

北京城区PM_{2.5}各组分污染特征及来源分析

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不同原料生物炭的理化特性及其作炭基肥缓释载体的潜力评价

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摘要: 生物炭作炭基肥缓释载体的能力与其理化性质密切相关, 因此在制备炭基肥前有必要对不同原料和热解温度制备的生物炭的理化性质进行评价. 以苹果枝条、棉秆和杜仲枝条为原料, 通过生物质干馏设备在 400、500、600 和 700℃ 热解温度下制备生物炭, 并对生物炭的 pH、比表面积及孔隙结构、表面官能团和矿物组成等理化性质进行表征和灰色关联度分析, 结合生产成本评价生物炭用于炭基肥缓释载体的潜力. 结果表明, 3 种原料制备的生物炭的产率均随热解温度的升高而降低, 其中 400℃ 制备的苹果枝条生物炭的产率最高 (37.4%). 所有生物炭的 pH 值均 > 10, 表现出强碱性. 在 400 ~ 500℃ 热解温度范围内, 苹果枝条、棉秆和杜仲枝条生物炭的比表面积和总孔容随温度的升高增大, 最大比表面积分别为 265.262 7、107.449 1 和 316.185 4 m²·g⁻¹; 当热解温度 > 500℃ 时, 比表面积和总孔容减小. FTIR 和 XRD 图谱分析表明, 所有生物炭具有丰富的芳香结构, 其中苹果枝条和棉秆生物炭含有较多的矿物组分, 杜仲枝条生物炭为非晶生物炭. 灰色关联分析表明当热解温度为 500℃ 时, 杜仲枝条生物炭的理化性质最优, 苹果枝条生物炭次之, 棉秆生物炭最差. 然而, 杜仲枝条生物炭的生产成本最高, 苹果枝条生物炭次之, 棉秆生物炭最低. 综合考虑, 苹果枝条生物炭作炭基肥缓释载体的潜力更大.

关键词: 生物炭; 灰色关联度; 炭基肥缓释载体; 杜仲枝条; 经济评估

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Physicochemical Properties of Biochars Prepared from Different Feedstocks and Evaluation of Its Potential as A Slow-release Carriers for Biochar-based Fertilizers

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Abstract: The ability of biochar to be a slow-release carrier for biochar-based fertilizers is closely related to its physicochemical properties. Therefore, it is necessary to evaluate the physicochemical properties of biochars prepared from different feedstocks and pyrolysis temperatures before preparing biochar-based fertilizers. Here, biochars were prepared from apple pruning branches, cotton stalks, and *Eucommia ulmoides* branches through biomass dry distillation equipment at different pyrolysis temperatures (400, 500, 600, and 700℃), and the physicochemical properties of biochars, such as pH, thermal stability, BET surface area and pore structure, surface functional groups, and mineral composition, were characterized. Gray correlation analysis and economic evaluation were performed to evaluate the potential of biochars as slow-release carriers for biochar-based fertilizers. The results showed that the yield of biochars prepared from the three different feedstocks decreased with the increase in pyrolysis temperature, and the yield of apple branch biochar prepared at 400℃ was the highest (37.4%). The pHs of all biochars were greater than 10, indicating strong alkalinity. In the pyrolysis temperature range of 400-500℃, the BET surface area and total pore volume of apple branch, cotton stalk, and *E. ulmoides* branch biochars increased with the increase in temperature, and the maximum BET surface areas were 265.262 7, 107.449 1, and 316.185 4 m²·g⁻¹, respectively. When the pyrolysis temperature was greater than 500℃, the BET surface area and total pore volume decreased. FTIR and XRD pattern analysis showed that the biochars had a rich aromatic structure, among which the apple branch and cotton straw biochars contained more mineral components, and *E. ulmoides* branch biochars were amorphous. Grey correlation analysis showed that when the pyrolysis temperature was 500℃, the physicochemical properties of biochar prepared from the *E. ulmoides* branches were the best, followed by those of apple pruning branches, and those of biochar from cotton stalks were the worst. However, *E. ulmoides* branch biochar had the highest production cost, followed by that of apple pruning branch and cotton stalk biochar. After comprehensive considerations, the apple pruning branch biochar overall had greater potential as a carrier for BF_s.

Key words: biochar; grey correlation degree; slow-release carriers of biochar-based fertilizers; *Eucommia ulmoides* branches; economic evaluation

生物炭是植物或废弃的原料通过热裂解而产生的固体材料^[1], 由于具有独特的理化性质被广泛用作土壤改良剂^[2~4]. 近来, 将生物炭用作缓释肥料的载体制备炭基肥 (biochar-based fertilizers, BF_s), 能够提高肥料利用率, 减轻地下水污染和水体富营养化, 以及温室气体排放等一系列环境危害, 而且当养分释放到土壤后, 生物炭还可以发挥其土壤改良剂的作用^[5~7]. 有研究表明生物炭吸附养分的能力

与其表面特性和结构密切相关, 具有稳固的芳香结构、丰富的官能团、孔隙结构和巨大比表面积的生物炭有利于作 BF_s 载体^[8,9]. 然而生物炭的理化性

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质主要取决于热解温度和生物质原料的选择^[1]. 通常在一定温度范围内,生物炭的 C 含量、pH、比表面积及总孔容、芳香性和热稳定性随热解温度的升高增大^[10,11];产率、极性和酸性含氧官能团含量随热解温度的升高降低^[12~14]. 此外,生物质原料也会影响生物炭的理化性质. 有机碳含量高和灰分含量低的生物质可以促进生物炭孔隙结构的发育^[15];木质素含量高的生物质有利于获得较高产量的生物炭^[16].

