

生物炭对滨海湿地盐碱土壤碳氮循环的影响

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摘要: 滨海湿地盐碱土壤在全球碳氮循环及调节气候变化中起着重要作用。环境友好型土壤改良剂生物炭(Biochar, BC)在缓解气候变化和促进农业可持续发展方面前景巨大。然而, 现有研究多关注BC对滨海湿地盐碱土壤中温室气体排放及土壤氮素流失的影响, 缺乏其对滨海湿地盐碱土壤碳氮循环的深入研究和系统总结。本文综合分析了施用BC对滨海湿地盐碱土壤植被碳库、有机碳库、有机碳矿化及生物固氮、硝化、反硝化、矿化、氨损失等碳氮循环过程的影响和可能机制。指出未来应关注长期野外研究, 利用宏基因组等现代分子生物技术, 阐明BC对土壤碳氮循环影响的分子生物学机制, 以期对滨海湿地生态系统的修复与功能保育提供理论依据。

关键词: 滨海湿地; 盐碱土壤; 碳封存; 土壤退化; 矿化; 氮循环

盐碱土壤是一类重要的土壤资源, 在全球总面积为 $0.95 \times 10^9 \text{ hm}^2$, 对发展综合性农业潜力巨大。滨海湿地土壤是典型的盐碱土壤, 在全球碳(C)循环及气候调节中起着重要作用^[1]。近年来, 由于气候变化和人类活动导致滨海湿地土壤退化严重^[2-4], 主要表现在土壤盐碱化加重, 透水和透气性差, 土壤氮(N)磷(P)和有机质(SOM)等养分含量降低, 植被覆盖率下降, 导致初级生产力低下^[5-6], 严重损害了滨海湿地生态系统的健康和功能。目前, 盐碱土壤的改良措施包括水利工程、生物修复(如种植耐盐植物、施加微生物菌剂与菌肥)和化学改良(添加土壤改良剂如石膏、过磷酸钙、无机肥料等)等方法, 这些方法虽然各有优点, 但仍在成本、时效、二次污染等方面存在问题^[7-10]。因此, 开发有效、低成本且环保的盐碱土壤改良剂, 仍是滨海湿地土壤修复和滨海湿地生态系统保育的关键。

生物炭(Biochar, BC)是生物质在限氧和低温($<700 \text{ }^\circ\text{C}$)下通过热解得到的一种稳定难溶的、多孔的且高度芳香化的固体富C产物^[11]。由于具有比表面积大、孔结构发达、表面官能团丰富、吸附能力强等优良特性, BC被广泛用作土壤改良剂、C封存剂和吸附剂^[11-13]。BC一般呈碱性(8.0~10.35), 常被用来改良酸性土壤或中性土壤^[14-18]。近年来, 越来越多的研究发现, BC不仅可以改善土壤酸碱性, 还能有效地改善土壤质地和养分有效性, 调节土壤微生物群落结构, 促进植物的生长, 因此也可作为盐碱土壤改良剂^[19-21]。C、N生物地球化学过程在滨海湿地生态系统物质循环和能量流动中发挥着十分重要的作用。因此, BC对滨海湿地盐碱土壤C、N循环的影响越来越受到关注^[22-25]。然

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而,滨海湿地土壤类型、BC种类特性和实验方法的差别,导致研究结果不尽相同,严重影响了读者对这方面研究的认识。因此,本文综述了近年来国内外关于BC对滨海湿地盐碱土壤C、N循环影响的研究现状,重点阐述BC对滨海湿地盐碱土壤植被C库、土壤有机碳(SOC)库和SOC矿化以及生物固N、N矿化、硝化和反硝化作用、氨(NH_3)损失等C、N循环关键过程的影响及可能机制;最后指出目前研究中存在的不足及未来的研究方向,以期BC技术的发展和推广提供理论依据,为维护滨海湿地生态系统健康与功能保育提供理论依据和技术支持。

1 BC对滨海湿地盐碱土壤C循环的影响

C是自然界中生命物质构成的最重要元素之一,也是SOM的关键组成。植物通过光合作用将二氧化碳(CO_2)转化为有机物,有机物通过食物链进入消费者体内;动植物凋亡后残体进入土壤形成复杂的SOM;最终SOM通过微生物分解作用,以 CO_2 的形式重新返回到大气中^[26]。如此循环往复,构成了土壤的C循环过程(图1)。滨海湿地盐碱土壤pH高,粘粒含量大,透气性差,易板结,养分含量低,不利于植被生长,大大限制了植被C库储量^[27-28],从而也影响了SOC库的储量。研究表明,BC能改善土壤质地,促进植被生长^[6,29-30],从而可增加植被碳库库容。另外,BC除自身可作为固C材料外^[11],也可抑制SOM的矿化^[25]。可见,BC影响土壤C循环的各个过程,从而会影响滨海湿地生态系统“蓝C”(blue carbon)库的库容及储量(图1)。

