和胺类等有毒官能团,从而促进土壤微生物群落向变形杆菌和拟杆菌等有益菌群的结构转化. 同时,生物炭种类和施用量也会改变土壤酶,如蔗糖酶、脲酶和磷酸酶等的活性. 例如,花生壳生物炭、互花米草生物炭和芦苇生物炭均可提升黄河三角洲滨海盐碱地中蔗糖酶的活性,抑制脲酶活性<sup>[98]</sup>. 生物炭的用量也可影响土壤酶活性,当生物炭施入量小于2%时,土壤酶活

性升高较迅速;当施入量大于2%时,土壤酶活性提升较缓慢<sup>[99]</sup>.

土壤动物的群落和数量与盐碱地土壤理化性质有密切联系,比如张建英等<sup>[100]</sup>认为蚁科、鼠妇科和象甲科等群类分布与土壤pH、碱化度和盐分含量呈负相关关系;土壤全盐和全氮等土壤因子对盐碱地中的土壤动物群落组成有决定性作用. 生物炭可以通过降低土壤盐分和改善土壤理化性质来为土壤动物提供更加适宜的生存环境. 与土壤微生物和酶相反,关于生物炭与盐碱地中蚯蚓等中小型动物的相关研究较少,仅有研究关注了生物炭固有的生态风险对土壤动物的影响,比如生物炭中的多环芳烃及持久性自由基可以对土壤动物产生毒性,抑制其生长繁殖<sup>[60]</sup>. 上述生物炭对土壤动物的负面效应间接反映了生物炭在盐碱地治理中存在的生态风险. 因此,如何保证生物炭的生态安全性是今后盐碱地治理中亟需解决的问题.

对陆生植物来说,生长在盐碱地中是十分具有挑战性的. 首先土壤溶液的高盐胁迫可直接抑制植物的生长. 其次,土壤结构差、空气和水分严重不足导致根系不发达、出苗率低. 最后,土壤养分匮乏导致植物营养不良. 由前文可知,生物炭在改良土壤盐含量高、结构差和营养低这3个方面表现优异,植物也因此得到了良好的生长环境. 但生物炭中的持久性自由基<sup>[101]</sup>会导致植物细胞加速老化,扰乱表皮细胞的生长代谢周期,抑制植物的发育. 另外,生物炭的高施加量<sup>[102]</sup>和生物炭施加后土壤pH和土壤含盐量升高也会对植物生长和发育产生负面作用. 因此,未来研究应继续关注生物炭对作物的内在影响和机制,针对低盐、低毒和高效改良盐碱地的新型生物炭的研发也不容忽视.

### 4 改性生物炭对盐碱地改良效果的提升

虽然生物炭在盐碱地改良方面优点众多,但是单一施加生物炭不仅用量大、成本较高;而且可能会提升盐碱地土壤pH和盐分含量,对盐碱地产生负面影响. 针对上述问题,多种可以提质增效的生物炭改性技术被提出,主要改性方法有:酸洗活化、负载活性组分、与传统肥料或改良剂物理混合等<sup>[103,104]</sup>,其改良机制见图2. 改性生物炭有着初级生物炭无法比拟的优势,极大提高了生物炭对盐碱地的改良效果<sup>[105,106]</sup>.

针对常规热解生物炭碱性较强的问题,研究人员提出了一种利用硝酸、盐酸等强酸处理生物炭的方法,即酸改性生物炭<sup>[107,108]</sup>. 经酸处理后,生物炭中的无机组分和有机质从表面和孔隙中浸出,碱性组

