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生物炭影响抗生素在土壤环境中行为的 Meta 分析

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摘要: 生物炭作为一种减污降碳相协同的土壤改良剂, 在抗生素污染控制方面均有较大应用前景. 为了系统研究生物炭施用对抗生素在土壤环境中行为的影响, 对 2011 ~ 2021 年发表的 20 篇文献进行 Meta 分析. 结果表明, 抗生素在生物炭改良土壤中的吸附、降解行为受生物炭施用量与性质的显著影响. 施用质量分数为 2% 时, 对抗生素吸附行为的影响最强, 效应值为 0.19; 施用质量分数为 5% 时, 对其降解作用影响显著, 效应值为 0.23; 生物炭比表面积、极性、稳定性和芳香化程度对分配系数的增加影响非常显著, 分别为 0.11、0.13、0.09 和 0.18; 而生物炭施用量和性质对抗生素迁移行为影响并不显著. 生物炭还可通过调控土壤环境间接影响抗生素环境行为. 但抗生素在土壤中多环境行为耦合对生物炭的响应机制仍不明确, 生物炭田间施用的长效性与负面效应仍缺乏基础数据支撑.

关键词: 生物炭; 抗生素; 土壤; 环境行为; Meta 分析

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Effects of Biochar on Antibiotic Environmental Behaviors in Soil: A Meta-analysis

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Abstract: Biochar, as a soil amendment for synergizing the reduction of pollution and carbon emissions, shows great potential and future prospects in controlling antibiotic contamination. In order to research the effects of biochar on antibiotic behaviors in soil systematically, a Meta-analysis was conducted based on 20 studies published from 2011 to 2021. The results showed that the adsorption and degradation of antibiotics in the soil were significantly affected by the application rate and property of biochar. A 2% biochar application dose seemed to be the highest effect size (ES) of 0.19 on adsorption, while there was a significant effect (ES = 0.23) on the degradation when the application rate was 5%. The specific surface area, polarity, stability, and aromaticity of biochar could increase the partition coefficient significantly, and the ES was 0.11, 0.13, 0.09, and 0.18, respectively, whereas the effects of antibiotic transport on the dose and property of biochar were insignificant. Biochar also indirectly controlled antibiotic behavior by altering the soil environment. However, the response of the coupling mechanism in antibiotic behaviors on biochar application into soil is still unclear. Moreover, the long-term and negative effects of biochar application in the field are still lacking basic data.

Key words: biochar; antibiotics; soil; environmental behaviors; Meta-analysis

随着经济社会发展, 抗生素生产量与使用量逐年增多, 且全球范围内近一半的抗生素用于动物养殖业^[1], 不规范使用与禽畜低吸收率导致环境中频繁检出 $\text{ng} \cdot \text{L}^{-1} \sim \mu\text{g} \cdot \text{L}^{-1}$ 级别抗生素^[2]. 然而, 仅痕量或微量的抗生素就可增加抗生素耐药基因丰度, 对土壤微生态系统与人体健康造成潜在威胁^[3]. 土壤是抗生素等污染物的最终归宿之地, 而具有固碳、增肥和污染控制于一身的生物炭对抗生素具有显著的调控能力^[4~7], 例如, 生物炭表面具有多孔的疏水表面与多种官能团, 可以显著增加土壤对抗生素的吸附^[8]; 也可通过调节土壤物理化学特性与微生物群落结构^[9~11], 促进土壤中抗生素的消减^[12]; 并且其对土壤水分循环的作用也能增加抗生素的滞留率, 从而抑制污染物迁移^[13]. 因此, 生物炭对土壤中抗生素的吸附、迁移和降解等环境行为均具有一定影响.

然而, 由于土壤类型多样, 性质复杂, 土壤中生物炭性能受到施用量、自身性质和土壤性质等影响^[14~16], 因此, 土壤中抗生素的吸附、迁移和降解等环境行为对生物炭施用的响应尚有诸多不确定

性. 以往有关研究仅针对生物炭及个别因素对吸附、迁移或降解等某一种环境行为的影响予以讨论, 但其实验条件和控制参数均不尽相同^[16~18], 其结果无法为生物炭污染控制提供有效的理论支持. 而近年来, 在生态环境领域, Meta 分析具有较为广泛的应用, 可有效解决单独个体研究发表性偏倚影响问题^[19,20], 为定量解析生物炭对土壤中抗生素环境行为影响提供了较好的分析手段.