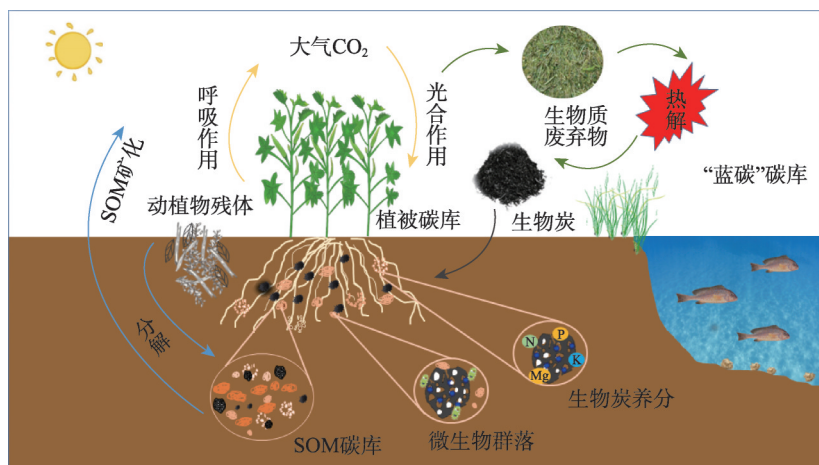


图1 BC对滨海湿地土壤C的生物地球化学循环过程的影响

Fig. 1 Effect of BC on biogeochemical cycling of soil C in coastal wetland

1.1 BC对植被C库的影响

植被C库一般包括植物地上部分和地下的活根。植物通过光合作用固定大气中的 CO_2 以维持生态系统的正常运转。因此,植被C库的活性非常高,它与大气C库间的交换是C循环的主要过程之一^[31]。滨海湿地土壤的盐碱胁迫是影响植被C库库容的主要限制因子。滨海盐碱土壤高含量的 Na^+ 、 Cl^- 等盐离子,会对植物造成严重的盐碱胁迫,同时也降低了营养物质及水分的可利用性^[32-33],导致了滨海湿地土壤初级生产力低下,进而限

制了植被C库储量。

研究表明,BC加入滨海湿地盐碱土壤,不仅能吸附土壤中的盐分^[34],改善土壤理化性质(如降低容重,提高CEC)^[19],从而缓解盐碱胁迫,还能为植物提供养分(如N、P、K等),进而促进植物生长,增加植物生物量,提高土壤初级生产力^[24,29-30]。例如,Zheng等^[21]通过盆栽试验探讨了花生壳BC在不同添加量下对盐生植物田菁(*Sesbania cannabina*)和锦葵(*Kosteletzkya virginica*)在黄河三角洲滨海湿地土壤中生长的影响。结果表明,BC以较低的添加量($\leq 5\%$)施用到供试土壤后,显著提高了两种植物的生物量,田菁地上部和地下部生物量分别较空白处理组增加了194%和176%,锦葵的地上部和地下部生物量分别增加了101%和176%。Lin等^[35]将玉米秸秆BC以 $16\text{ t}\cdot\text{ha}^{-1}$ 的添加量应用于江苏盐城滨海盐碱土壤后,发现大豆和小麦的株产量较未处理组分别增加了24%和28%。Kim等^[36]将稻壳BC加入受潮汐影响的盐碱土壤中,发现当BC添加量为5%时,玉米地上部干重较未处理组增加101%。这些研究表明,添加BC可以作为提高滨海盐碱土壤中植被C库的有效措施。

BC促进滨海盐碱土壤中植物生长的机制可归纳为以下几点:(1)BC自身富含N、P、K、Ca、Mg等营养元素^[37],尤其是以畜禽粪便为原料的BC^[38-39],可直接为植物提供更多的营养物质^[21,40-41];(2)BC可改善盐碱土的理化性质,如降低土壤容重,增大土壤持水能力,提高土壤CEC,从而在一定程度上缓解了土壤的盐碱胁迫^[19,42];(3)BC可为土壤微生物的生长与繁殖提供良好的生境,调节土壤微生物群落结构,增加其数量和活性^[12],从而改善植物根际土壤的理化性质^[21,24,35];(4)BC中富含的K释放后被植物吸收,可提高植物组织液中的盐度,使植物在渗透压力下可调节气孔的闭合,从而调节植物体内水循环,缓解盐碱胁迫对植物的不利影响^[35-36,43];(5)BC具有较好的吸附能力,可吸附土壤中的盐分,从而缓解盐碱胁迫或减轻植物的应激反应^[34]。

