

多源有机固废堆肥对土壤有机质连续体的更新效应

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摘要 土壤有机质(soil organic matter, SOM)是评估土壤质量的核心指标, 对维持农业可持续发展, 调节土壤生态功能及响应气候变化具有重要作用. 系统解析多源有机固废(organic solid waste, OSW)堆肥对SOM的更新效应, 对推动OSW高效资源转化, 促进以功能为导向的精细化堆肥技术的发展, 并指导堆肥-土壤对征利用具有重要意义. SOM的本质经历了腐殖化理论、选择性保存理论和连续体模型的发展. 堆肥可通过3种核心路径更新SOM. 首先是分子组成更新, 堆肥调节土壤中脂质等不稳定化合物和酚类等难降解物质含量, 并通过分子量分馏重构SOM连续体. 其次是微生物群落调控, 堆肥可增强真菌和细菌相互作用网络复杂度, 激活芳香碳降解功能菌, 改变微生物碳泵效率和SOM微生物转化分子组装机理. 最后是功能分子位点更新, 堆肥改变SOM氧化还原和质子络合位点的丰度、化学形态和空间构型, 调节 π - π 共轭系统和电子云密度, 最终影响土壤生物地球化学循环. 未来应从有机质连续体角度全面评估多源OSW堆肥对SOM的分子组成、结构、功能和组装机理的影响及其对温度的响应. 特别需要以微生物碳泵为核心, 量化长时间多源OSW堆肥施用SOM连续体分子动态和稳定性阈值, 为不同类型堆肥固碳潜力评估和对标土壤需求提供依据.

关键词 有机固废, 堆肥土壤利用, 有机质连续体, 微生物碳泵

有机固体废物(organic solid waste, OSW)具有资源和污染双重属性, 其在环境管理和可持续发展中具有重要地位. 目前, OSW资源化利用已成为绿色低碳循环经济发展的重要组成部分, 对于推动全球生态系统的可持续发展具有重要作用. 好氧堆肥技术被广泛认为是实现有多源OSW源头体量削减, 过程资源转化和无害化处理的主要策略之一^[1,2]. 《WHAT A WASTE 2.0》数据显示, 在全球OSW管理中采用堆肥技术的比例约为5.5%^[3], 并且这一比例在我国呈现逐年上升的趋势. 另一方面, 在过去的两个世纪中, 全球农业土壤损失了约133 Pg有机碳, 其中约三分之一的农业土壤退化, 小麦和玉米分别减产60%和32%^[4]. 堆肥产物(以下

简称“堆肥”)的品质和功能对提高土壤的生态功能和服务功能至关重要. 因此, 开发一种与生态服务功能和土壤用途精确匹配的堆肥-土壤对征利用技术已成为农业可持续发展的迫切需求.

堆肥作为一种稳定化和清洁化的天然有机肥料, 富含活性微生物和微生物残体物质^[5-7]. 堆肥土壤利用被视为土壤有机碳再生, 降低化肥需求, 提高作物产量并促进循环农业可持续发展目标转型的有效途径^[8-10]. 然而, 长期的研究发现, 由于堆肥-土壤系统的高度复杂性和可变性, 堆肥土壤利用存在一系列挑战. 首先, 堆肥特性(如碳氮比、碳磷比、pH和电导率)受OSW来源和类型控制, 不同物料堆肥之间存在巨大差异^[11]. 其

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次,堆肥施用后其养分有效性和有机质功能特性(如氧化还原和吸附络合)呈现出显著的土壤依赖性,随土壤生物类群和物理环境差异发生变化,不同来源OSW堆肥养分的生物可利用性及有机质功能分子的有效性差异显著且通常不可预测^[12,13]。因此,不同来源OSW的堆肥品质难以优化,加之多样化和不断变化的土壤管理制度导致堆肥质量与土壤需求难以精确匹配,堆肥通常作为一种通用产品未能满足特定土壤需求^[4]。以上原因导致堆肥在土壤中的应用效果并不理想。