本研究通过收集 2011 ~ 2021 年间的相关文献, 采用 Meta 分析, 探明了施用生物炭对土壤中的抗生素的吸附、迁移、降解等环境行为的影响, 阐释了施用生物炭后土壤理化性质的变化, 揭示了土壤性质、生物炭性质和抗生素性质对抗生素在土壤中的吸附、迁移和降解的影响作用结果, 以期控制抗生素在土壤中的污染提供理论依据.

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1 材料与方法

1.1 数据来源及选择标准

抗生素种类繁多,土壤抗生素的组成与积累程度受人类活动和土壤性质的共同影响^[21]. 畜禽粪便和土壤中检出率较高、研究较多的抗生素类型有磺胺类、四环素类、喹诺酮类和大环内酯类等^[22],因此,将其作为主要研究对象. 通过 Web of Science 数据库和中国知网,以“抗生素、土壤、生物炭、四环素、磺胺、喹诺酮、吸附、迁移和降解”等作为关键词检索 2011~2021 年间发表的文獻.

文献筛选标准为:①文献至少研究生物炭对一种抗生素在土壤中环境行为的影响;②实验必须包含严格的对照组和实验组;③必须开展平行实验;④文献中的原始数据必须在文章或补充数据中可用. 基于以上条件,共获得 20 篇有效文献.

1.2 数据的收集及分类

收集的数据包括:生物炭热解温度、种类和施用量;生物炭性质:H/C、O/C、C/N 和比表面积(specific surface area, SSA, 采用 BET 法测定值);抗生素的分配系数、滞留率和降解率等数据.

数据的分类如下:抗生素的环境行为:①吸附,②滞留和③降解;生物炭施用量:①质量分数≤1%,②质量分数为2%和③质量分数为5%.

将分类后的数据 min-max 标准化^[23]消除量纲后进行 Meta 分析,公式如下:

$$y_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (1)$$

1.3 Meta 分析

本研究使用 Revman5.4 进行 Meta 分析,采用连续型变量类型,输入平均数、标准差和样本数量进行分析,采用均值差 MD(mean difference)作为效应统计指标,采用固定效应模型(fix effect model)进行分析,均值差 MD 的公式如下:

$$MD = \overline{X_E} - \overline{X_C} \quad (2)$$

式中, $\overline{X_E}$ 和 $\overline{X_C}$ 分别为添加生物炭和不添加生物炭土壤中抗生素的分配系数(或滞留率、降解率).

综合效应值(effect size, ES)固定效应模型的计算公式为^[24]:

$$ES = \sum_{i=1}^k W_i r_i / \left(\sum_{i=1}^k W_i \right) \quad (3)$$

式中, r_i 为第*i*项指标的效应值, W_i 为第*i*项指标的权重, k 为指标个数.

计算综合效应值的 95% 置信区间 CI,计算公式为^[24]:

$$95\% \text{ CI} = ES + t_{0.05} SE \quad (4)$$

$$SE = \sqrt{1/W_i} \quad (5)$$

式中,SE 为结合效应值的标准误差. 当综合效应值大于 0 时,说明生物炭对抗生素在土壤中的分配系数(或滞留率、降解率)有增加效应,反之则为降低效应. 若置信区间 CI 不包含 0,则认为该效应值显著,反之则不显著. 具体来说,若置信区间都大于 0,则施用生物炭显著增加了抗生素在土壤中的吸附、滞留和降解作用;若置信区间都小于 0,则施用生物炭显著降低了抗生素在土壤中的吸附、滞留和降解作用.

1.4 数据处理

通过 Microsoft Excel 2016 软件收集整理数据, Revman 5.4 软件进行 Meta 分析, Origin 2018 软件进行绘图.