有研究发现,以农林废弃物为原料热解制备的生物炭是一种理化性能优良的缓释肥料载体,其不仅来源广泛,而且富含多种表面官能团,如羟基、羧基和羰基等^[17,18]. 我国是世界上最大的棉花、苹果和杜仲种植国,每年产生大量的苹果修剪枝条、棉秆和杜仲叶林枝条. 将这些废弃物通过慢速热解制备理化性能优良生物炭,对农林业的可持续发展具有重要意义. 目前已就苹果枝条、棉秆和杜仲枝条生物炭开展了研究,但热解工艺、材料来源和应用途径等的不同,生物炭的质量差异较大^[19~21],且以 BF_s 缓释载体为最终应用目的的生物炭的理化性能评价仍有不足. 因此有必要对 3 种原料制备的生物炭理化性质进行表征,并评价其作 BF_s 缓释载体的潜力.

本研究以苹果修剪枝条、棉秆和杜仲叶林枝条为原料,利用生物质干馏设备在 400、500、600 和 700℃ 这 4 个热解温度下制备生物炭. 通过 SEM、FTIR 和 XRD 等方法对生物炭的理化性质进行表征,探究原料和温度对生物炭理化性质的影响. 并对生物炭作 BF_s 缓释载体的潜力进行了灰色关联分析和经济评估,以期为农业生产制备性能优良的 BF_s 缓释载体提供一定的参考依据.

1 材料与方法

1.1 生物炭的制备

棉秆(cotton stalks, CS)采集于新疆,苹果修剪枝条(apple pruning branches, AB)和杜仲叶林枝条(*Eucommia ulmoides* branches, EB)均采自陕西杨凌. 将风干的 CS、AB 和 EB 处理成 2 cm 的小段,于电热恒温鼓风干燥箱 80℃ 干燥 24 h. 称取一定量预处理后的原料装入生物质干馏设备(XINKYO, 农业部农村可再生能源开发利用西部科学观测实验站)制备生物炭. 升温速率为 2℃·min⁻¹,分别达 400、500、600 和 700℃ 后,保温 2 h. 待干馏装置冷却至室温后取出生物炭,计算生物炭的产率;经研磨过筛(100 目)后待后续测定. 苹果枝条、棉秆和杜仲枝条生物炭分别标记为 ABX、CSX 和 EBX,其中 X 代表热解温度,如 EB400 表示 400℃ 热解制备的杜仲枝条生

物炭.

1.2 生物炭的表征

用元素分析仪(德国 Vario EL III)测定样品中 C、H、N 和 S 的质量分数,用差减法计算 O 含量;通过复合电极法测定生物炭的 pH,去离子水和生物炭的质量之比为 5:1;利用热分析仪(美国 TGA55)对生物炭进行差热/热重分析(TG/DTG),气体流速为 100 mL·min⁻¹,以 10℃·min⁻¹升温至 900℃;以高纯 N₂ 为吸附质,利用比表面积及孔径分析仪(美国 TriStar II 3020)测定生物炭的 BET 比表面积和孔径;利用扫描电子显微镜(日本 Hitachi X650)观察生物炭在放大 2 000 倍数下的表面形貌;用傅里叶变换红外光谱仪(日本 IRPrestige-21)表征生物炭的表面官能团;X 射线衍射仪(德国 Bruker D8 Advance)对生物炭进行物相分析,以 CuK 为发射源,设置 2θ 为 5°~80°,管电压为 40 kV,管电流为 150 mA,扫描步长为 0.02°.

1.3 灰色关联分析

计算 12 种生物炭的比表面积、总孔容、H/C 量比、pH 和氮含量这 5 个指标的灰色关联度,并对其进行排序,综合评价各生物炭的理化性质. 根据 Li 等^[22]和 Huang 等^[23]介绍的方法计算灰色关联度. 公式如下:

$$X_i(k)^* = X_i(k)/X_0(k) \quad (1)$$

$$\Delta X_i(k)^* = |X_0(k)^* - X_i(k)^*| \quad (2)$$

$$\varepsilon_i(k) = \frac{\Delta(\text{Min}) + \rho \cdot \Delta(\text{Max})}{\Delta X_i(k)^* + \rho \cdot \Delta(\text{Max})} \quad (3)$$

$$r_i = \frac{1}{n} \sum_{k=1}^n \varepsilon_i(k) \quad (4)$$

式中, $X_i(k)^*$ 为原始数据转化后的无量纲数据; $i = 0, 1, 2, \dots, m$; $k = 1, 2, \dots, n$; m 为影响指标数, n 为生物炭数量, X_0 为影响因素中最有利的值; $\Delta X_i(k)^*$ 为初始数据与比较数据的绝对差值; $\varepsilon_i(k)$ 为关联系数; $\Delta(\text{Max})$ 为最大绝对差; $\Delta(\text{Min})$ 为最小绝对差; r_i 为灰色关联度; ρ 为分辨率,通常取 $\rho = 0.5$.