然而,与酸性或中性土壤类似,并不是所有BC的添加都能促进盐碱土壤中植物的生长^[19,44-45]。Luo等^[19]发现将花生壳BC与贝壳粉、腐殖酸和无机化肥制备成炭基修复剂以10%的添加量施加至黄河三角洲滨海湿地盐碱土壤中,显著抑制了田菁和锦葵的生长,总生物量降低了61.0%和74.9%。这主要是由于过多量的BC的添加使土壤盐度进一步增大。Lonardo等^[46]发现向盐水灌溉的盆栽培养基中添加BC对樱桃月桂的生长并没有影响。这些研究结果表明,BC选择或者添加不当可能抑制植物生长,导致土壤植被C库储量降低,从而总体上也削弱了BC自身的固C潜力。因此,BC添加至盐碱土壤时,针对不同种类及特性的盐碱土壤,需要慎重考虑BC的种类和添加量。这方面尚需大量的研究进一步揭示BC种类与盐碱土壤特性和植物生长响应之间的关系,方可有助于促进植被C库的储量。

1.2 BC对SOM碳库的影响

1.2.1 BC对SOM矿化的影响

SOM作为土壤的重要组成,主要包括颗粒有机物、腐殖质、微生物量C以及根系分泌物。盐碱土壤中SOM含量相对较低,这主要由两个原因造成:一方面,盐碱土壤中初级生产力低下,植物C库储量少,导致向土壤中输入的有机质较少;另一方面,滨海湿地盐碱土壤中高浓度的 Na^+ 不利于土壤团聚体形成,在无土壤团聚体保护的情况下SOM更容易分解^[24,47]。SOM的矿化是有机质被微生物降解为简单的无机化合物并释放 CO_2 的过

程。这个过程直接关系到土壤中养分元素的释放与供应、温室气体 CO_2 的形成以及土壤质量的保持,最终决定着SOC库的储量^[48]。SOC矿化受多种因素影响,如有机质的结构和组成、土壤理化性质以及微生物种群组成和活性等^[49-51]。目前,BC对滨海湿地SOC矿化影响的研究多聚焦于对温室气体 CO_2 排放的影响上,缺乏对BC影响SOC矿化内在机制的深入探究。因此,深入了解BC对滨海湿地SOC的矿化作用对于评估SOC库容至关重要。

迄今,关于BC对滨海湿地SOM矿化的影响结果不一,有正激发效应(促进矿化)^[52]、负激发效应(抑制矿化)^[25,53]和无显著影响^[35]。Sun等^[52]评估了温度和水分对添加了BC的土壤中SOC矿化的影响,发现在不同温度与湿度的条件下,小麦秸秆BC的施加均促进了黄河三角洲滨海湿地盐碱土壤SOC的矿化。Lin等^[35]发现玉米秸秆BC对江苏盐城滨海湿地盐碱土壤 CO_2 及 CH_4 的累积排放量无显著影响,表明BC对该盐碱土壤中SOM的矿化无显著影响。然而,也有研究表明,BC添加对滨海湿地盐碱土壤具有负激发效应。Luo等^[53]发现花生壳BC添加量为1%和3%(w/w)时,黄河三角洲滨海湿地土壤中SOC矿化率的增加仅占BC引入C的0.32%和0.17%,远低于所加入BC引起SOC矿化的理论增加值,表明BC抑制了土壤SOC的矿化。同样地,Zheng等^[25]发现350℃和550℃热解制备的玉米秸秆BC分别使黄河三角洲滨海湿地土壤团聚体的SOC矿化率降低了13.4%~37.2%和16.8%~24.9%,呈现出负激发效应。BC对SOC的负激发效应,有助于增加SOC库的储量,这不仅使更多的SOM保留在土壤中,增加了土壤肥力,同时也减少了土壤中温室气体的释放,一定程度上也缓解了全球温室效应。

BC对SOM负激发效应的研究已有大量报道,这方面的机制已经有了较清晰的认识,主要机制包括:(1)从短期效应来看,BC含有较多不稳定的C源,易被微生物优先利用,从而降低了SOC的矿化^[54-56];(2)从长期效应来看,BC对SOM降解相关的微生物和酶的吸附固定导致微生物和酶活性降低,减弱了SOM的分解^[57];(3)BC表面的含氧官能团(羟基和羧基)通过络合或配位作用与土壤矿物形成复合体,增强了SOC的稳定性^[25,58];(4)BC通过与土壤中 Ca^{2+} 、 Al^{3+} 等多价阳离子的桥联作用吸附固定了SOC,提高了粉—粘团聚体含量和SOC稳定性^[25];(5)BC提高了土壤溶液pH,导致SOM分解释放的 CO_2 一部分通过碳酸盐沉淀的形式固定在土壤中,从而降低了 CO_2 表观释放量^[53];(6)BC提高了土壤C/N比,使土壤细菌群落向低C周转型转变,或是真菌/细菌比例增大,总体微生物对SOC矿化速率减慢^[25,59]。