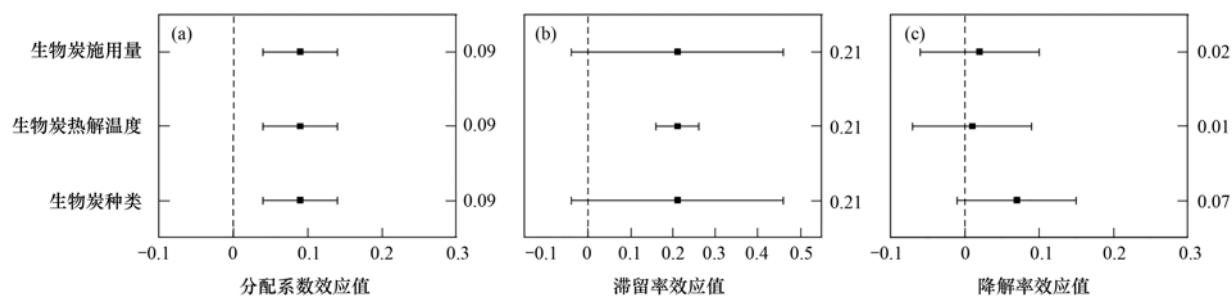
2 结果与讨论

2.1 生物炭施用对土壤中抗生素环境行为的影响

生物炭进入土壤后,自身的强吸附作用提高了炭土混合物对污染物的吸附与滞留能力,对微生物的富集作用促进了降解效应,图 1~3 表明生物炭对土壤中的抗生素的吸附、降解有明显的正效应,对滞留有微弱的正效应.

土壤中生物炭施用对抗生素的吸附、迁移和降解行为均会产生一定的影响^[8,22,25~27]. 生物炭的强吸附能力是近年来关注的重点,其对有机污染物的吸附能力是土壤吸附能力的几百倍,甚至几千倍. 例如,小麦和水稻生物炭对有机农药的吸附能力比土壤高 400~3 800 倍^[28,29];磺胺甲噁唑与磺胺二甲氧嘧啶在生物炭中的分配系数比在土壤中的高 500~874 倍^[30,31]. 生物炭的强吸附能力也预示着对抗生素迁移的阻控作用,Jeong 等^[13]的研究表明,生物炭在土壤中对泰乐菌素有更强的阻滞作用,突破曲线穿透更晚,拖尾更长. 由于抗生素在土壤环境中的停留时间增加,为其降解提供了更多的条件,土壤中混施生物炭-黑麦草对抗生素的消散作用比单独施用黑麦草更强^[6]. 然而,大多数研究中均发现生物炭的上述作用受到施用量、种类和热解温度的显著影响^[14,16,17,32,33],其影响总效应如图 1 所示.

如图 1(a)所示,生物炭施用量、热解温度和种类与分配系数均具有显著正相关($P < 0.05$),但各因子间效应值无差异;相较于分配系数,生物炭对抗生素在土壤中的迁移行为的影响研究较少,样本数据量的不足导致滞留率效应值均值差较大,仅有生物炭热解温度对滞留率的影响是显著的 [$P < 0.05$, 图 1(b)];与对分配系数的影响相似,图 1(c)



右侧纵坐标表示生物炭对抗生素在土壤中的环境行为的效应值,下同

图1 抗生素在施炭土壤中环境行为的影响因素总效应

Fig. 1 Total effects of antibiotics on environmental behaviors in soil applied with biochar

中所有影响都不显著($P > 0.05$),但生物炭种类影响最大.影响抗生素滞留率与降解率的生物炭热解温度与原料种类,是生物炭制备过程中两个重要的控制参数,也影响了生物炭的基本理化性质,如比表

面积以及芳香化程度等(表1).因此,生物炭作为土壤改良剂对抗生素环境行为的影响主要体现在施用量及其理化性质,即生物炭的“质”与“量”两个方面.

表1 生物炭热解温度与种类对生物炭理化性质的影响¹⁾

Table 1 Effects of pyrolysis temperature and species of biochar on physicochemical properties of biochar

原料种类	热解温度/℃	比表面积/ $\text{m}^2 \cdot \text{g}^{-1}$	芳香化程度(H/C)	文献
壳类	≤ 400	3.30 ~ 15.20	0.51 ~ 1.29	[17,34,35]
	400 ~ 600	18.58 ~ 248.99	0.57 ~ 0.91	
	≥ 600	159.00 ~ 315.11	0.28 ~ 0.58	
木质类	≤ 400	3.39	1.19	[14,35]
	400 ~ 600	178.77 ~ 431.91	0.80 ~ 0.87	
	≥ 600	443.79 ~ 795.00	0.01 ~ 0.66	
秸秆类	≤ 400	1.71 ~ 70.72	0.06 ~ 0.89	[14,17,36]
	400 ~ 600	6.04 ~ 15.37	0.03 ~ 0.04	
	≥ 600	134.67 ~ 320.77	0.02 ~ 0.28	