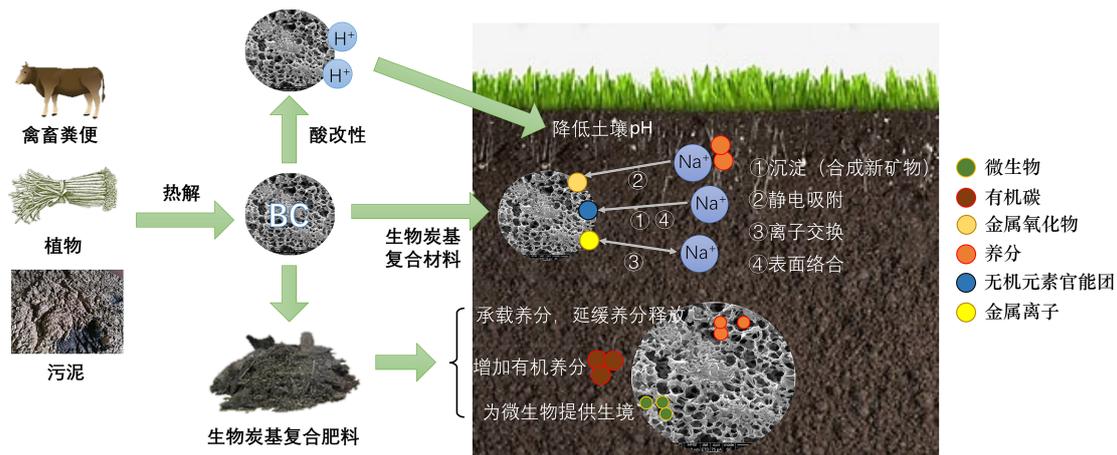


图2 改性生物炭对盐碱地的改良机制

Fig. 2 Amelioration mechanism of modified biochar on saline-alkali soil

分被去除或中和后,暴露更多微孔,提升材料的比表面积<sup>[109]</sup>和含氧官能团<sup>[110]</sup>,从而强化生物炭对土壤盐离子的吸附。同时,酸改性生物炭也可显著提升土壤的孔隙度和通透性,增加水稳性大团聚体的比例<sup>[59]</sup>。也有研究提出在强酸环境下通过水热处理制备生物炭<sup>[107]</sup>,会保留更多的酸性含氧官能团和孔隙结构<sup>[111]</sup>,提升对土壤盐离子的吸附能力<sup>[112]</sup>,对盐碱地的改良效果更好。目前强酸改性相关研究较多,但在实际盐碱地中应用的稳定性、经济成本和改良效率还存在着挑战,需要在未来研究中进一步评估。

由于生物炭中有限的养分含量,施用单一生物炭并不能为作物提供足量的养分<sup>[113]</sup>。因此,研究人员研发出了生物炭基肥料。它不仅能直接补充所需养分<sup>[114]</sup>,而且可以延缓肥料在土壤中的养分释放,降低养分损失,把生物炭变成肥料增效的载体<sup>[115]</sup>。但不同类型的肥料,作用效果和机制也略有不同:①家禽粪便等有机肥具有丰富的有机碳,可使盐碱地中土壤微生物群落丰度增加,有助于作物生长<sup>[116]</sup>;同时生物炭的表面积可因吸附的堆肥源物质堵塞微孔而下降,所以生物炭与有机肥共施也会缓解过量生物炭对土壤带来的负面影响<sup>[117]</sup>。②生物炭与氮肥、磷肥等无机肥组合,可产生更高水平的有效养分,提高盐碱地土壤酶活性和微生物丰度<sup>[118]</sup>;同时生物炭还可吸附养分,减少无机氮磷等养分在土壤中的淋溶。值得注意的是,由于正磷酸( $\text{PO}_4^{3-}$ )这种有效态磷在较高pH值的情况下容易发生吸附或沉淀反应,磷肥在盐碱地中和生物炭可能会相互产生负作用<sup>[119]</sup>。③生物炭与微生物肥料共施时,生物炭不仅可以作为肥料向植物提供营养物质<sup>[120]</sup>,而且会为微生物提供适宜的生境<sup>[121]</sup>,避免盐碱地恶劣环境的胁迫。总的来说,生物炭基肥料的施用显著提升了生物炭对盐碱地的改良效率,降低了经济成本。但是,针对不同类

型和质地的盐碱地,需要加强生物炭基肥料的适用性规律研究,对于精确施肥调控和提高生物炭的利用效率具有重要指导意义。

生物炭和负载物通过物理化学结合的方式来开发新型复合材料(改良剂)是当前的研究热点。生物炭由于自身粗糙、多孔的表面形貌被认为是优良的承载介质之一,而负载物可在生物炭表面生成全新的官能团和盐离子吸附位点。常见的负载物有金属化合物、粘土矿物等。生物炭基复合材料改良盐碱地的机制主要包括:①负载物可引入新的元素和新的官能团<sup>[122]</sup>,提高生物炭对土壤可溶性盐离子的络合和沉淀能力,减轻土壤可溶性盐含量和碱化度。Zhang等<sup>[33]</sup>研究指出生物炭负载红磷后,表面会形成新的含磷官能团,可与土壤中金属离子形成新的含磷矿物,显著降低盐碱土壤导电性和土壤可溶性盐含量,同时提高了盐碱地植物可利用磷的含量。②新物质负载可为土壤氮、磷等养分提供更多吸附位点,减少土壤养分的淋溶<sup>[34, 123]</sup>。③复合材料中负载的铁、钙和镁等金属物种可以释放出大量的金属阳离子,可交换出土壤胶体中吸附的 $\text{Na}^+$ ,在土壤过水过程中加速 $\text{Na}^+$ 的迁移,提高土壤淋洗效果,降低土中钠盐含量<sup>[124]</sup>。综上,生物炭基复合材料可兼具生物炭和负载物的优点,可针对不同地域的盐碱地类型负载不同的物质,以实现盐碱地的高效精确改良与治理。