2 结果与讨论

2.1 生物炭特性

2.1.1 生物炭产率

3 种原料在不同热解温度下制备的生物炭产率如表 1 所示. 随着温度升高,产率均呈现递减趋势,苹果枝条、棉秆和杜仲枝条生物炭的产率分别从 37.4%、35.3% 和 29.9% 降低到 30.5%、30.2% 和 26.3%,与孙涛等^[13]和赵伟宁等^[24]的研究结果一致. 低温(<200℃)时,生物质内部以脱水和脱氢反

应为主,随着温度的提高,生物质 3 组分逐渐被分解,其中半纤维素和纤维素主要在 170 ~ 310℃ 范围内热解,木质素在 300 ~ 550℃ 范围内热解^[25]. 进一步提高热解温度,有机组分的化学键发生断裂并重排形成稳定的芳香烃类,使得生物炭产率随温度升高而降低^[26]. 此外,同一温度制备的杜仲枝条生物炭的产率最低,这可能是因为杜仲叶林枝条的木质素和灰分含量低于苹果枝条和棉秆^[27~29]. 因此,当热解温度较低且以苹果枝条为原料时,可获得相对较高产率的生物炭.

2.1.2 生物炭 pH

3 种原料在 400 ~ 700℃ 热解条件下制备的生物炭 pH 均大于 10,且随温度的升高,表现出先增大后减小的趋势,在 600℃ 时达到最大(表 1). 热解过程中,原料中的有机酸随着热解温度的升高发生脱水,同时碱性基团的量不断增加,从而使得生物炭为碱性;温度过高时可能导致一些矿质元素的挥发,使得生物炭 pH 下降^[30]. 同一热解温度下,棉秆生物炭的 pH 最大,苹果枝条生物炭次之,杜仲枝条生物炭最小,这可能与生物炭的灰分含量有关. 有研究发

现生物炭的 pH 与生物炭灰分组成呈正相关关系^[31]. 灰分中的 Na、K、Ga 和 Mg 等元素以碳酸盐或氧化物的形式存在,溶于水后生物炭呈碱性^[32]. 与 XRD 结果一致. 已有研究发现生物炭的高 pH 可能会增加氮肥的挥发^[33]. 因此,低温制备的杜仲枝条生物炭作 BF_s 缓释载体对 NH₄⁺-N 的负效应可能较小.

2.1.3 生物炭的元素组成

热解过程中,随着热解温度的升高,生物质内部逐渐发生脱氧和脱氢反应,致使生物炭的 H 和 O 含量随温度升高而降低,而 C 含量不断增加(表 1). 同时,苹果枝条、棉秆和杜仲枝条生物炭的 H/C、O/C 和(N + O)/C 随热解温度的升高表现出下降的趋势,表明 3 种原料制备的生物炭的芳香性随热解温度的升高加强,极性随温度升高而减弱^[34],这与范世锁等^[35]的研究结果一致. 此外,同一温度制备的杜仲枝条生物炭的芳香性大于苹果枝条和棉秆生物炭,这种稳固的芳香碳结构可以抵抗土壤中微生物的分解,在土壤中持续长达 100 ~ 1 000 a^[8],有利于减缓 BF_s 缓释载体的降解速度.

表 1 生物炭的产率、pH 和元素组成
Table 1 Yield, pH, and element composition of biochars

样品	产率/%	pH	ω/%				H/C	O/C	(N + O)/C
			C	H	N	O			
AB400	37.4	10.33	80.43	2.99	0.59	15.78	0.45	0.15	0.15
AB500	32.3	10.56	82.26	1.51	0.47	15.60	0.22	0.14	0.15
AB600	30.8	10.99	81.84	1.13	0.58	16.33	0.17	0.15	0.16
AB700	30.5	10.82	83.90	0.99	0.58	14.43	0.14	0.13	0.13
CS400	35.3	10.53	68.36	1.79	1.24	28.28	0.31	0.31	0.33
CS500	34.7	10.69	69.05	1.40	1.12	28.12	0.24	0.31	0.32
CS600	32.2	12.10	70.01	1.10	1.14	27.43	0.19	0.29	0.31
CS700	30.2	11.00	72.60	0.99	0.79	25.27	0.16	0.26	0.27
EB400	29.9	10.13	84.48	3.04	0.88	11.50	0.43	0.10	0.11
EB500	27.5	10.30	87.72	2.35	0.73	9.08	0.32	0.08	0.08
EB600	26.9	10.55	88.40	1.98	0.63	8.90	0.27	0.08	0.08
EB700	26.3	10.50	89.16	1.06	0.72	8.96	0.14	0.08	0.08