1.2.2 BC对SOM碳库储量的影响

SOM的循环主要包括有机质(植物残体和根系分泌物)的输入、分解和转化。进入土壤的有机质在土壤中转化为活性SOC、缓性SOC和惰性SOC,三者在土壤中相互转化,最终通过矿化、淋溶以及人类生产转化等形式从土壤中输出^[60]。SOC库容大小取决于SOM输入与输出之间的平衡,主要受有机物的化学组成、土壤理化特性以及人类活动的综合影响^[61]。以BC为改良剂进行土壤修复的农业活动,显著影响了SOC库的外源C的输入和内源C的输出。BC中的C稳定性强,大多数难以被微生物分解,半衰期可达数百至数千年^[62]。因此,无论是酸性土壤,还是碱性土壤,BC均可作为固C材料,增加SOC库储量^[63]。此外,BC添加至滨海盐碱土壤,一方面可通过提高初级生产力,导致更多的植物凋落物回归土壤^[19,21,35];另一方面,BC可降低SOC的矿化分解,导致SOC累积量增

加^[25,53],从而有效提高SOM含量。Zheng^[21]等和Luo等^[19]利用花生壳BC改良黄河三角洲滨海盐碱土壤,结果表明,添加BC显著提高了SOC含量。同样,Lin等^[35]发现加入玉米秸秆BC可显著提高江苏盐城滨海盐碱土壤SOC含量,且其增加幅度与BC的添加量成正比。Bhaduri等^[64]也发现,酸性花生壳BC加入人工模拟的不同盐度的土壤中均可增加其SOC。BC的稳定性是影响其增加土壤SOC含量的决定性因素^[65-66]。随着热解温度的升高,BC中芳香化C比例增加,其稳定性增强^[65]。因此,从增强滨海湿地固C的角度来讲,应该选择高温($\geq 500\text{ }^{\circ}\text{C}$)热解制备的BC。

BC增加滨海湿地盐碱土壤SOC库储量的主要原因包括:(1)BC富含的多C芳香族结构稳定性强,难被微生物降解,能够将C长期封存在土壤中^[11];(2)BC通过多价阳离子桥连作用增强粘土颗粒与SOM的结合,从而促进微团聚体的形成,有利于SOM在盐碱土壤的累积^[25,36,67];(3)BC能改善盐碱土壤的理化性质,在一定程度上缓解盐碱胁迫,从而促进根际微生物和植物的生长,刺激根系分泌物的释放,进而增加外源C的输入以及内源C的形成^[24,68];(4)BC可减弱SOM的矿化作用,减少了SOM的损失^[25,53,64]。

BC对SOC储量的贡献受到众多因素的影响。不同原料和制备条件下产生的BC对于不同类型的盐碱土壤和不同种类的植物所产生的效果差异较大^[35,69]。因此,BC对不同类型盐碱土壤SOM分解和转化的影响,需要更多的研究进一步探究其内在机制,明确BC特性、土壤类型及性质与SOM转化之间的关系,方可准确评估BC的输入对滨海盐碱土壤SOC库容的影响。

2 BC对滨海湿地盐碱土壤N循环的影响

N素通常是限制滨海湿地植物生长的重要营养元素^[70]。土壤N库中的N主要以有机N的形式存在,无机N仅约占土壤总N的1%。植物能吸收的N大部分都是无机N,所以有机N通过微生物矿化转化为可吸收的无机N,对作物生产至关重要^[71-72]。因此,探究滨海湿地土壤中的N素循环意义重大。BC作为土壤改良剂施加于滨海湿地盐碱土壤,不仅能够吸附土壤中的游离 NH_3 、 NH_4^+ 和 NO_3^- ^[73],从而减少无机N素的损失,还可以改善土壤的理化性质(如保水性、CEC)和微生物群落结构,进而影响土壤生态系统中N素的转化^[64],对土壤N的生物地球化学循环过程产生影响(图2)。

