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生物炭添加对土壤温室气体排放影响的长短期效应研究进展

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摘要: 人类活动引起的大气温室气体浓度增加是气候变暖的主要原因, 全球变暖已经成为了当今人类社会所面临的严峻挑战, 应对气候变暖的关键是减少温室气体排放和增加生态系统碳汇, 由于生物炭特有的理化和生物学特性, 将其施入土壤被认为是一种有前景的减排增汇措施。因此进行生物炭对土壤温室气体排放的影响研究对于减缓温室效应和实现“碳中和”具有重要意义。通过综述生物炭对土壤温室气体排放影响的长短期效应及其影响机制, 发现生物炭添加对土壤温室气体排放的影响因生物炭原料类型、热解温度、添加量、土壤和植被类型的不同而不同。此外, 因老化时间、老化方式和培养方法的不同, 老化生物炭对土壤温室气体的减排效应可能增强或减弱甚至消失。同时, 在总结现有研究不足的基础上, 对未来生物炭影响土壤温室气体排放研究的方向和重点进行了分析和展望, 提出了今后应加强 CO₂、N₂O 和 CH₄ 排放影响的同步研究、减排与固碳效应的同步研究、不同老化方式生物炭和不同培养方法的联合研究和利用 ¹³C 和 ¹⁵N 示踪技术从过程层次上揭示影响机制。

关键词: 生物炭; 温室气体排放; 土壤; 短期效应; 长期效应

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Review on the Long-term and Short-term Effects of Biochar Addition on Soil Greenhouse Gas Emissions

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Abstract: Increasing concentrations of greenhouse gases in the atmosphere caused by human activities are the main cause of climate warming. Global warming is a severe challenge confronted by human society today. Reducing greenhouse gas emissions and increasing carbon sinks are the keys to addressing climate warming. Biochar addition is considered to be a promising way to reduce greenhouse gas emissions and increase carbon sinks, due to its unique physical, chemical, and biological properties. Therefore, it is of great significance to study the effects of biochar on soil greenhouse gas emissions to mitigate the greenhouse effect and achieve “carbon neutrality.” The long-term and short-term effects of biochar on soil greenhouse gas emissions and their influencing mechanism were reviewed. It was found that the effects of biochar on soil greenhouse gas emissions varied with the types of biochar feedstock, pyrolysis temperature, application ratio, and soil and vegetable types. In addition, due to the different aging times and modes and cultivation methods, the mitigation effect of aged biochar on soil greenhouse gas could be enhanced or weakened or even disappeared. Further, based on the deficiencies of the previous research, the direction and focus of future research on the effects of biochar on soil greenhouse gas emissions were analyzed and prospected. It was proposed to strengthen simultaneous research on the effects of biochar on CO₂, N₂O, and CH₄ emissions; reducing greenhouse gas emissions and carbon sequestration; different aging modes and cultivation methods of biochar; and revealing the influencing mechanism at the process level, through exploring the effects of biochar on soil carbon and nitrogen dynamics and tracing the source of greenhouse gases using ¹³C and ¹⁵N tracer technology.

Key words: biochar; greenhouse gas emission; soil; short-term effect; long-term effect

人类活动为主导因素引起的大气温室气体浓度不断增加, 进而导致温室效应加剧和全球气候持续变暖, 使自然生态系统平衡和人类的生存发展受到了严重的威胁^[1,2]。政府间气候变化专门委员会 (IPCC) 第六次评估报告指出, 多重证据表明气候变化已经影响了地球上各个区域, 过去所经历的变化将随着全球继续升温而加剧^[3]。因此, 如何应对气候变化是当前世界面临的最严峻的挑战之一, 而减少温室气体排放和增加陆地生态系统碳汇是应对全球变暖的关键^[4~6]。为了有效应对全球气候变化, 我国提出了“双碳目标”, 即力争 CO₂ 排在 2030 年前达到峰值, 努力争取 2060 年前实现碳中和。如何