1)官能团:低温时含氧官能团含量较高,随着温度升高,有机组分发生脱水 and 脱羧反应,羟基基团、烷基基团、羧基基团和酮基基团减少

2.2 生物炭施用量对土壤中抗生素环境行为的直接影响

生物炭的施用量对抗生素在土壤中吸附行为具有显著的影响,而对滞留率与降解率的影响并不显著,但施用量仍是近年来生物炭作为土壤改良剂研究领域中最主要的控制变量,由于生物炭对土壤水分的吸持作用,随施用量增加,植物有效水将降低,过量施用生物炭会造成植物萎蔫,如当生物炭施用量为1%和5%时,黑麦草产量随着施用量增加而增加,但当施用量为20%时,产量反而下降^[37].因此,在大多数研究中用于农田土壤改良的生物炭施用的质量分数一般不超过5%^[6,8,14~16,30,38~43].生物炭对有机污染物的吸附能力是土壤的几百倍到几千倍不等^[28~31],其施用量小幅度变化就会对抗生素的环境行为产生较大的影响,通常来说,生物炭施用量越大,对抗生素的吸附能力和降解能力越强^[13,44].但如图2所示,随着生物炭施用量增加,分配系数与降解率分别呈现先增加后减少和先减少后增加的趋势,施用质量分数为2%时,对分配系数增加的效应值最大,甚至超过了分配系数均值更高的5%施用

量,这预示着生物炭施用量对吸附作用与降解效率的影响在质量分数5%以下存在阈值.这可能是随着施用量提高,生物炭表面溶出更多的溶解性有机质或胶体颗粒,其会与抗生素竞争生物炭和土壤颗粒上的吸附点位^[45],或与其产生协同运输^[46],同时可能会将生物炭表面孔隙阻塞,从而发生竞争吸附与位阻效应^[47],并且土壤溶液中更多的有机物质会对疏水性抗生素产生增溶效应^[48],从而增加抗生素在液相的分配.而生物炭施用量对滞留率的影响效应均值变化不明显且数据波动性大(标准差为28.00%~37.00%).如表2所示,随着生物炭吸附能力的增强,对抗生素的迁移阻滞率也提高了2.22%~100.00%^[16,30,38,43],但是阻滞率与分配系数的变化却不一致.如图2所示,当施用生物炭质量分数为5%时,其阻滞率出现了下降且低于质量分数小于等于1%的处理,这可能是由于抗生素等污染物的迁移不仅受到吸附剂的影响,还受到土壤类型、结构和土壤水分运动等因素的复杂干扰:较高生物炭的施用虽然提高了吸附性能,但也不可逆地影响了土壤物理结构与水分运动特征,丰富了土壤孔隙结

构,增加了饱和和导水率,促进了污染物随水分的弥散过程^[49].有研究表明,在较低生物炭施加量下,其可以抑制土壤中水分的扩散,但在高生物炭施加量下会促进水分扩散^[50];生物炭对磺胺类抗生素在壤土中的截留能力高于黏土^[43];并且当土壤中存在大孔隙时,溶质运移速度加快,到达深层土壤时浓度更大^[51].因此,虽然施用生物炭可减缓抗生素在土壤中

迁移,但阻滞效果对生物炭施用量的响应无显著性差异.此外,生物炭施用量越大,对抗生素在土壤中的降解能力越强^[13,44].降解能力在施用质量分数为1%和2%时影响非常微弱,当施用质量分数为5%时,降解能力增加,与分配系数的变化不一致,呈相反的趋势,可能是因为土壤颗粒对抗生素的高吸附亲和力会导致土壤中抗生素的降解百分比较低^[18].