2.1 生物固N

豆科植物(如大豆、苜蓿)的根瘤菌等微生物的生物固N作用是土壤N素的主要来源^[72]。生物固N实质是土壤微生物将分子态 N_2 还原为 NH_3 ,然后进一步同化为氨基酸和蛋白质作为自身养分的过程^[72]。盐碱土壤中过量的盐分导致根瘤菌的数量和活性降低;此外,盐胁迫也会损害根瘤菌感染根毛的能力,从而抑制结瘤的形成^[24]。这两方面的作用均减弱了盐碱土壤中微生物的固N作用。

对于非盐碱土壤,已有研究证明,BC的添加可增强生物固N作用^[74]。例如,Mia等^[74]发现BC的添加显著提高了三叶草(*Trifolium pratense* L.)的生物固N能力,且添加量在 $10\text{ t}\cdot\text{ha}^{-1}$ 时效果最优。然而,BC对滨海盐碱土壤中生物固N作用影响的研究较少,缺少直接的证据。宋延静等^[75]研究发现,向莱州湾滨海湿地盐碱土中添加棉花秸秆BC,土壤中*Ideonella*和*Skermanella*等固N菌及*nifH*等固N基因丰度显著增加,促进了土壤N素的固定。Luo等^[19]将堆肥处理的BC施加至黄河三角洲滨海湿地盐碱土壤中,豆科植物田菁

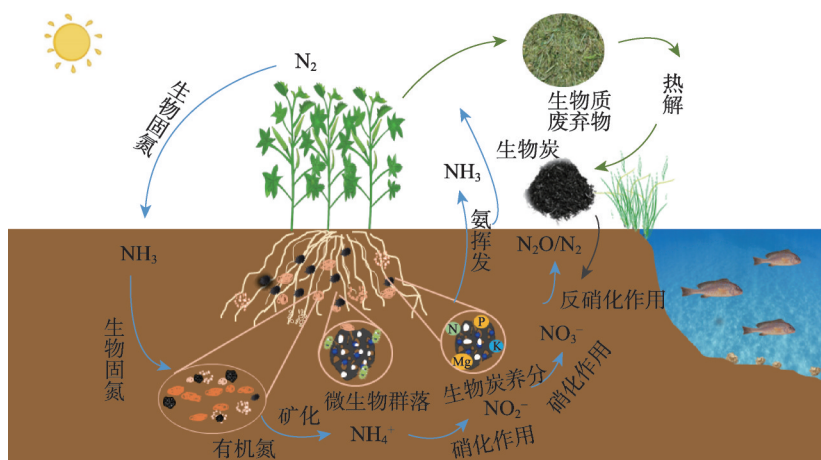


图2 BC对滨海湿地土壤N的生物地球化学循环过程的影响

Fig. 2 Effect of BC on biogeochemical cycling of soil N in coastal wetland

(*Sesbania cannabina*) 根际土壤 NH_4^+ -N 的含量显著增加, 推断可能是 BC 促进了田菁根际微生物的固 N 作用。但是, 该研究缺乏对土壤固 N 微生物群落结构及种属的分析, 无法解释固 N 作用增强的具体机理。然而, 虽然缺乏相关研究, 根据已有研究结果及 BC 对非盐碱土壤中固 N 作用的影响, 推断 BC 促进滨海湿地盐碱土壤生物固 N 作用的主要原因是 BC 的添加刺激了土壤固 N 菌群的生长以及群落结构的改变^[76]。这方面可能的具体机制包括: (1) BC 富含 S、K、Cu、Zn 等固 N 微生物生长的必须元素, 这些元素的释放直接刺激了固 N 微生物的增殖^[75,77-78]; (2) 添加 BC 使土壤的 C/N 升高, 高 C/N 的土壤中固 N 微生物的活性更高^[22,67]。(3) BC 可通过吸附结瘤因子和黄酮类物质而干扰细胞间的信息传递, 从而促进根瘤的形成^[74,79-80]。

2.2 硝化作用

硝化作用是指 NH_3 或 NH_4^+ 在氨氧化细菌 (AOB) 和氨氧化古菌 (AOA) 的作用下氧化成 NO_2^- , 然后由亚硝化菌氧化为 NO_3^- 的过程^[81]。在透气性较好且 NH_4^+ 充足的土壤中, 即使土壤 pH 值为碱性, NH_4^+ 也会被快速氧化和硝化为 NO_3^- ^[79]。然而, 滨海湿地盐碱土壤透气性差, 易板结, 大大限制了硝化作用的进行^[25]。