2.1.4 热重分析

TG 和 DTG 曲线可以表征生物炭的热稳定性. AB、CS 和 EB 经不同热解温度制备的生物炭在 0 ~ 900℃ 内的 TG 和 DTG 曲线如图 1 所示. 所有生物炭的质量损失主要有两个阶段. 第一阶段发生在 200℃ 以下,质量损失较少,这通常与生物炭初始水分的散失有关^[36]. 最大质量损失主要发生在第二阶段,以苹果枝条生物炭为例,AB400、AB500、AB600 和 AB700 分别在 342 ~ 772、524 ~ 687、549 ~ 675 和 557 ~ 681℃ 温度范围内发生严重损失[图 1(b)]. 说明当外界温度低于生物质热解温度时,生物炭具有相对较好的热稳定性. TG 曲线显示热解温度越高,所制备的生物炭热损失越少,热稳定性越好

[图 1(a)]. 苹果枝条和棉秆生物炭的 DTG 曲线峰值所对应的温度均在 630℃ 左右,而杜仲枝条生物炭随着生物炭制备温度的增高,其峰值所对应的温度也越高,总热损失变少[图 1(b)],这与范方宇等^[37]的研究结果一致. 说明 3 种原料制备的生物炭中杜仲枝条生物炭的热稳定性最好,这可能与它们炭化的程度有关.

2.1.5 比表面积与孔隙结构

生物炭的大比表面积和丰富的孔隙结构使其具有强大的吸附能力,能够吸附速效养分,减少养分流失,提高养分利用率^[38]. 不同原料制备的生物炭 BET 比表面积随热解温度的升高先增大再减小(表 2),在 500℃ 时达到最大,具体表现为: EB500

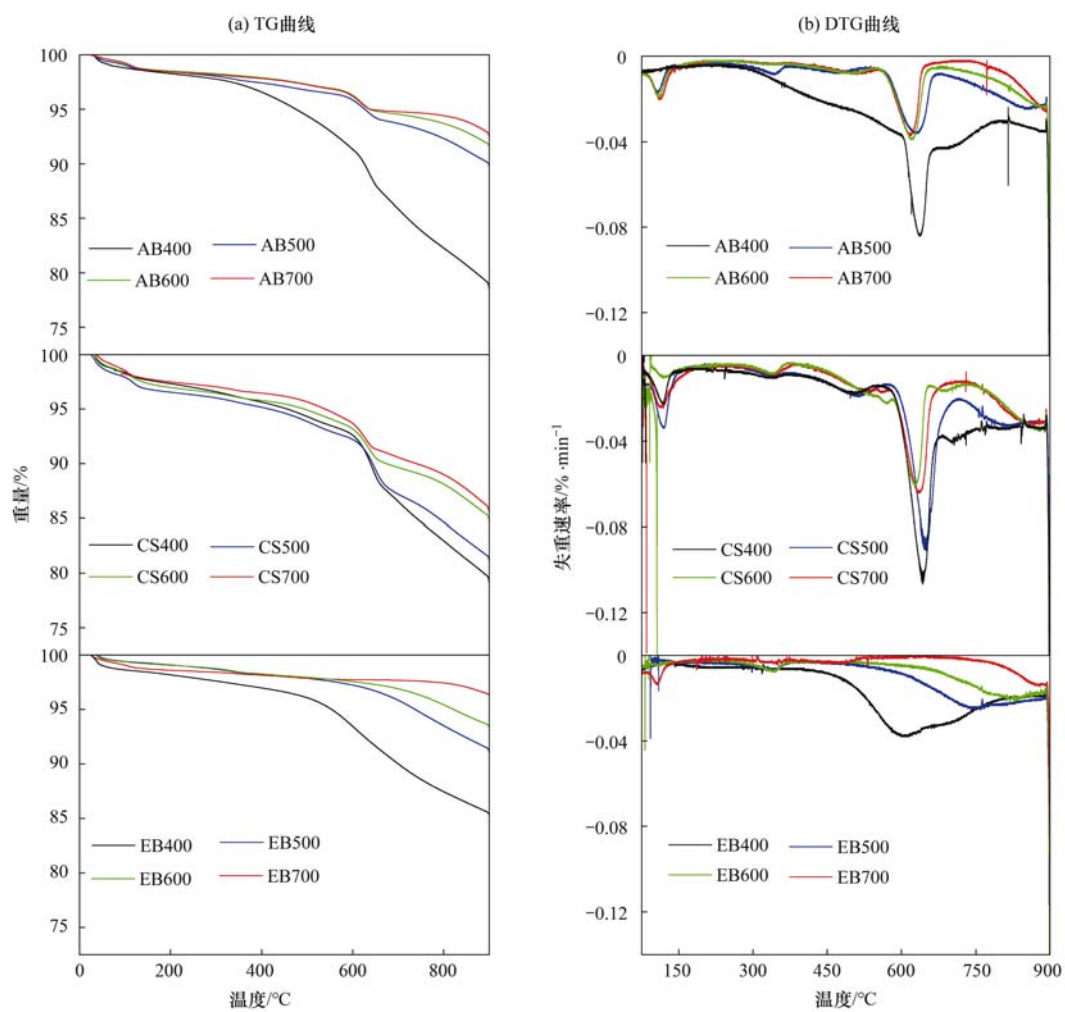


图 1 不同原料和热解温度制备的生物炭的热重分析

Fig. 1 Thermogravimetric analysis of biochars derived from different feedstocks and pyrolysis temperatures