土壤有机质(soil organic matter, SOM)是衡量土壤质量和生态功能的核心指标^[14-16]。1809年, Thaër提出“腐殖质学说”^[17]。德国学者Sprengel^[18]于1826年进一步明确了土壤腐殖酸的概念。1938年, Waksman^[19]系统阐释了腐殖质的起源、化学成分及其重要性。Steven-son^[20]在1994年系统阐释了土壤腐殖质的定义。2011年, Nebbioso和Piccolo^[21]提出“腐殖质组学”。以上理论成为多年来土壤学及相关学科中土壤有机质形成和结构特征的主流观点。近年来,高分辨率质谱等先进技术的发展,为从分子水平深入理解SOM的本质提供了新的视角。2015年, Lehmann和Kleber^[22]提出土壤有机质连续体模型,通过分析微生物产物在土壤中的持留状态及其与生命活动的关联,重新阐释了SOM的本质。2017年, Liang等人^[23]提出了“土壤微生物碳泵”(soil microbial carbon pump, SMCP)的概念,认为微生物激发效应(即微生物加速SOM的分解并促进CO₂排放)和埋葬效应(即微生物代谢产物和残体物质不断累积并形成稳定SOM)之间的动态平衡调节着土壤碳库的稳定。随着对SOM认识的不断深入,多源OSW堆肥对SOM的“更新效应”有待重新评估,同时对堆肥产品的功能与土壤类型的适配性也提出了更高的要求。亟需开展多源有机固废堆肥土壤利用系统研究,探究不同物料堆肥长期施用对SOM微生物转化的影响,全面了解多源有机固废堆肥施用对SOM激发效应和埋葬效应的影响及其对温度的响应。在此基础上,进一步揭示不同物料堆肥施用对SOM功能特性(如氧化还原及吸附络合功能)的影响。以上研究对于推动我国多源OSW资源高效转化,反向预测堆肥品质提升,并指导堆肥-土壤对征利用具有重要意义。

1 土壤有机质本质的发展

在近300年的研究历程中, SOM的本质主要有三种竞争性理论,包括经典的“腐殖化”理论,“选择性保存”

理论和“SOM连续体”模型。以上理论都假设土壤中植物残体和动物残块在分解初期首先被分解成小块碎片^[24-27],而后才能被微生物利用和转化。“腐殖化”理论假设初始分解产物通过微生物介导的次级合成作用转化为分子量较大、具有特定功能结构的深色难降解化合物^[28]。然而,自然生态系统中的腐殖质是由相对较小的异质分子通过范德华力、 π - π 等自组装而成的超分子结构^[29],其本质特性受控于特定人工提取流程(如碱-酸分级法)^[30]。这导致人工提取的腐殖质难以真实表征自然生态系统中原位有机质的完整组成、化学特性及生态功能^[31]。植物残体一直被认为是SOM形成的初始底物。20世纪末,学者们基于植物残体分解研究提出了植物生物聚合物的选择性保存(或优先降解)理论^[32,33]。该理论的核心假设为有机物由易降解和相对难降解化合物组成,后者需待前者被微生物消耗后方可被微生物利用^[34,35]。然而,近年来研究发现,微生物对顽固性物质的分解能力远超既往认知,缩合芳烃、烷烃等高分子化合物,甚至聚乙烯等持久性物质或可被快速优先降解^[36,37]。此外,在大分子木质素的微生物分解过程中发现,木质素在分解初期呈现加速降解现象(可及性较高时),且小分子有机物作为微生物能量源可进一步促进其矿化^[38,39]。