研究表明, 添加 BC 可促进滨海湿地盐碱土壤中的硝化反应。Song 等^[82]发现棉花秸秆 BC 加入黄河三角洲滨海盐碱土壤增强了硝化作用, 主要原因是 BC 增加了 AOB 和 AOA 的丰度。石玉龙等^[83]发现棉花秸秆 BC 促进了华北农田盐碱土壤的硝化作用, 推测可能是因为 BC 促进了土壤有机 N 矿化, 从而增加了硝化反应的底物。Prommer 等^[84]发现山毛榉 BC 增加了黑钙土 AOB 的丰度, 从而增加了土壤总硝化速率。但是, 也有研究表明, BC 对滨海盐碱土壤的硝化作用无显著影响^[85], 甚至会抑制硝化作用^[86]。例如, Sun 等^[86]发现小麦秸秆 BC 使江苏射阳滨海盐碱土壤中 NH_4^+ -N 含量增加 (22.9%~45.7%), 而 NO_3^- -N 含量降低 (3.8%~13.0%), 从而推断 BC 减弱了土壤硝化作用。Luo 等^[85]发现花生壳 BC 可降低黄河三角洲滨海土壤净硝化速率 14.5%~25.2%, 但对添加了芦苇秸秆和尿素的土壤处理组的净硝化速率无显著影响。BC 对滨海盐碱土壤硝化作用的影响与 BC 和土壤性质密切相关。BC 促进滨海盐碱土壤硝化作用的可能原因包括: (1) 添加 BC 使 SOC 含量增

加,进而提高了土壤微生物活性,促进了硝化作用^[83,87]; (2) BC丰富的孔结构和优良的持水能力可为微生物提供良好的生境,有利于硝化细菌生长繁殖^[88-89]; (3) BC可以促进N素矿化作用,从而增加硝化作用的底物 $\text{NH}_4^+\text{-N}$ 的浓度,进而促进硝化作用^[83,87,90]。相反地,BC抑制滨海盐碱土壤硝化作用的可能原因包括: (1) BC使土壤pH值升高,促使 $\text{NH}_4^+\text{-N}$ 转化为 NH_3 ,加速了土壤中 NH_3 的挥发,进而减少了硝化作用的底物^[91-93]; (2) BC通过静电作用和孔填充作用等吸附土壤中的 $\text{NH}_4^+\text{-N}$,降低了 $\text{NH}_4^+\text{-N}$ 的生物可利用性^[22,94]。然而,这些可能机制尚需大量的室内外研究去进一步证实。

2.3 反硝化作用

反硝化作用是在低氧或缺氧的土壤中厌氧微生物将 NO_3^- 或 NO_2^- 还原成 NO 、 N_2O 和 N_2 的过程^[95]。土壤的反硝化活性与土壤质地和土壤理化性质密切相关。滨海盐碱土壤呈碱性,透气性和透水性差,有利于反硝化细菌的生命活动。因此,BC施加导致的滨海盐碱土壤理化性质的改变势必会影响土壤反硝化作用。石玉龙等^[83]发现棉花秸秆BC抑制了滨海盐碱土壤的反硝化作用,减少了温室气体 N_2O 的排放量。作者推测这可能由两个原因造成:一方面,BC能吸附土壤 $\text{NO}_3^-\text{-N}$,减少反硝化细菌可利用的底物^[96];另一方面,BC的某些组分(如酚类)抑制了反硝化酶的活性^[97]。然而,Cao等^[98]发现加入稻壳BC的滨海湿地土壤中硝酸盐还原酶的活性较对照组显著增高,表明BC对土壤中的反硝化作用起促进作用。He等^[99]也发现将小麦BC加入长江冲积沉积土后,促进了土壤中的反硝化作用。BC对滨海盐碱土壤的反硝化作用受土壤 $\text{NO}_3^-\text{-N}$ 和SOC含量、pH、水分、空气等条件的影响^[100]。BC抑制盐碱土壤反硝化作用的可能原因包括: (1) BC富含含氧官能团,且孔结构丰富,比表面积大,可以吸附土壤中的 $\text{NH}_4^+\text{-N}$ 和 $\text{NO}_3^-\text{-N}$ ^[101],减少反硝化细菌可利用的底物,减弱反硝化作用^[102]; (2) BC因其多孔性和较小的容重,可降低土壤容重,增加土壤孔隙度,改善土壤透气性,进而抑制反硝化作用^[103-105]; (3) BC抑制了反硝化基因(*nos Z*)的表达,从而抑制了反硝化作用^[76,90,106]。但是BC添加至土壤也会促进反硝化作用^[98-99]。例如,在土壤透气性等条件不变的情况下,BC促进土壤硝化作用而使土壤中 $\text{NO}_3^-\text{-N}$ 的含量增加时,则会为反硝化作用提供更多的反应底物,进而会促进反硝化作用^[99]。此外,BC能提高土壤中反硝化细菌和酶的活性和丰度,进而促进土壤反硝化作用。土壤中反硝化作用不仅造成了N肥资源的损失,产生的 N_2O 更是重要的温室气体,对全球增温的贡献巨大^[107],所以开发高效且环境友好的土壤 N_2O 减排产品一直是农业生产及环境保护中的重要任务。BC抑制反硝化作用的良好表现为土壤 N_2O 的减排提供了一种新思路^[107]。然而,目前的研究结果表明,受BC原料和土壤质地的影响,BC对滨海盐碱土壤反硝化作用的影响结果不一^[83,98-99],且大多基于实验室研究,造成这种现象的内在原因尚不清楚。因此,在BC技术推广之前,尚需要大量的研究去证实盐碱土壤中BC与 N_2O 释放之间的内在关系。