($316.1854\text{ m}^2\cdot\text{g}^{-1}$) > AB500 ($265.2627\text{ m}^2\cdot\text{g}^{-1}$) > CS500 ($107.4491\text{ m}^2\cdot\text{g}^{-1}$). 总孔容随温度变化的趋势与比表面积一致,而孔径正好相反. $400\sim 600^\circ\text{C}$ 热解制备的苹果枝条和杜仲枝条生物炭孔隙结构发达,且孔为中孔;热解温度为 700°C 时,孔为大孔.而 $400\sim 700^\circ\text{C}$ 热解制备的棉秆生物炭的孔多为大孔^[39].当温度介于 $400\sim 500^\circ\text{C}$ 时,生物质中的纤维素、半纤维素和木质素被大量分解,挥发气体释放形成的囊泡破裂,导致小孔数量的增多和比表面积的增大(图 2)^[40].热解温度进一步升高至 $600\sim 700^\circ\text{C}$ 时,维管束遭到严重破坏,出现灰分熔融,部分孔穴坍塌,孔隙结构被堵塞(图 2),使得生物炭的比表面积下降^[41].此外,相比于杜仲枝条和棉秆生物炭,苹果枝条生物炭表面更加粗糙,富含固体颗粒[图 2(a)],主要是生物质中的灰分在生物炭表面富集所致^[42].在 $400\sim 500^\circ\text{C}$ 热解温度范围内,升高温度能够促进生物炭孔隙结构的发育,但过高的热解温度($>500^\circ\text{C}$)会破坏生物炭的孔结构.3 种原料制备的生物炭中,以 500°C 热解制备的杜仲枝条

表 2 不同原料和热解温度制备的生物炭的 BET 比表面积和孔隙特性

Table 2 BET surface area and pore characteristics of biochars produced from different feedstocks and pyrolysis temperatures			
样品	BET 比表面积 / $\text{m}^2\cdot\text{g}^{-1}$	总孔容 / $\text{m}^3\cdot\text{g}^{-1}$	平均孔径 / nm
AB400	114.980	0.086	30.054
AB500	265.263	0.157	23.735
AB600	65.862	0.058	35.280
AB700	15.384	0.031	81.417
CS400	16.400	0.033	80.112
CS500	107.449	0.086	32.185
CS600	31.344	0.052	65.743
CS700	27.278	0.041	59.452
EB400	221.461	0.136	24.573
EB500	316.186	0.179	22.652
EB600	312.597	0.178	22.827
EB700	12.184	0.025	81.896

炭对养分的吸附潜力最大.