2015年, Lehmann和Kleber^[22]重新审视了SOM真实结构,提出了SOM的连续体模型,认为SOM是不断分解的有机化合物的连续体。微生物通过持续的代谢活动可将碳源不断以代谢产物(胞外聚合物、胞外酶等)和微生物残体(壳聚糖、胞壁酸、几丁质等)的形式转化为SOM的重要组成部分^[31]。SOM的微生物分解与其在团聚体内部的空间分布和物理隔离密切相关。同时,有机质分子与矿物质构成有机-矿物复合体形成物理化学保护,有效阻隔SOM与微生物分解酶的直接接触^[40]。因此, SOM可以被视为一系列异质化合物的集合体,该集合体由处于不同分解阶段的有机分子构成^[41],这些分子同时被包裹于不同粒径团聚体内部或吸附于其表面^[42]。基于有机物质的差异性分解状态以及参与分解的微生物群落特征,分解程度低的生物大分子物质与初期分解阶段的真菌及其残体物质主要在较大粒径团聚体中固存;而充分分解的小分子有机物和后期分解阶段的细菌及其残体则主要聚集于小团聚体中^[22,43]。土壤团聚体的结构异质性可能赋予SOM分子的多样性,进而影响微生物群落划分、种群的多样性及微生物功能多样性^[44]。由于土壤中团聚体是连续分布的,有

机质分子的空间分布及相应地微生物分布也呈现出连续性, 构成了土壤生态系统的整体特征^[22].

2 堆肥对微生物碳泵驱动下的土壤碳循环的影响

2.1 微生物碳利用率

SMCP概念框架强调土壤微生物在土壤有机碳的形成、保存和损失中的关键作用, 提出了微生物的合成代谢和分解代谢与有机质的激发效应和埋葬效应为核心的全新的土壤碳固存理论^[23,45]. 微生物分解代谢导致土壤有机碳损失, 而其合成代谢促进微生物生物量、代谢产物和微生物残体的累积, 从而提升碳固存能力. 尽管微生物对土壤有机质的累积与损失的影响途径复杂多样, 微生物碳利用率(carbon use efficiency, CUE)成为捕捉这些过程平衡的关键指标^[46]. CUE不仅反映微生物在新陈代谢中用于生长与呼吸作用的碳分配^[47], 还被认为SOM储量及其空间变化的最重要预测因子^[48]. 具体而言, 较高的CUE代表了更强土壤碳储存能力, 而较低的CUE表示有机碳主要以CO₂形式损失^[46]. 不同物料堆肥对土壤微生物CUE的影响如图1所示. 一项跨度十年田间管理研究发现, 施用秸秆来源的有机质土壤有机碳含量提升50%~102%, 同时降低SOM的芳香性, 并增强其生物可利用性^[49,50]. 此外, 添加秸秆来源的有机质土壤中氮、磷养分含量分别增加了18%和11%, 微生物增殖和代谢活性增强, 胞外酶分泌显著增加, 这些因素共同促进了微生物的分解代谢与合成代谢, 提高了微生物碳利用率^[50,51], 促进碳累积. 然而, 秸秆来源的有机碳添加也促进原位SOM的激发效应, 70天内累积CO₂排放增加11%, 这在一定程度上限制了土壤有机碳的持续增加^[50]. 基于化学计量平衡的污泥堆肥土壤利用碳动力学研究发现, 9184 kg ha⁻¹的污泥堆肥施用后土壤总碳含量提升12.7%, 但显著降低了土壤微生物CUE, 与原位土壤相比, 施用污泥堆肥的土壤中CO₂排放量增加了22%^[52]. 此外, 长期(6年)施用畜禽粪便堆肥土壤中溶解性有机质(dissolved organic matter, DOM)含量比施用化肥土壤增加54%, 微生物拷贝数(尤其是具有芳香族化合物降解潜力的微生物)增加76%, 显著提高了微生物CUE, 进而促进土壤团聚体的稳定性和碳储存能力^[53]. 另有研究表明, 以海藻和鱼粉为原料的堆肥施用导致土壤有机质和微生物群落之间的营养元素化学计量失衡, 加剧微生物的碳限制,