2.4 有机N矿化

有机N矿化是土壤中的有机N在土壤动物和微生物的作用下,转化为无机N的过程。滨海湿地土壤中的N大部分(85%~95%)以有机N的形式存在,难以被植物直接吸收利用。盐碱土中有机N的含量和矿化速率决定土壤N素的生物可利用性,进而影响土壤的初级生产力^[108-109]。与N的其他转化过程一样,BC加入滨海湿地盐碱土,可以通过改变土壤理化性质,直接或间接地影响土壤微生物的群落结构,进而影响土壤有机N的矿

化过程^[110-113]。Luo^[85]等通过150天的培养实验对比探究了花生壳BC、天然生物质芦苇秸秆以及有机N肥尿素的施加对黄河三角洲滨海湿地土壤有机N矿化的影响。结果表明,BC的添加显著降低了土壤的净N累积矿化量,而芦苇秸秆的添加增强了土壤矿质N的生物固持作用。可见,相比植物秸秆,BC的添加显著抑制了黄河三角洲滨海湿地土壤的有机N矿化。作者把这种现象归因于BC添加导致了土壤C/N的显著升高以及脲酶活性显著降低。Lentz等^[114]将牛粪和硬木BC单独或联合施用于钙质土壤中,发现BC降低了土壤净N矿化量达33%。然而,受土壤类型和BC特性的影响,BC对土壤有机N矿化过程的影响效果并不一致。Nelissen等^[87]将青贮玉米BC添加至沙壤土中,发现土壤总N矿化增加了185%~221%,且与550℃制备的BC相比,350℃的BC对土壤有机N矿化的促进作用更显著。作者认为这是因为BC促进了SOM矿化,刺激了土壤微生物活动,使得土壤N的矿化增强;而低温(350℃)BC中不稳定C含量更高,导致土壤微生物活性更强,因而对土壤有机N矿化的促进作用更显著。综合分析,BC促进滨海湿地盐碱土壤有机N矿化的可能原因有:(1)BC能为微生物提供营养,增强土壤中微生物或酶的活性,促进有机N矿化^[87,115];(2)BC促进了土壤中的生物固N作用,增加了土壤有机N含量,为N的矿化提供了更多的反应底物^[82]。然而,相比于SOC矿化的研究,BC对有机N矿化的研究较少,尤其是盐碱土壤中。因此,BC对滨海湿地盐碱土壤N矿化的影响还需要进一步探究。

2.5 NH₃的挥发

NH₃挥发是土壤生态系统N损失的主要途径之一^[116]。全世界每年因NH₃挥发导致的N损失约为32×10⁶t^[117]。土壤中NH₃的挥发受各种因素相互作用的影响,包括N素含量、土壤酶和微生物活性、土壤水分、温度等^[104,117]、农业耕作活动^[118-119]以及气候条件^[120]等。研究表明,添加BC可减少滨海湿地盐碱土壤中NH₃的累积挥发量。Mandal等^[93]将家禽垫料制备的BC和坚果壳BC添加至澳大利亚南部5种不同来源的土壤中发现,BC通过吸附作用固定NH₃或促进硝化作用,减少了约70%的NH₃挥发。周一诺等^[121]也证实了在竹林土壤中施用BC后抑制了NH₃的挥发。BC减少NH₃挥发的主要原因包括:(1)BC具有发达的孔隙结构,较大的比表面积和阳离子交换能力,因而能吸附NH₄⁺,减少NH₄⁺向NH₃转化,或直接吸附NH₃,从而使土壤NH₃挥发量减少^[79,94,122];(2)BC通过影响土壤微生物群落结构,促进了微生物对NH₄⁺-N的同化^[93]。然而,也有研究报道BC的添加促进了滨海湿地盐碱土壤中NH₃的挥发。Sun等^[86]将小麦秸秆BC以不同比例添加到江苏射阳滨海盐碱土,结果发现,相比对照组,2%和4%(w/w)的BC处理组NH₃累积挥发量显著增加了25.6%~53.6%。这可能是因为BC的添加使土壤的pH升高,促进了NH₄⁺向NH₃的转化,进而使NH₃挥发量增大^[79,92-93]。土壤NH₃的挥发影响土壤N素的利用效率,如何通过BC的添加更加有效地控制NH₃挥发,需要进一步从微观机制和宏观技术两个层面去开展更多的研究。