通过减排增汇实现“碳中和”已经成为当前气候变化研究的热点^[7~10]。

将生物炭施入土壤被认为是一种有前景的减排增汇措施^[6,11,12], 这是由于: ① 生物炭是富碳有机物质, 主要由抗生物降解的芳香族化合物组成, 稳定性高, 可以在土壤中稳定存在几十年至几千年, 可以提升土壤稳定性碳库储量, 将碳封存在土壤

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中^[13,14]; ② 生物炭因其特殊的理化和生物学特性(如:发达的孔隙结构、巨大的比表面积、高碱性和丰富的表面官能团)会对土壤理化和生物学特性产生影响,进而影响土壤碳氮代谢过程,最终影响土壤温室气体排放^[15~18]. 因此,在遏制全球变暖的大背景下,生物炭添加对土壤温室气体排放影响研究已经成为研究热点. 本文综述生物炭对土壤温室气体排放影响的长短期效应,总结生物炭对土壤温室气体排放的影响机制和生物炭老化导致减排效应改变的发生机制,同时探讨现有研究工作中的不足,对未来的研究方向提出展望,以期为科学合理地利用生物炭进行减排增汇和实现“碳中和”提供理论基础.

1 生物炭添加对土壤温室气体排放影响的短期效应

1.1 新鲜生物炭对土壤 CO₂、N₂O 和 CH₄ 排放的影响

CO₂、N₂O 和 CH₄ 是最主要的温室气体,在气候变化中起到重要作用^[2],因此得到了广泛关注. 土壤 CO₂ 排放对生物炭添加的响应结果并不一致,在研究中出现了促进排放^[4,19,20]、无影响^[21]和抑制排放^[22,23]这 3 种情况. 现有研究发现生物炭添加量会对 CO₂ 排放产生影响,Tang 等^[20]研究发现添加生物炭增加了土壤 CO₂ 排放,并且 CO₂ 排放量随着生物炭添加量的增加而增加.Zhang 等^[24]采用 Meta 分析结果表明生物炭的添加量 < 10 t·hm⁻² 时,使土壤 CO₂ 排放量增加了 15%,而当添加量超过 80 t·hm⁻² 时,使土壤 CO₂ 排放量降低了 36%. 土壤和植被类型也会影响生物炭的作用效果,例如,Zhou 等^[25]研究发现虽然生物炭添加使温带森林土壤 CO₂ 排放量增加,但对亚热带森林土壤无显著影响;另外,Pokharel 等^[17]研究发现生物炭显著降低了森林土壤 CO₂ 累积排放量 16.4%,但对草地土壤则没有显著降低. 此外,热解温度和原料类型也是重要的影响因素,Li 等^[26]研究发现 300℃ 生物炭使土壤 CO₂ 排放量显著增加,但 700℃ 生物炭使土壤 CO₂ 排放量显著降低.Liu 等^[27]研究发现稻草生物炭对稻田土壤 CO₂ 排放抑制作用比竹子生物炭更加明显. 对于 N₂O 和 CH₄,多数研究发现生物炭添加抑制土壤 N₂O 和 CH₄ 排放^[9,28~31],但也有研究发现生物炭添加对土壤 N₂O 和 CH₄ 排放无影响^[32,33],甚至有促进作用^[34~37]. 生物炭对于 N₂O 和 CH₄ 的作用效果同样受到添加量、热解温度、原料类型、土壤和植被类型的影响. 例如添加量方面,Feng 等^[38]研究发现生物炭对土壤 N₂O 排放的影响因生物炭添加量不同而不同,0.5% 生物炭添加量导致土壤 N₂O 排放增