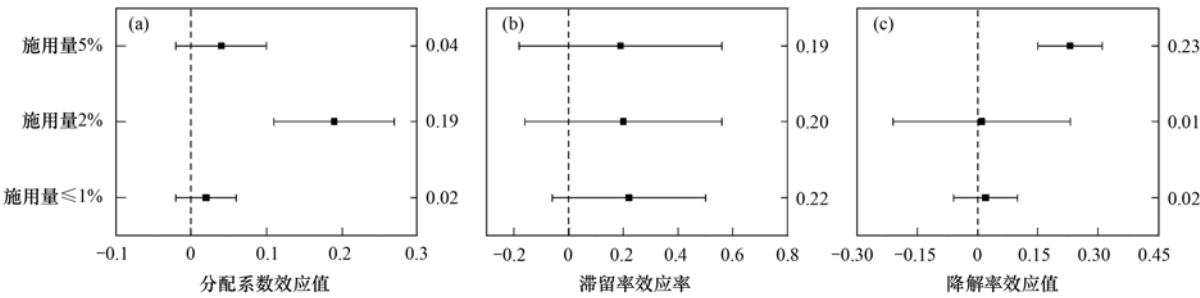


图2 生物炭施用量对土壤中抗生素的环境行为的影响

Fig. 2 Effects of biochar application amount on environmental behaviors of antibiotics in soil

表2 生物炭施用量对抗生素在土壤中环境行为的影响

Table 2 Effects of biochar application amount on environmental behaviors of antibiotics in soil

项目	质量分数			文献
	≤1%	2%	5%	
分配系数/L·kg ⁻¹	0.39 ~ 157.00	0.47 ~ 229.37	0.41 ~ 67.56	[8,14 ~ 16,30,38 ~ 40]
滞留率/%	11.83 ~ 100.00	21.00 ~ 86.00	2.22 ~ 88.78	[16,30,38,43]
降解率/%	0.22 ~ 81.14	4.40 ~ 86.64	51.56 ~ 53.64	[6,41,42]

2.3 生物炭理化性质对土壤中抗生素环境行为的直接影响

受控于制备条件(温度与原料)的生物炭理化性质对生物炭-抗生素相互作用的影响是不可忽视的^[52].例如,当热解温度升高时,生物炭对诺氟沙星的吸附能力增加^[53].生物炭与抗生素的吸附往往是通过疏水分配、阳离子交换或 π - π 电子供受体等作用发生的,加之生物炭表面丰富的孔道调控了土壤水分循环,也丰富了微生物群落结构,从而影响了污染物的迁移与降解^[25,54].现有的研究中,生物炭极性、稳定性和芳香化程度分别由O/C、C/N和H/C来表征,比表面积采用BET法测定^[55~59].如图3所示,生物炭比表面积、O/C、C/N和H/C对分配系数的增加非常显著,其中,芳香化程度与极性对分配

系数的影响更大;而对滞留率和降解率的效应虽有增加但影响较小,方差较大,这是由于统计的样本量过小(集中于5篇文献),这说明对于生物炭影响抗生素迁移与降解的研究仍处于对应用效果的讨论,缺乏对二者之间的构-效关系与作用机制的探究.

生物炭表面的芳香性、极性、可生化性与比表面积直接影响了其与抗生素的相互作用.高温生物炭碳化增强,芳香性高,比表面积大^[16,60],可为土壤中抗生素吸附提供更多的吸附点位.而低温生物炭比表面积较小,但保留了更多的活性基团(如—OH、—COOH和—CO—等),提供了持久性自由基,增加了反应活性^[61,62].例如,软木片生物炭含有大量羧基和酚基团,具有高度反应性,对磺胺二甲嘧啶的极性官能团的亲和力高^[30];低温茶渣生物炭含有较

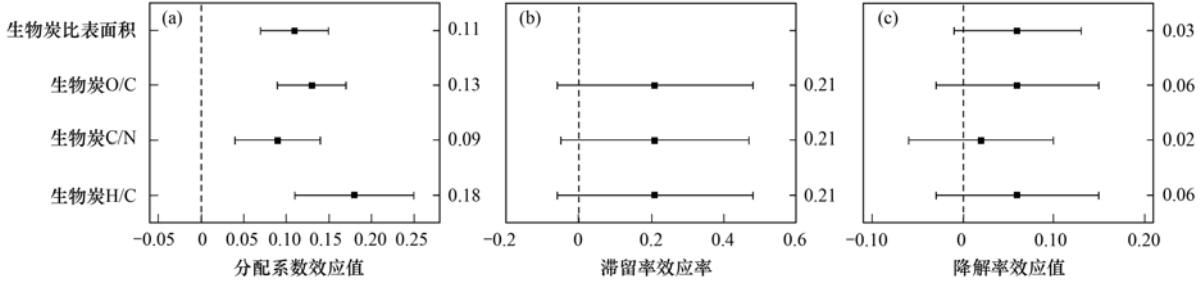


图3 生物炭性质对土壤中抗生素的环境行为的影响

Fig. 3 Effects of biochar properties on environmental behaviors of antibiotics in soil