从而降低土壤CUE^[54]. 上述研究虽为多源OSW堆肥土壤利用的碳泵调控机制研究提供理论基础, 但仍存在一定局限. CUE受到微生物群落特性(生物控制)和外部环境(非生物控制)的共同影响. 具体而言, 微生物群落的组成, 尤其是真菌与细菌生物量比, 微生物底物利用策略和相互作用关系是决定CUE的关键生物因子^[48,55]. CUE还受到土壤养分有效性、水分、温度等多种环境因子的影响^[52,56], 而堆肥引发的土壤微环境的巨大扰动进一步增强了CUE评估的不确定性. 此外, 外源养分的输入可能导致营养限制而显著影响微生物的生长和呼吸, 进而改变其资源的获取利用策略和有机碳稳定化途径^[52]. 因此, 未来的研究需整合代谢组学、宏基因组学和有机质组学等多组学技术, 系统解析微生物的功能基因序列与有机物代谢途径(如纤维素和木质素降解、脂质代谢等)的关联机制, 同时考虑环境因素、微生物与底物的化学计量平衡以及微生物的底物利用策略, 从而更准确的评估多源OSW堆肥在土壤碳储存方面的潜力.

2.2 有机质激发效应和埋葬效应

土壤有机碳库的储量约为大气碳库的2倍, 是陆地生态系统中最大的动态碳库^[57,58]. 土壤碳储量的动态变化主要取决于微生物分解和合成代谢之间的平衡, 即激发效应和埋葬效应的平衡^[59]. 有机质矿化和迭代累积贯穿了微生物的胞内与胞外两条代谢途径, 即体外修饰和体内周转^[60]. 体外修饰是指微生物分泌胞外酶, 促进大分子生物降解与转化的过程, 体现了微生物作为分解者或者加工者的作用^[61]. 体内周转指微生物通过直接摄取小分子物质合成自身生物量, 并经历细胞生长、增殖、死亡及残体生成与积累等迭代循环过程, 体现了微生物作为贡献者的作用^[62,63].

研究发现, 施用堆肥同时刺激了微生物的分解代谢与合成代谢. 施用牛粪和餐厨垃圾堆肥可以有效促进富碳化合物的分解, 提升土壤中溶解性有机碳含量, 同时显著提高脂质物质的微生物利用效率, 促进土壤中丹宁衍生的酚类化合物等难降解有机碳的累积^[64], 20%的牛粪堆肥施用土壤中单宁含量可提高20%以上. 此外, 牛粪堆肥施用还可提高酸杆菌门和放线菌门等微生物丰度, 加速有机物矿化和分解, 促进生态系统物质循环^[65]. 而秸秆生物有机肥可增加稻田土壤生态系统中细菌生物量, 改善微生物群落组成, 提升碳代谢功能多样性^[66]. 此外, 园林废弃物堆肥土壤利用可显著提