## 5 展望

生物炭以其独特的理化性质、丰富的来源、可再生性和环境友好性等优点使其在盐碱地改良中具有广阔应用前景。但是,生物炭在盐碱地改良研究与应用中仍存在诸多问题,需要进一步研究和探索:

(1)生物炭改良盐碱地基础理论研究方面存在诸多争议性和不确定性,生物炭对盐碱地土壤理化

性质及功能、氮磷等关键元素地球化学循环、土壤微生物群落演替及功能的影响不明确,调控机制不清楚,尤其是生物炭性质与不同类型盐碱地改良效果的关联规律,仍需进一步系统研究和验证。

(2)生物炭改良盐碱地的研究大多数停留在实验室模拟阶段,缺乏长期定点、规模化的大田试验来分析其实际应用的适用性和作用机制,比如,生物炭作用下土壤水盐运移规律是否受盐碱地类型、农艺措施和灌溉条件等的影响,微生物和作物根系对生物炭-土壤团聚体结构和稳定性的影响等。同时,应综合考虑生物炭老化、气候、地质和水文等因素,并结合土壤质量评价对生物炭进行长期动态地跟踪监测,评价生物炭改良效果的持续性和环境风险。

(3)改性生物炭的批量生产和规模化应用存在阻碍,其制备选材和工艺研究多处于实验室阶段,难以进行高效、经济的规模化放大生产。而且,实际盐碱地土壤环境是一个复杂的多元化体系,改性生物炭在实际土壤中效果表现如何,还受诸多条件的影响。未来应该在生物炭改性方法及原理、规模化应用、经济成本核算和环境安全性提升等方面加强研究。

## 6 结论

生物炭技术是近年来土壤学和环境学领域的研究热点,在改良盐碱地方面已经取得了一定的进展。具体表现在生物炭具有比表面积大、吸附能力强等特点,对土壤养分具有直接或间接的调控作用,能够提高盐碱地土壤有机质含量、阳离子交换量、通透性和微生物活性,减少氮磷流失,增加土壤团聚体结构的形成,在盐碱地土壤改良、水分增持和作物抗盐抗碱胁迫等方面都具有积极的功效。同时,生物炭返田后扩大了土壤碳库,对碳的增汇减排效果优于其他农业措施。生物炭基肥料或复合材料用于盐碱地改良,可延缓肥料的释放,增加土壤肥力持效性,提高作物对盐碱地的适应性。

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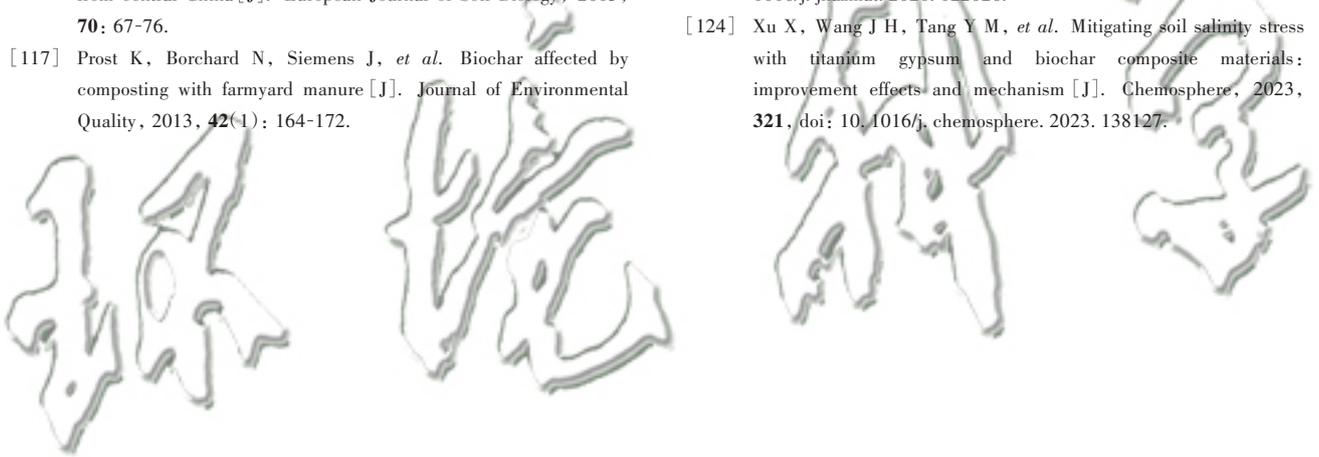
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