加,而 1% 和 2% 生物炭添加量分别降低土壤 N₂O 排放量 2% 和 24%. Liu 等^[27]通过稻田试验证明高生物炭添加量对 CH₄ 的抑制作用高于低添加量. 热解温度和原料类型方面,有研究发现虽然高温热解生物炭显著降低土壤 N₂O 排放,但低温热解生物炭对土壤 N₂O 排放无显著影响^[17,39]. Feng 等^[40]对比了不同热解温度生物炭对稻田土壤 CH₄ 排放的影响,发现 300℃ 和 500℃ 生物炭对 CH₄ 的排放有显著抑制作用,而 400℃ 生物炭无显著影响. 还有研究发现松芯片生物炭使土壤 N₂O 排放显著增加,而胡桃壳生物炭虽然使土壤 N₂O 排放增加,但未达到显著水平^[41]. 同一土壤上的植被类型不同也会产生不同影响,胡剑等^[42]研究发现在辣椒-萝卜轮作菜地施加生物炭使萝卜季的 N₂O 排放减少 28.76% ~ 67.88%,但对辣椒季排放无显著影响. 可见,生物炭对土壤温室气体排放的影响因生物炭原料类型、热解温度、添加量、土壤和植被类型的不同而不同. 有研究通过 Meta 分析也发现生物炭原料类型、热解温度、添加量和土壤质地等会对生物炭的减排效应产生影响^[24,43]. 生物炭原料类型和热解温度对生物炭减排效应产生影响是由于它们对生物炭特性有显著影响^[43~45].

水稻土是 CH₄ 的最主要来源,所以现有关于 CH₄ 的研究多是针对水稻土开展的(表 1),其他土壤 CH₄ 排放量虽小,但由于 CH₄ 的全球增温潜势(GWP)较强,是 CO₂ 的 25 倍^[2],其对温室效应的贡献仍然显著,因此,在其他类型土壤上开展生物炭对土壤 CH₄ 排放的影响研究也十分必要. 同一生物炭可能对土壤 CO₂、N₂O 和 CH₄ 排放产生不同影响. 例如,有研究表明生物炭添加增加了土壤 CH₄ 和 CO₂ 排放量,但降低土壤 N₂O 排放量^[24,46,47]. 但是,现有研究同时测定 3 种温室气体的相对较少(表 1),同时测定 3 种气体可以通过计算 GWP 更加准确地评估生物炭的减排效应^[48]. Zhang 等^[49]同时测量了生物炭添加后连续两个水稻周期的 CO₂、N₂O 和 CH₄ 排放,其中生物炭添加使 CH₄ 排放升高,对 CO₂ 排放无影响,N₂O 排放降低,总体 GWP 降低.

1.2 新鲜生物炭对土壤 CO₂、N₂O 和 CH₄ 排放的影响机制

生物炭添加引起土壤 CO₂ 排放增加被归因于以下 3 个方面:① 生物炭中的溶解性有机碳的生物降解^[57,58]; ② 生物炭中无机碳的非生物释放^[19,59]; ③ 生物炭对土壤有机碳分解的正激发效应^[60,61]. 生物炭添加导致土壤 CO₂ 排放降低则被归因于生物炭对土壤有机碳分解的负激发效应^[8,62,63],主要机

表 1 添加生物炭对温室气体排放的影响¹⁾
Table 1 Effects of biochar applications on greenhouse gas emissions