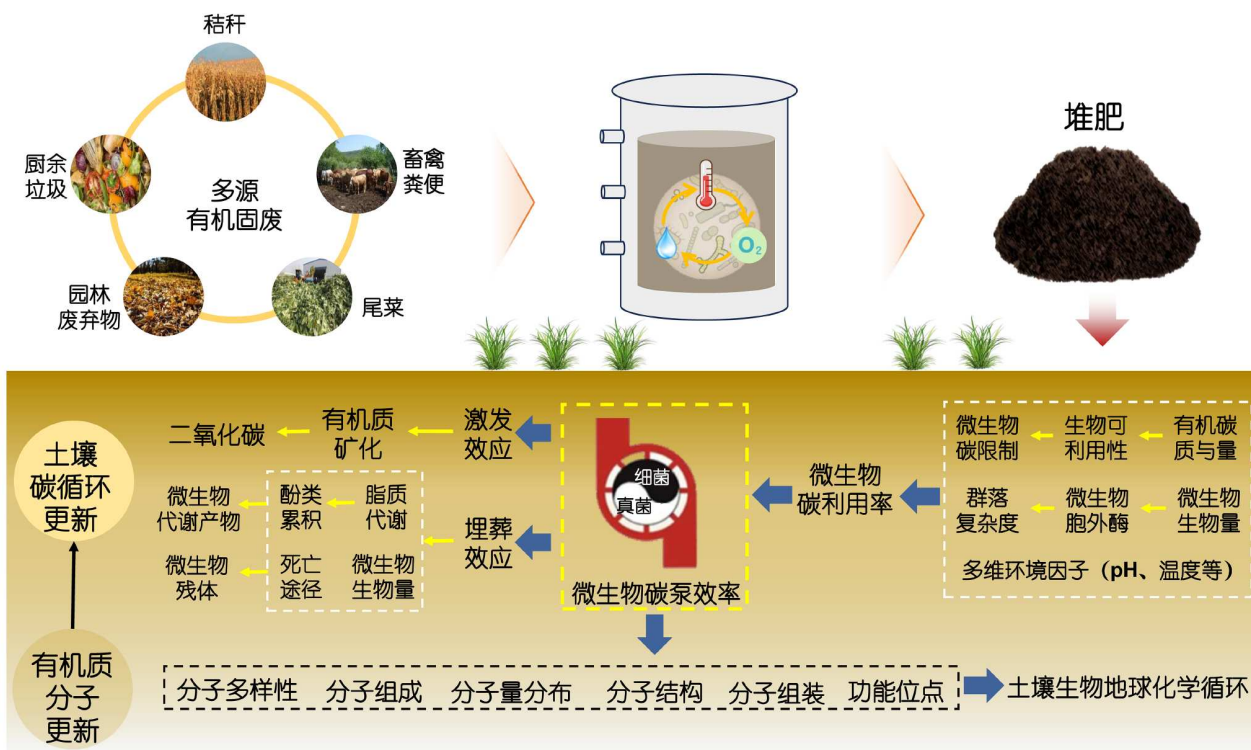


图1 多源有机固废堆肥对土壤有机质的更新

Figure 1 The renewal of soil organic matter by multi-source organic solid waste compost

升盐渍土的有机碳库储量,使有机碳含量增加6.5倍,并通过促进大团聚体的形成增强有机碳库的稳定性^[67]。一项六年的堆肥-土壤田间实验发现,持续的畜禽粪便堆肥输入通过提高土壤微生物可利用碳和溶解性有机碳含量来维持土壤团聚体稳定性和碳固存^[53]。因此,利用不同物料堆肥部分替代化肥可提高农田生态系统中微生物驱动的关键生态服务功能,如土壤团聚体形成和有机碳固持。最新研究表明,在15°C与25°C温度梯度下,经历23年粪肥持续输入的土壤体系中,土壤有机碳顽固性指数下降17%~21%,SOM稳定性降低,并且热敏感型微生物相对丰度下降,微生物群落复杂性和稳定性的增强,同时*Thaumarchaeota*的二氧化碳拦截能力提高,这些变化共同作用,最终减少了因气候变暖导致的土壤有机碳损失^[68]。

尽管堆肥-土壤系统中,有机质激发效应和埋葬效应的研究已取得初步进展,然而长期以来多将有机质看作一个整体进行宏观有机质含量及组成的检测,受到所研究的堆肥种类的限制,对不同物料堆肥施用SOM的动态变化认识不清。SOM组成的复杂性、异质性决定了激发效应和埋葬效应过程的复杂性和多变性。

未来研究亟需从有机质连续体角度出发,全面解析不同物料堆肥施用土壤中有机质组成,包括微生物代谢产物(如胞外酶、胞外聚合物)、微生物残体(如壳聚糖、胞壁酸、几丁质等)、微生物生物量(细菌、真菌)等的动态变化及其对温度的响应。值得注意的是,微生物死亡途径,包括死亡原因和所涉及的生物化学转化,直接决定了残体源土壤有机碳的形成^[69]。堆肥是否会改变微生物死亡途径进而影响土壤有机质激发和埋葬效应,目前并不清楚。