2.1.6 傅里叶变换红外(FTIR)光谱分析

不同温度制备的苹果枝条、棉秆和杜仲枝条生物炭的 FTIR 分析如图 3 所示. 3420 cm^{-1} 附近的峰

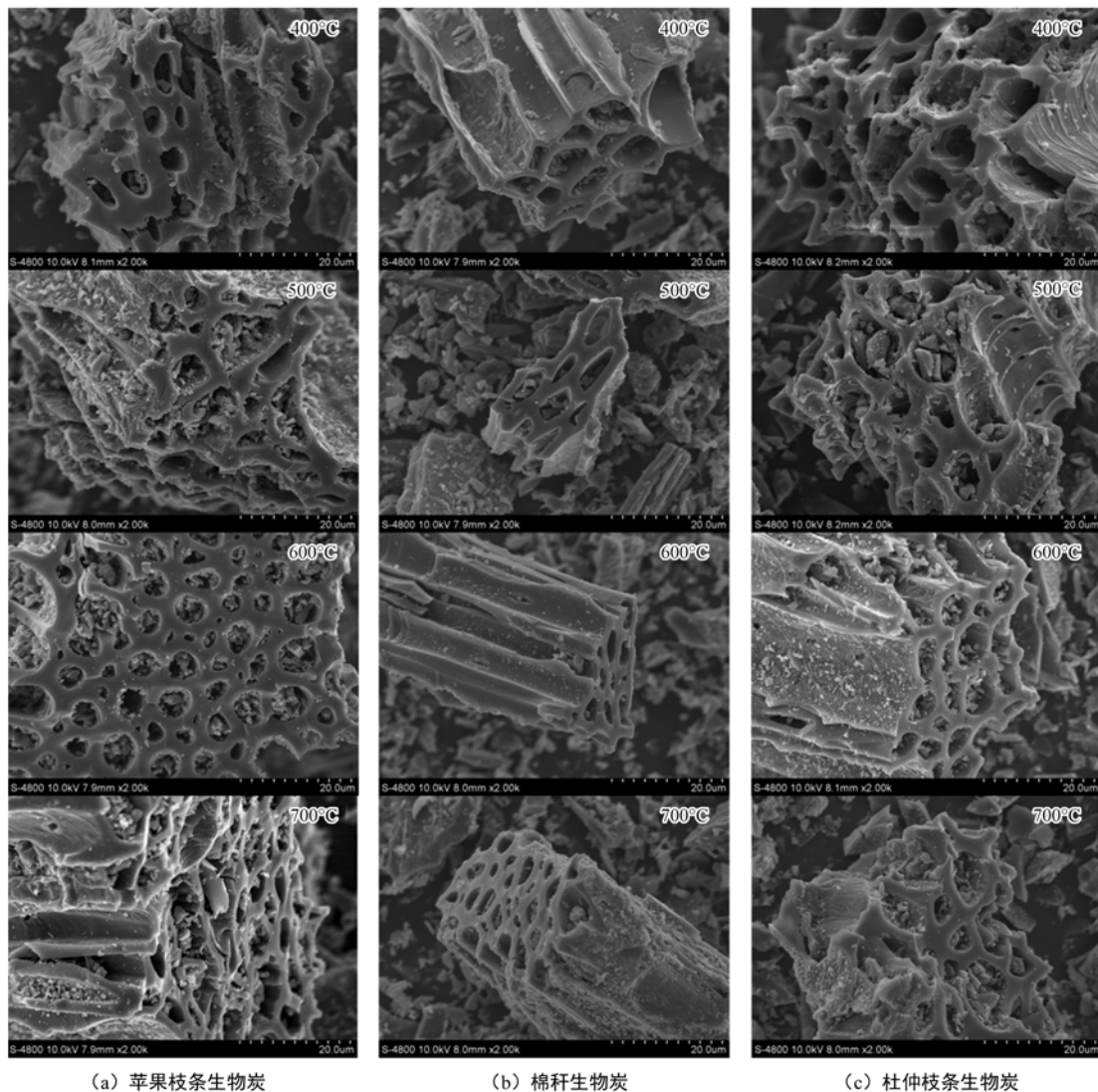


图 2 不同原料和热解温度制备的生物炭的扫描电镜图

Fig. 2 Microscopic scanning of biochars produced from different feedstocks and pyrolysis temperatures

是醇或酚羟基 ($-\text{OH}$) 的伸缩振动引起^[43], 峰强度随着热解温度的升高明显变弱, 且热解温度 $> 400^{\circ}\text{C}$ 时, 相同温度制备的杜仲枝条生物炭的峰强度最强. $1\,669\text{ cm}^{-1}$ 的峰是 $-\text{C}=\text{O}$ 基团的吸收峰, 表明生物炭可能含有羰基、羧基或酯基等官能团^[44], 但 3 种原料在 400°C 热解制备的生物炭的该吸收峰强度较弱, 随着热解温度升高逐渐消失. 有研究发现带正电荷的营养离子 (例如 K^{+} 、 NH_4^{+} 、 Ca^{2+} 和 Mg^{2+}) 可以附着在含有羧基、酚类和醇类官能团生物炭的表面^[45]. 可见, 过高的热解温度不利于带正电离子通过官能团附着在生物炭上. $1\,595\text{ cm}^{-1}$ 左右的峰是芳香烃或苯环的吸收峰^[43], 峰强度随热解温度的升高增强, 说明热解温度越高, 制备的生物炭的芳香性越强, 与元素分析结果一致 (表 1).

2.1.7 X-射线衍射 (XRD) 分析

X-射线衍射光谱可用于研究生物炭内部的结晶物质. 不同热解温度制备的苹果枝条生物炭的 XRD

图谱中能明显地观察到两个较强的峰. $2\theta = 26.6^{\circ}$ 处的衍射峰是石英矿物的特征峰, $2\theta = 29.4^{\circ}$ 处的衍射峰是方解石的特征峰, 这两种峰的锐度和强度随热解温度的变化不大 [图 4(a)]. 棉秆生物炭 XRD 图谱在 $2\theta = 29.4^{\circ}$ 处也出现了很强的方解石特征峰 [图 4(b)], 且随热解温度的升高峰强度缓慢变小, 此外还在 2θ 为 24.2° 和 31.4° 观察到了较强的 KHCO_3 衍射峰, 峰的强度随热解温度的升高先增大后减小, 600°C 制备的峰强度最高. 杜仲枝条生物炭的 XRD 图谱中 [图 4(c)], 未见明显的峰, 说明杜仲枝条生物炭为非晶生物炭. Liu 等^[46] 的研究发现生物炭的灰分组成主要是钾盐、硅酸盐和碳酸钙等矿物. 因此, 苹果枝条和棉秆生物炭含有较高的灰分, 杜仲枝条生物炭灰分含量较低. 有研究表明, 生物炭所含的盐能够提高生物炭对 PO_4^{3-} 的吸附, Al、Fe、Ca 和 Mg 可与 PO_4^{3-} 的静电或配体键形成桥键, 因此, 棉秆和苹果枝条生物炭更有利于负载