多官能团,能参与到四环素的去除当中^[63].另外,生物炭的可生化性较低,稳定性极高,有研究表明,在 8.5 a 纯培养的条件下仅可矿化 6%^[64],其在土壤中长期停留可以增加有机污染物的分解^[10].生物炭在土壤中的稳定性与低反应性可促进微生物群落的保护,影响微生物的活性、丰度及多样性^[65],降低微量或痕量污染物对土壤生态的干扰,进而提高对有毒物质的降解效率.例如,用生物炭培养的细菌对磺胺甲噁唑和氯霉素的降解效率增加^[66].

如表 3 所示,由于数据量较少,数据不完整,生物炭施用量及其性质对滞留率的影响并不显著,且效用值方差极大.这说明生物炭低剂量的施用 (<5%) 和性质虽然对“生物炭-土壤-抗生素”三元

吸附具有显著的影响,但耦合水文过程后,吸附过程受到水分运动的强烈干扰^[25],导致生物炭对土壤中抗生素的吸附作用减弱,从而在统计上对滞留率的影响效应异质性增强.目前生物炭阻控抗生素在土壤中的迁移的研究主要为室内填装土柱,而原状土柱和田间试验研究很少,当存在着结构性孔隙与优先流时,污染物会不经过土壤基质,直接随水流从大孔隙等优先通道流出,使其快速远距离迁移^[51,67,68].这说明生物炭对土壤中抗生素的迁移仍需开展进一步研究,很难采用批量平衡实验或填装土柱淋溶实验结果简单评估其迁移行为,需要重点考察生物炭对结构性孔隙与土壤水分运动的影响机制,从而有效评估生物炭对抗生素在土壤中迁移行为的影响.

表 3 生物炭性质对抗生素在土壤中环境行为的影响

Table 3 Effects of biochar properties on environmental behaviors of antibiotics in soil					
项目	比表面积	O/C	C/N	H/C	文献
分配系数/L·kg ⁻¹	0.39 ~ 229.37	0.39 ~ 229.37	0.39 ~ 229.37	0.82 ~ 229.37	[8,14 ~ 16,38,39]
滞留率/%	/	2.22 ~ 100.00	2.22 ~ 100.00	2.22 ~ 100.00	[16,38,43]
降解率/%	0.22 ~ 97.59	0.22 ~ 81.14	0.22 ~ 7.59	0.22 ~ 81.14	[6,17,18,41,54,69 ~ 72]

2.4 生物炭通过改良土壤环境间接影响抗生素的环境行为

生物炭表面的多孔结构与丰富的表面官能团等可显著影响土壤的物理化学特征,如提高土壤 pH 值、总有机碳和可溶性有机碳含量^[73]以及阳离子交换量(cation exchange capacity, CEC)^[74];改善土壤结构质量与特性^[75],如提高土壤持水量^[31]、促进大中团聚体的形成、提高团聚体稳定性^[76]等;促进微生物群落增长,增加微生物作用^[47].这些变化均间接影响抗生素在土壤中的环境行为,并且变化的幅度与土壤原始性质和生物炭性质密切相关^[77,78].

抗生素在土壤中的吸附作用受 pH 值和 CEC 的影响.不同土壤中添加生物炭对其 pH 值影响差异较大.由于生物炭呈碱性,其可明显提高酸性土壤的 pH 值,但对碱性土壤影响不明显^[79].例如,土壤 pH 值为 5.44 时,添加稻草生物炭后 pH 值提高到 6.07^[15],而在 pH 值为 7.8 的土壤中添加生物炭后, pH 值处于相似水平(7.7 ~ 8.1)^[39].土壤的 pH 值会影响抗生素在水土环境中的离子形态,进而影响吸附机制:随着 pH 值降低,磺胺甲噁唑、磺胺甲嘧啶和磺胺嘧啶等抗生素多呈现阳离子态,很容易被土壤和生物炭上带负电荷的官能团吸引^[43];而当 pH = 3 时,磺胺甲嘧啶的吸附可归因于 π - π 电子供体受体相互作用和静电阳离子交换,当 pH 值为 5 ~ 7 时,吸附机制则以阳离子交换为主^[16];同时,土壤 pH 可影响 CEC,在酸性土壤中,生物炭可以明显提高土壤的 CEC,而在碱性土壤中这种变化不明