3 堆肥对土壤有机质分子结构及组装机制的影响

3.1 有机质分子组成

DOM是SOM中最活跃的组分^[70],是可通过0.45 μm的可溶性有机物质的一部分^[71]。早期的研究多通过光谱技术揭示DOM的物质组成,将DOM划分为酪氨酸、色氨酸、富里酸、腐植酸和溶解性微生物代谢物等^[72]。随着质谱技术的发展,Fievré等人^[73]首次使用FT-ICR MS分析了天然有机质标准样品的分子组成,由

此展开了在分子层级表征DOM的序幕。DOM是不同类型有机分子的非均质集合,从元素组成来看,以C、H、O为主体元素并含有少量N、P、S元素^[74,75]。Van Krevelen图作为FT-ICR MS数据最主要的可视化方法,通过氢碳比(H/C)和氧碳比(O/C)来区分不同类别的化合物^[76]。DOM可表征为Van Krevelen图上的氨基糖、蛋白质、碳水化合物、木质素、脂质和单宁等^[77,78]。不同物料堆肥对土壤DOM分子组成的影响不同。近期的一项研究表明,施用牛粪和餐厨垃圾堆肥导致土壤DOM中的分子平均C数减少, N和S增加^[64]。此外,堆肥可显著降低DOM中脂质含量,提高酚类化合物及难降解有机碳含量^[64]。在分子层面上关于不同物料堆肥对土壤DOM组成的研究还存在大量空白。

分子量(molecular weight, MW)是有机化合物的内在属性,几乎决定了DOM化学特性和微生物可利用性,直接影响DOM的生物地球化学循环^[29,79]。DOM的组成、结构和反应性在不同的MW范围内存在显著差异^[80,81]。研究发现,DOM的物质组成及其含量与MW存在显著响应关系($P<0.01$),不同分子量DOM的微生物可利用性不同,低MW有机质表现出更强的微生物转化潜力^[82],且不同分子量DOM分子之间存在生物转化,低分子量DOM(<650 Da)可转化为高分子量DOM(>10 kD),同时高MW组分可以作为小分子的储备,在适当的环境条件下释放^[83]。其次,MW控制DOM分子的化学结构,影响DOM的反应特性^[81,84]。不同分子量DOM中烷基、羰基、脂肪族和芳香族等化学结构分布差异显著,大分子量有机质含有更多的芳香族官能团,对土壤中重金属或污染物的氧化还原转化起着重要作用^[81]。当前DOM物质组成研究主要聚焦于200~800 Da范围,这仅反映了其部分特征。实际上,DOM是一个从数百到数万道尔顿的连续分布体系,包含大量异质性化合物。堆肥施用将更新土壤DOM的分子量分布。目前研究范围的局限性导致我们对DOM的分子量分布的认识仍不清晰。分子分级透析是实现DOM在范围更大的分子量区间进行物质分离的有效手段。未来研究需在更广泛的分子量范围内揭示堆肥土壤利用对DOM分子结构的影响。