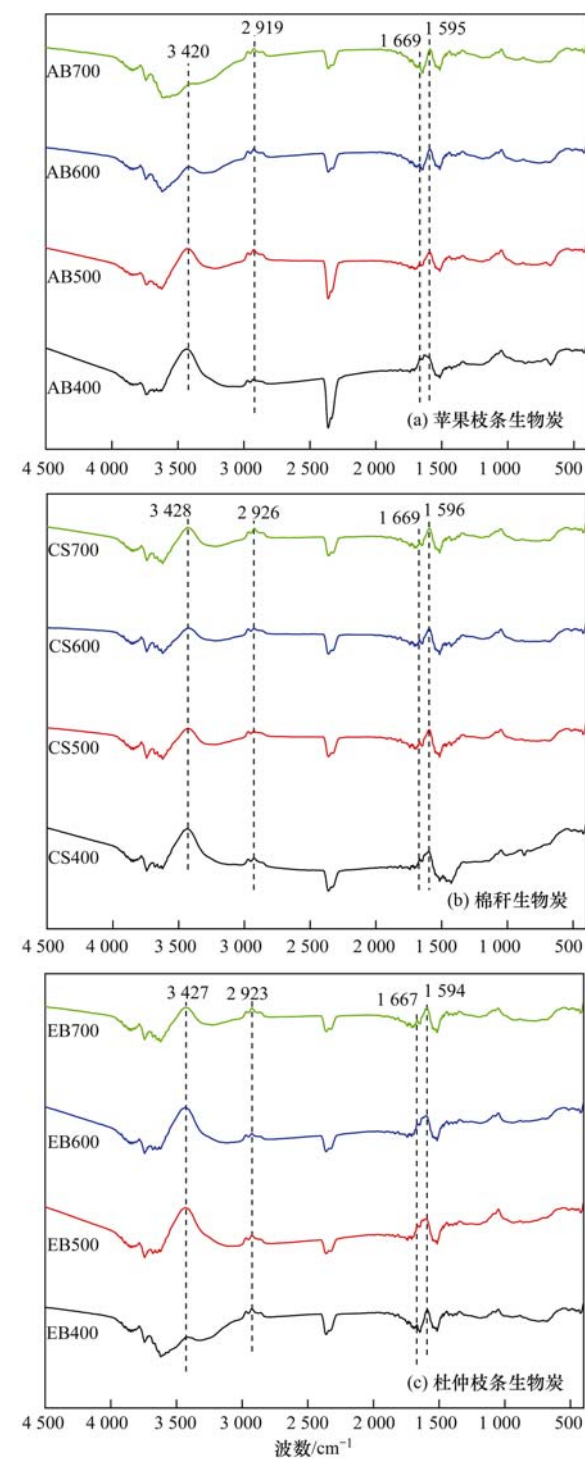


图3 不同热解温度下生物炭的 FTIR 谱图

Fig. 3 FTIR spectrum of biochars produced from different feedstocks and pyrolysis temperatures

PO_4^{3-} [47].

2.2 生物炭作 BF_s 载体的潜力评价

2.2.1 灰色关联分析

灰色关联度被推荐为综合评价的一种衡量标准,可以用来评价不同理化性质的生物炭作 BF_s 缓释载体的潜力^[22]. 高比表面积、高孔容、高 H/C、高含 N 量和低 pH 的生物炭可能适宜作 BF_s 缓释载体^[48]. 因此,基于这 5 个指标计算的不同原料和热