显^[49],可能是因为 pH 影响了土壤胶体羟基的解离,当 pH 值升高时,负电荷增加,CEC 增加^[80].在酸性土壤中,添加了污泥生物炭的 CEC 从 7.3 cmol·kg⁻¹ 升高至 8.5 cmol·kg⁻¹^[81].由于土壤对泰乐菌素和磺胺二甲嘧啶的吸附能力与 CEC 成正比^[82],因此,生物炭可通过调控 CEC 间接影响抗生素的吸附行为.

而土壤中污染物迁移行为既受到上述吸附作用的影响也被土壤水文过程所控制,土壤物理结构与水分特征是重要的影响因素.生物炭的施用显著提高了土壤的团聚能力和团聚体稳定性,有效降低了土壤容重,增加了土壤孔隙率,影响土壤的水文特征和体积密度^[41],增加了土壤水容量^[31],增加了土壤有效水含量.例如,在 1% 和 5% 的施用条件下,土壤水容量分别增加了 10% ~ 15% 和 16% ~ 24%^[31],在施用 2% 生物炭的情况下,土壤的饱和导水率增加了 46.2%,总有效孔径增加了 8.3%^[83].因此,添加生物炭能改变土壤中水分与溶质的迁移行为.

相比于吸附和迁移行为,污染物的降解行为受到水分、光、微生物等诸多因素共同作用.生物炭可以提高土壤中的总氮、总磷、总钾、有效磷和有效钾的含量,分别为 42.1%、26.2%、6.78%、78.2% 和 687%^[42],可以为微生物提供更多的营养物质,生物炭的多孔性为土壤中微生物提供了生存空间,保持了水分,且能增加真菌门类之间的相互作用^[70],例如,真菌群落中,子囊菌门、壶菌门、接合菌门和生物炭处理有着正相关性^[84];虽然酸杆菌

和宝石单胞菌细菌相对丰度下降,但变形菌、拟杆菌和放线菌的相对丰度增加,总体上增加了细菌多样性^[85].此外,生物炭施用能在一定程度上影响土壤酶活性,例如能整体促进蔗糖酶、脲酶、过氧化氢酶和中性磷酸酶的活性^[86].因此,添加生物炭能促进土壤中抗生素的降解.

3 展望

(1)生物炭对抗生素在土壤中的迁移行为影响的研究严重不足,并且相对忽视了生物炭对土壤水分运动的调控作用,尤其是针对存在优先流的土壤.

(2)现有研究更多集中于室内模拟实验,生物炭在复杂自然环境中的长期、定位研究较为缺乏,其对抗生素在不同研究尺度下的多因素耦合效应仍不明确.

(3)由于生物炭施入土壤后的不可逆性,老化作用会降低其效能,并且可能引入外源污染物(如生物炭结构崩塌产生的胶体生物炭),可能会导致与其他污染物产生协同运输效应,其负面影响仍需进一步评估.

4 结论

(1)生物炭施用量对土壤中抗生素的吸附与降解行为影响显著,当施用质量分数2%时,对分配系数的增幅最大;当质量分数为5%时,对降解率的影响显著;而抗生素在土壤中的迁移行为受到生物炭施用量的影响并不明显.

(2)生物炭比表面积、极性、稳定性与芳香化程度等理化性质对抗生素在土壤中吸附作用的影响极显著,但对迁移行为与降解行为的影响并不具有显著性差异.

(3)生物炭不仅可以通过自身理化性质影响抗生素在土壤中的吸附、迁移和降解行为,也可通过改良土壤环境间接影响抗生素的环境行为,如调控土壤孔隙结构、离子交换与水分循环等,可为抗生素与土壤颗粒发生物理-化学-生物耦合作用提供更优的条件.

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