生物炭原料	热解温度/℃	试验/老化方式	土壤酸碱度	土壤类型	生物炭添加量	CO ₂	N ₂ O	CH ₄	文献
松木屑	300	方法一	×	森林土壤 草地土壤 森林土壤 草地土壤	1.5%	—	—	×	[17]
	550					—	—	×	
						↓ (16.4%)	↓ (27.5%)	×	
						—	↓ (14.8%)	×	
油菜秸秆	300	方法一	×	黑钙土	2%	↑	↑	—	[26]
	700					↓	—	↓	
水稻秸秆	550	方法一	5.2	水稻土	1%	↑	×	↑	[36]
猪粪	350	方法一	6.4	砂质土壤	1:69	↑	↑	×	[39]
柳木	700					—	↓	×	
	350					↑	↑	×	
	700					—	↓	×	
玉米秸秆	300	方法一	7.6	水稻土	24 t·hm ⁻²	×	×	↓	[40]
	400					×	×	—	
	500					×	×	↓	
小麦秸秆	350~550	方法二	6.5	水稻土	10 t·hm ⁻²	—	↓ (40%)	—	[49]
					20 t·hm ⁻²	—	↓ (58%)	↑ (154%)	
					40 t·hm ⁻²	—	↓ (51%)	↑ (54%)	
水稻秸秆	500	方法一	5.09	水稻土	2.5%	×	×	↓ (39.5%)	[50]
小麦秸秆	500	老化一	5.7	粉质黏壤土	20 t·hm ⁻²	×	↓ (19.5%)	↓ (11.2%)	[51]
					40 t·hm ⁻²	×	↓ (26.3%)	↓ (17.5%)	
甘蔗渣 稻壳	600	老化二	6.9	冲积土	1%	↓ (10%)	×	×	[52]
						↓ (36%)	×	×	
水稻秸秆	500	新鲜生物炭 老化四	6.1	×	2%	—	↓	×	[53]
				×		↓	↓	×	
小麦秸秆	400	老化三	4.83 7.62	肥熟旱耕人为土	20 t·hm ⁻²	×	↓ (48%)	×	[54]
						×	↓ (22%)	×	
小麦秸秆	500	新鲜生物炭 老化三 老化四	8.5	黏土盐土	40 t·hm ⁻²	×	↓ (13.5%)	×	[55]
						×	↓ (38.3%)	×	
						×	—	×	
小麦秸秆	350~500	老化一	5.7	粉质黏壤土	20 t·hm ⁻²	×	↓ (48%)	×	[56]
					40 t·hm ⁻²	×	↓ (38%)	×	

1) —: 无显著影响; ×: 文中未提及; ↑: 促进作用; ↓: 抑制作用; () 内数值为添加生物炭后与未添加相比气体排放升高或降低百分比; 方法一: 室内试验, 方法二: 田间试验, 老化一: 生物炭田间自然老化后进行原位试验, 老化二: H₂O₂ 氧化生物炭进行室内培养, 老化三: 富集老化生物炭土壤直接进行室内培养, 老化四: 从田间土壤中分离出来的自然老化生物炭加入对照土壤中进行室内培养

制包括: ①吸附土壤有机碳在生物炭表面, 生物炭添加加速微团聚体的形成, 增强对土壤有机碳物理保护; ②降低微生物活性和代谢, 包括有机碳降解酶的活性^[22,23]. 生物炭抑制土壤 N₂O 排放被归因于: ①生物炭增加了土壤的 pH 值, 增加 N₂O 还原酶的活性, 促进完全反硝化作用, 因此, 更多的 N₂O 转化为 N₂^[31,64~66]; ②生物炭增强了土壤对 NH₄⁺ 和 NO₃⁻ 的吸附, 降低了微生物可利用矿物质氮的含量, 最终抑制了 N₂O 的排放^[46,67~69]; ③生物炭可以增加土壤通气性, 反硝化细菌丰度降低, 抑制反硝化作用, 减少 N₂O 排放^[28,31,70]. 对于生物炭促进土壤 N₂O 排放则被归因于: ①生物炭为反硝化提供了额外的碳底物, 并为微生物提供了更多的矿物质氮, 促进反硝化反应, 增加了 N₂O 的排放^[35,39,71]; ②生物炭表面的羧基官能团对土壤 N₂O 还原酶电子传递产生干扰, 降低了土壤 N₂O 的还原潜力, 增加了土

壤 N₂O/(N₂O + N₂) 排放比^[72]. CH₄ 排放是土壤 CH₄ 的产生、氧化和传输 3 个过程综合作用的结果, 主要由产甲烷作用和甲烷氧化作用控制. 生物炭抑制土壤 CH₄ 排放, 可能是由于: ①生物炭添加改善了土壤通气条件, 使土壤条件不利于产甲烷菌的生长, 减少 CH₄ 的产生, 同时, 增强土壤通气可以增加 CH₄ 的氧化, 从而减少 CH₄ 的排放^[4,27,50]; ②土壤 pH 值是决定土壤 CH₄ 排放的另一个重要因素, CH₄ 排放与 pH 呈现负相关, 生物炭的碱性使土壤的 pH 值升高, 进而抑制土壤 CH₄ 排放^[51,73]; ③生物炭对 CH₄ 产生物理吸附作用, 从而减少 CH₄ 排放^[74], 并且被生物炭表面吸附的 CH₄ 可以被甲烷氧化菌更有效地利用, 这也有助于减少 CH₄ 排放^[4]. 也有研究发现, 生物炭添加不仅不会降低土壤产甲烷微生物丰度, 反而会促进产甲烷菌的生长^[40], 进而促进土壤 CH₄ 排放.