3 结论与讨论

滨海湿地盐碱土壤是全球重要的土壤资源,在全球C循环及调节气候变化中起着重要作用。BC具有优良的物理化学性质,且稳定性较高,能够长期固存在土壤中。BC能促进植物生长,增加植被C库;抑制SOM矿化,促进土壤C的固定进而增加土壤C库储

量,缓解温室效应。此外,BC能够吸附土壤中游离的 NH_3 、 NH_4^+ 和 NO_3^- ,从而减少无机N素的损失,并通过改善土壤的理化性质,调节微生物群落结构及其活性,影响土壤生态系统中的N素转化。然而,现有研究多关注BC对滨海湿地土壤中温室气体 CO_2 和 N_2O 排放以及土壤N素流失的影响,关于BC对滨海湿地盐碱土壤C、N循环的各个过程影响的深入研究尚不够。本文认为主要应从以下几个方面展开研究:

(1) 现有研究使用的BC来源于不同的原材料和制备方法,性质差异很大,导致有些不稳定的BC施加到土壤并不能达到固C减排的效果。改性是优化BC性质和拓展BC功能的有效措施。因此,针对于不同类型的土壤,需要探究不同方法改性的BC对滨海湿地盐碱土壤C、N循环的作用效果及内在机制,为改良滨海盐碱土壤找到可靠的材料。

(2) 土壤C、N循环实质上是微生物介导的过程。目前关于BC改良滨海湿地盐碱土壤的研究大多停留在对土壤化学指标的测量上,而对微生物的关注相对较少。因此,需要积极应用高通量测序、宏基因组等现代分子生物技术,明确BC影响土壤C、N循环过程中的关键微生物及关键环境因子,明确BC种类、土壤性质与微生物群落组成及生态功能之间的内在关系。

(3) 关于BC添加对滨海湿地盐碱土壤C、N循环影响的研究目前多停留在实验室模拟阶段,相关的长期野外大田试验较少,大大限制了研究结果的准确性以及BC技术的推广。因此,需开展长期大田试验,探究自然环境条件下(如温度、降雨等)BC如何影响滨海湿地盐碱土壤C、N循环及生态功能。

(4) 滨海湿地是土壤、植物和水分三要素组成的复杂生态系统。现有室内模拟研究更多地关注了非淹水条件下BC对土壤特性及C、N循环的影响。在接近自然湿地的现实条件下,如淹水或干湿交替,BC的施加如何影响土壤C、N的转化过程,许多问题尚不明确。因而,在以后的研究中,实验条件的设计要更切合滨海湿地独有的环境条件。

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Effects of biochar amendment on carbon and nitrogen cycling in coastal saline soils:

A review

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Abstract: Coastal saline-alkaline soil plays important roles in global carbon and nitrogen cycling and climate change regulation. Biochar (BC), as an eco-friendly soil amendment, shows a promising prospect in terms of alleviating climate change and promoting sustainable agricultural development. However, most of the previous studies focused on the influence of BC application on greenhouse gas emissions and nitrogen availability and loss in coastal saline-alkaline soil, but little information that comprehensively summarized the effect of BC on the soil carbon and nitrogen cycling is available. As a result, the objective of this review is to comprehensively summarize that: (1) The influences of BC on soil carbon pools (vegetation and soil organic carbon) and soil organic carbon mineralization in the coastal saline-alkaline soil; (2) The influences of BC on nitrogen cycling, including biological nitrogen fixation, nitrification, denitrification, nitrogen mineralization, and ammonia volatilization; (3) The underlying mechanisms responsible for the BC-regulated carbon and nitrogen cycling in the soil. At last, we also point out that more efforts should be paid to the investigation of long-term experiments in field circumstances in future, and the explanation of the microbial mechanisms underlying soil carbon and nitrogen cycling affected by BC application using modern molecular biotechnology (e.g., metagenomics). This review would provide useful information for maintaining health and function of the coastal soil ecosystem by incorporation of BC.

Keywords: coastal wetland; saline-alkaline soil; carbon sequestration; soil degradation; mineralization; nitrogen cycling