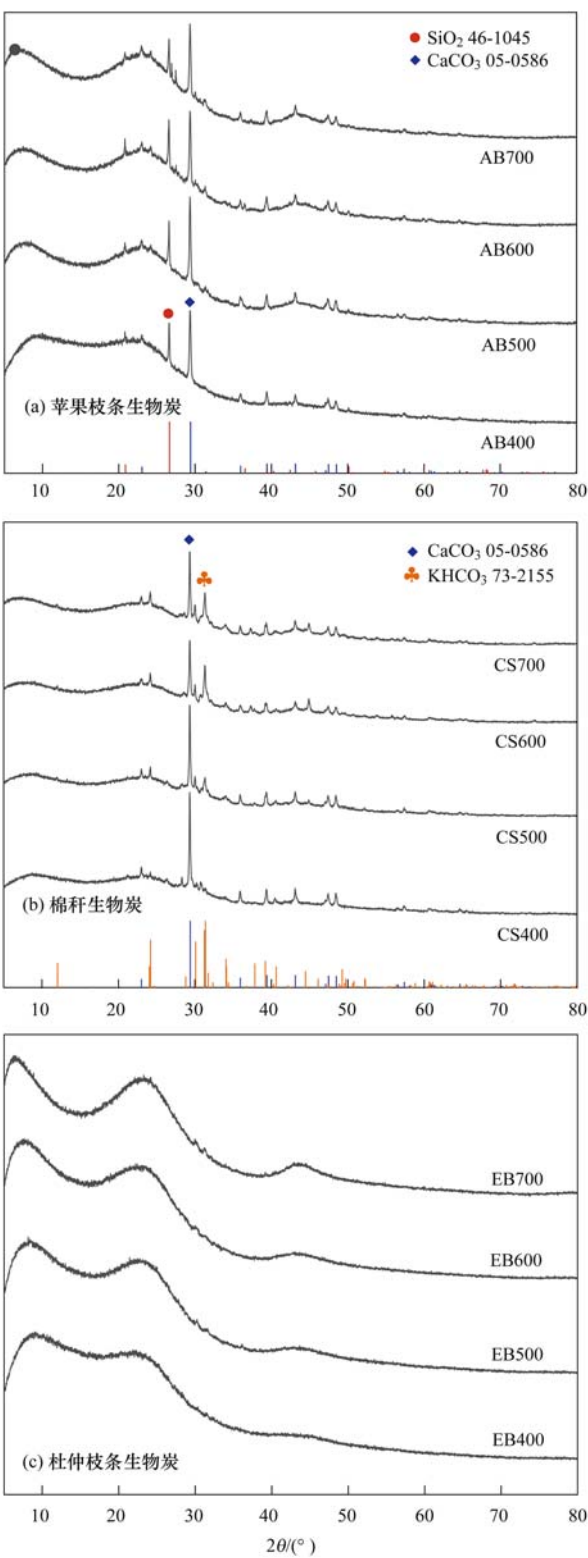


图4 不同热解温度下生物炭的 XRD 谱图

Fig. 4 XRD pattern of biochars produced from different feedstocks and pyrolysis temperatures

解温度制备的生物炭的灰色关联度结果如表 3 所示. 受原料和热解温度影响,不同生物炭的灰色关联度表现出明显差异. 随热解温度的升高,棉秆生物炭的灰色关联度下降; 400 和 500℃ 热解制备的苹果枝条生物炭的灰色关联度相差不大,温度 > 500℃

时,随温度升高而下降.杜仲枝条生物炭的灰色关联度随温度升高先增大后减小,在 500℃ 时达最大.并且当温度 < 600℃ 时,同一温度制备的杜仲枝条生物炭的灰色关联度最大,苹果枝条生物炭次之,棉秆生物炭最小.以上结果说明,作 BF_s 缓释载体时,低温热解制备的生物炭的理化性质优良,且在相同热解温度下,表现为:EB > AB > CS.

表 3 通过 5 个指标得到的不同原料和热解温度制备的生物炭的灰色关联度¹⁾

Table 3 Correlation degree of biochars derived from different feedstocks and pyrolysis temperatures using five indicators

原料	热解温度/℃			
	400	500	600	700
AB	0.670	0.678	0.511	0.493
CS	0.648	0.626	0.553	0.515
EB	0.764	0.826	0.786	0.513

1) 5 个指标:比表面积、总孔容、氮含量、H/C 和 pH

2.2.2 经济评估

将生物炭用作 BF_s 缓释载体时,除要求其具有优良的理化性质外,还需考虑大规模生产的经济可行性,其中生物炭的产率和原料成本是两个极其重要的因素.当热解温度 < 600℃ 时,3 种原料中苹果枝条和棉秆生物炭的产率相对较高,杜仲枝条生物炭产率最低.并且每年杜仲枝条的产量远低于棉秆和苹果枝条,制备生物炭的原料成本较高.在仅考虑生物炭产率和原料成本的情况下,以 500℃ 热解制备的生物炭为例,AB、CS 和 EB 制备 1 t 生物炭的成本约为 557、519 和 1 273 元.可见生物炭生产成本表现为:EB > AB > CS(表 4).

表 4 500℃ 热解制备 1t 生物炭的原料成本

Table 4 Feedstock cost for preparing 1t of biochar via pyrolysis at 500℃

原料	产率/%	原料价格/元	生物炭成本/元
AB	32.3	180	557
CS	34.7	180	519
EB	27.5	350	1 273

3 结论

本研究对不同原料和热解温度制备的生物炭的理化性质进行了表征和灰色关联度分析,并基于其理化性质和生产成本评估了生物炭作 BF_s 缓释载体的潜力.结果表明,升高热解温度不利于生物炭的产率、极性和表面官能团种类,但在 400 ~ 500℃ 热解温度范围内,生物炭的比表面积和总孔容随温度升高而显著增大,且表现为:EB500 > AB500 > CS500.此外,生物炭的热稳定性、芳香性和碱性随热解温度升高增强,相同热解温度下,杜仲枝条炭的热稳定性和芳香性最强,pH 最小.从理化性质角度考虑,低

温制备的杜仲生物炭作 BF_s 缓释载体的性能最优,苹果枝条次之,棉秆最差;从经济效益来看,杜仲枝条制备生物炭的生产成本最高,苹果枝条次之,棉秆最低.综合考虑生物炭的理化性质和生产成本,苹果枝条生物炭作 BF_s 缓释载体的潜力最大.

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