可见, 现有影响机制大多还是基于生物炭对土壤理化性质和生物学特性的影响, 对引起土壤温室气体排放的碳氮转化过程初级速率的直接测定相对较少, 也较少对温室气体进行溯源并量化不同转化过程对土壤温室气体排放的贡献率. 土壤温室气体排放受土壤有机碳分解、 CH_4 产生及氧化、土壤有机氮矿化、硝化、有机氮异养硝化和反硝化等过程的控制. 因此, 明确生物炭对上述土壤碳氮转化过程的影响和各转化过程对温室气体排放的贡献率, 对于深刻揭示生物炭对土壤温室气体排放影响机制十分必要. ^{13}C 和 ^{15}N 示踪技术在揭示碳氮转化过程和对温室气体进行溯源上具有明显优势, 但目前利用 ^{13}C 和 ^{15}N 示踪技术探讨影响机制的研究还很有限^[8,75].

2 生物炭添加对土壤温室气体排放影响的长期效应

2.1 老化生物炭对土壤 CO_2 、 N_2O 和 CH_4 排放的影响

生物炭施入土壤后, 受到物理、化学和生物作用而发生老化现象, 随着生物炭在土壤中的老化, 其理化性质 (例如, 比表面积、孔隙体积、阳离子交换量、元素组成、表面官能团和 pH 值) 会发生变化^[76~78]. 以上改变会对土壤碳氮转化过程产生影响, 进而对土壤 CO_2 、 N_2O 和 CH_4 的排放产生影响. 生物炭老化后是否还能维持新鲜生物炭的作用值得关注. 因此, 近几年老化生物炭对温室气体排放的影响成为研究热点.

室内模拟老化可以加速生物炭老化, 使生物炭性质发生明显改变, 短时间内获得老化生物炭. 双氧水 (H_2O_2) 氧化得到的生物炭整体组分没有发生显著变化而表面含氧官能团增加, 这与自然老化特征相似, 所以是目前采用最多的模拟老化方法^[79]. Rahman 等^[52]采用 30% H_2O_2 氧化法制备老化生物炭, 研究发现与新鲜生物炭相比, 老化生物炭更能显著降低土壤 CO_2 排放. 这种室内模拟老化虽有利于反映生物炭的更长期效应, 但室内模拟老化的缺点是未能考虑到老化过程中土壤与生物炭的交互作用, 不能全面反映生物炭的长期效应.

田间自然老化生物炭的研究也开展了很多. 有的是将老化生物炭从土壤中分离出来, 然后将其加入不含生物炭的对照土壤中进行培养. 例如, Wang 等^[53]通过将田间土壤中分离出来的 1 a 老化生物炭加入对照土壤中进行培养, 发现与新鲜生物炭相比, 老化生物炭显著降低了土壤 CO_2 的排放, 对土壤 N_2O 排放的抑制作用增强. 但 Spokas 等^[80]采用相同的研究方法发现老化生物炭与新鲜生物炭相比

促进 CO_2 的排放. 此外, Duan 等^[81]和 Zhang 等^[82]研究发现与新鲜生物炭相比, 经历 3 a 或 5 a 老化的生物炭丧失了最初抑制土壤 N_2O 排放的能力. 也有很多研究则是直接采用早期添加了生物炭的土壤进行室内培养, 例如, Zhang 等^[54]研究发现老化生物炭分别降低了酸性和碱性土壤 48% 和 22% 的 N_2O 排放量; Liao 等^[75]和 Fan 等^[83]研究也同样发现老化生物炭能够降低土壤 N_2O 排放. 但值得注意的是, 以上研究并没有同时研究新鲜生物炭对 N_2O 排放的影响, 所以无法判断与新鲜生物炭相比, 老化生物炭抑制土壤 N_2O 排放的作用是增强还是减弱. Kubaczynski 等^[4]研究发现新鲜生物炭促进土壤 CO_2 排放, 但 5 a 老化生物炭促进作用不明显, 在 60% 含水量条件下, 老化生物炭对土壤 CH_4 排放有抑制作用, 但抑制作用低于新鲜生物炭. 此外, Liu 等^[84]研究发现新鲜生物炭促进 CO_2 排放, 但 6 a 老化生物炭能够减少 CO_2 排放. 可也有研究发现与新鲜生物炭相比, 老化生物炭对土壤 CO_2 排放有促进作用^[85]. 此外, Wu 等^[55]通过同时开展“将从土壤中分离出来自然老化生物炭加入到不含生物炭的对照土壤中进行培养”和“将早期添加了生物炭的土壤直接培养”两种室内培养方式, 发现与新鲜生物炭相比, 从土壤中分离出来的老化生物炭失去了抑制土壤 N_2O 排放的能力, 但是富集老化生物炭土壤仍然具有新鲜生物炭相似的抑制土壤 N_2O 排放的能力. 还有的研究则是在田间进行原位试验, 例如, Wu 等^[51]开展了 6 a 田间试验, 发现生物炭施入初期 (新鲜生物炭) 对土壤 CH_4 排放没有显著影响, 但是后期 (老化生物炭) 显著降低土壤 CH_4 排放. 吴震等^[86]研究发现新鲜生物炭促进水稻土 CH_4 排放, 但 3 a 老化生物炭降低水稻土 9% 的 CH_4 排放量. Zhang 等^[56]基于一个 6a 的长期生物炭添加试验, 研究发现老化 6 a 生物炭可以降低水稻土 38%~48% 的 N_2O 排放量; 朱爽阁等^[87]通过田间定位试验, 研究发现新鲜和老化生物炭均降低土壤 N_2O 排放, 但与新鲜生物炭相比, 老化生物炭的抑制作用减弱, 且老化时间越长抑制作用越弱. 值得注意的是, 生物炭在田间自然条件下发生明显的性质变化可能需要数年至数十年的时间, 现有田间自然老化研究生物炭最长没有超过 10 a, 与生物炭长达数十年甚至数百年的稳定性相比, 相当于反映生物炭的中短期效应.

可见, 现有生物炭长期效应研究采用的老化生物炭主要是通过室内模拟老化和田间自然老化两种方式获得. 现有研究要么是采用室内模拟方法, 要么是采用田间老化方法, 很少将两种方法相结合 (表 1), 而单一方法都有一定的局限性. 此外, 室内模拟

老化方法可以分为生物、物理和化学老化,现有研究多是采用化学老化,而关于生物和物理老化生物炭的研究很少,生物炭在土壤中同时发生生物、物理和化学老化,尤其是在高纬度寒冷地区,冻融交替所产生的物理老化占有重要地位,因此,除了开展化学氧化生物炭研究,同时开展冻融交替老化和生物老化生物炭的研究对于深刻阐述老化生物炭对土壤温室气体排放的影响十分必要。

2.2 生物炭老化导致减排效应改变的发生机制

老化生物炭降低土壤 CO_2 排放被归因于:随着生物炭老化耗尽了生物炭中不稳定的碳组分,增加了生物稳定性;老化生物炭机械性能的提高抑制了生物炭颗粒的破碎,减少了生物炭中挥发性组分的释放和随之而来的 CO_2 排放^[52]。老化生物炭促进土壤 CO_2 排放则是由于:老化过程中,生物炭孔径可能被堵塞,微孔减少,原吸附的气体可能会在老化过程中释放出来,且老化后生物炭的 pH 值降低,吸附的 CO_2 在低 pH 环境中也不利于碳酸盐矿物的生成,从而造成 CO_2 在老化过程中逸出^[88]。老化生物炭抑制土壤 N_2O 排放作用增强被归因于:老化的生物炭对硝化和氨氧化的抑制作用优于新鲜生物炭^[53];老化生物炭比表面积增大,微孔结构增多,增加对 N_2O 的直接吸附^[89]。老化生物炭对土壤 N_2O 排放抑制作用减弱甚至丧失则被归因于:老化生物炭孔隙结构被堵塞、表面附着硝化反硝化抑制剂被分解,导致其对 N_2O 的吸附和抑制能力下降^[80];随着生物炭老化,氧化和酸化作用使得生物炭表面酸性含氧官能团羧基 ($-\text{COOH}$) 和羟基 ($-\text{OH}$) 等增加, pH 值降低,电子传递能力减弱,导致生物炭老化过程中 N_2O 减排效果逐渐降低甚至 N_2O 排放升高^[72,90];老化的生物炭增加了土壤中氨氧化细菌的基因丰度,促进了硝化过程,土壤 NO_3^- -N 含量和 ($nirS + nirK$)/ $nosZ$ 比值的增加,导致抑制能力下降甚至促进 N_2O 排放^[81,87]。老化生物炭抑制土壤 CH_4 排放效果低于新鲜生物炭被认为是由于:虽然老化生物炭对甲烷氧化细菌的活性和丰度影响的正效应仍然存在,但是程度非常有限^[4]。老化生物炭对土壤 CH_4 减排效果优于新鲜生物炭则被认为是由于:生物炭对微生物的影响存在滞后性,添加生物炭虽然会增加土壤中甲烷氧化菌的丰度和生物多样性,但在添加多年后的土壤中微生物群落更大,导致老化生物炭对土壤 CH_4 减排效果更好^[91,92];新鲜生物炭施入土壤后,会为产甲烷菌的活动创造合适的环境,增加 CH_4 产量^[86]。

可见,现有生物炭老化导致减排效应改变的发生机制多是基于生物炭老化后自身表面形态结构、

官能团和理化性质的改变,进而产生对土壤理化和生物学特性的影响。与新鲜生物炭影响机制相同,相对较少从过程层次上来揭示老化生物炭的影响机制。更重要的是,采用田间自然老化生物炭进行生物炭长期效应的研究,有的是将老化生物炭从土中分离出来,然后加入不含生物炭的对照土壤中进行培养^[53,81,82],这种做法由于生物炭-有机-矿物-微生物组合没有保存下来,只考虑了老化生物炭自身性质改变的影响,而忽略了多年来经过生物炭改良的富集生物炭土壤特性的影响,不能全面反映老化生物炭的效应;有的则是直接采用早期添加了生物炭的土壤进行室内培养^[83,93],这种方法虽然能够反映老化生物炭的实际效应,但由于老化生物炭对温室气体排放的影响包括“生物炭自身理化性质改变”和“多年来经过生物炭改良的富集生物炭土壤特性”两个方面,这种方法无法将两方面影响有效区分,不利于深入理解老化生物炭的影响机制,而将两种培养方法联合起来开展的研究十分有限^[55]。

3 展望

在努力实现“碳中和”、积极应对气候变化大背景下,国内外学者已经认识到生物炭在减排增汇方面具有重要作用,并对“生物炭添加对土壤温室气体排放的影响”开展了广泛研究,但是本领域的一些核心问题依然未能解决,未来在对生物炭进行相关研究时,应该着重关注以下 3 个方面。

(1) 加强生物炭对土壤 CO_2 、 N_2O 和 CH_4 这 3 种气体排放的影响和固碳效应的同步研究。

生物炭添加可能会对 3 种温室气体产生不同影响,且 3 种温室气体的增温效应存在显著差异^[2],因此,同时测定 3 种温室气体进而计算全球增温潜势,这有助于准确评估生物炭添加在减缓气候变暖方面的有效性。此外,生物炭添加于土壤后,有“影响温室气体排放”和“增加碳汇”的双重作用,但目前研究多是将生物炭固碳潜力与土壤温室气体减排效应分开考虑,缺乏关于生物炭对土壤温室气体排放和其固碳效应的综合贡献研究,而进行生物炭减排和对固碳效应的同步研究有助于全面评估生物炭在减缓气候变暖中的贡献。

(2) 加强田间自然老化和室内模拟老化以及不同培养方式的联合研究。

根据生物炭老化特点,充分考虑化学、物理和生物老化过程,同时开展室内化学老化、生物老化、冻融交替老化模拟和田间自然老化生物炭研究,既有助于掌握老化生物炭的实际效应,又可有效预测生物炭的更长期效应。此外,同时利用“老化生物炭

加入不含生物炭对照土壤进行培养”和“富含老化生物炭的土壤直接培养”两种培养方法开展研究, 可将“老化生物炭自身性质改变”和“多年来经生物炭改良的富集生物炭土壤特性”两方面影响有效区分, 有助于深刻阐述生物炭的长期效应及其机制。

(3) 加强利用 ^{13}C 和 ^{15}N 示踪技术, 从过程层次上揭示生物炭添加对土壤温室气体排放的影响机制研究。

^{13}C 示踪技术结合混合模型可以识别土壤中不同碳库, 对 CO_2 进行溯源, 进而明确生物炭对土壤原生有机碳分解的激发效应, 也可以明确 CH_4 产生和氧化的相对贡献。 ^{15}N 标记技术结合数值分析方法可获得N素初级转化速率, 并可定量区分 N_2O 来源。因此, ^{13}C 和 ^{15}N 示踪技术可对现有机制进行验证, 并从过程层次揭示生物炭对土壤温室气体排放的影响机制, 有助于深入理解生物炭的影响机制。

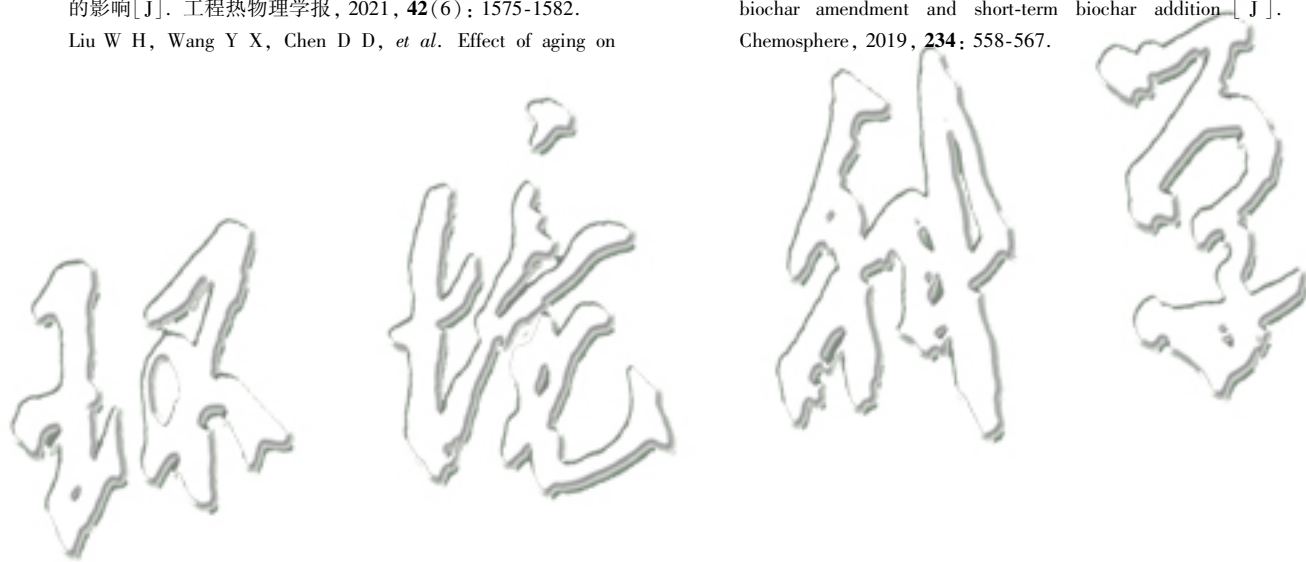
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