3.2 有机质分子微生物转化/组装机制

DOM与微生物群落的复杂相互作用机制一直是土壤环境研究的热点。在土壤生态系统中,DOM的分子组成代表了长期历史过程的集体演化结果,这些过程导

致了个体DOM分子的增加、损失和转化^[85,86]。与微生物生态群落的出生率和死亡率相似,DOM分子群落也经历了个体分子的产生和降解速率的波动,以上过程受非生物和生物转化共同驱动^[82]。DOM是微生物代谢和增殖过程中物质与能量的关键来源^[87,88]。微生物不仅可降解DOM分子从而降低土壤溶解性有机碳浓度,影响土壤碳循环^[89],还可通过提高微生物活性和增加真菌细菌生物量导致溶解性残体物质增加,进而导致DOM浓度增加^[90]。目前,DOM与微生物群落互作机制的研究主要通过构建特定溶解性有机物组分与微生物群落的相互作用网络,以识别发挥作用的关键物种并试图解释其转化途径。2018年,元群落生态学理论的初步应用进一步揭示了DOM的化学多样性与微生物群落之间的动力学互作机制^[87],也为识别分子层面的有机质转化提供了有效工具。元群落生态学中的生态位理论与中性理论也已成功用于解析DOM分子组装机理(图2)^[82,91~93]。近期的一项研究为复杂底物的微生物转化分子机制提供了分析框架,涵盖分子化学多样性评估、核心分子识别、关键生化反应分析和生物可降解性评价^[94]。研究发现,微生物作用DOM分子的组装过程受分子量控制。其中,低分子量DOM的组成和装配主要受确定性过程调控,而高分子量DOM则受随机性过程主导^[82]。这种分子量依赖的组装模式与微生物的底物利用策略密切相关,低分子量DOM主要由生物稳定性较低且易被微生物利用的组分构成^[95],因此承受更大的微生物选择压力,表现为确定性过程;而高分子量DOM的转化则依赖于少数特定微生物群(如*Streptomyces*、*Rhodococcus*、*Pseudomonas*、*Bacillus*、*white rot fungi*和*brown rot fungi*)的降解作用^[96]。因此,高分子量DOM的复杂混合体系中官能团的随机结合和取代可能导致无序转化。微生物底物利用策略的差异,不仅决定了微生物对DOM分子的转化方式,也可能通过物质共代谢影响SOM的质与量^[89]。堆肥除更新SOM分子外,对微生物群落也存在显著影响,具体表现为可增加真菌与细菌之间的互作或竞争关系^[97,98],进而影响SOM生物转化组装机理。在全新的分子转化理论框架下,多源OSW堆肥对SOM微生物转化组装机理的影响有待深入研究。

4 堆肥土壤利用有机质分子结构和功能

DOM是土壤中的核心活性物质,包含多种活性反应位点,通过调节土壤中的氧化还原反应、吸附络合

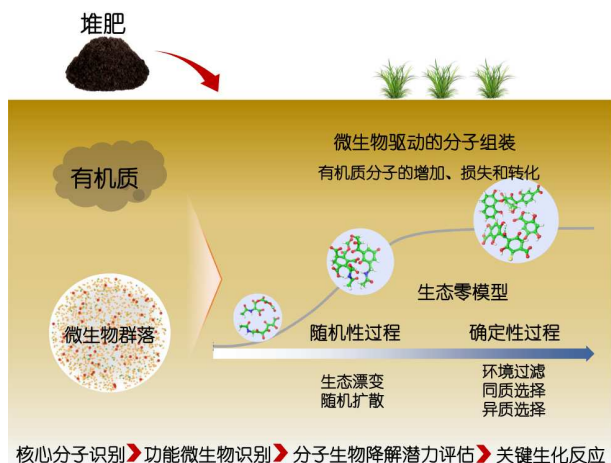


图2 多源有机固废堆肥土壤利用溶解性有机质分子组装概念框架
Figure 2 Conceptual framework of molecular assembly of soil dissolved organic matter with application of multi-source organic solid waste composts

等过程,在生物地球化学循环中发挥着关键作用^[99~101]. DOM的独特之处在于其分子结构中含有多种活性功能基团,使DOM能够在土壤环境中充当电子穿梭体^[102]. DOM的氧化还原电位范围在+0.15~0.3 V之间,这种电位范围的多样性源于DOM中不同分子氧化还原活性单元的本质差异^[64]. DOM中蕴含着不同氧化还原潜力的分子簇,Ar-OH、醌、Ar-SH和Ar-NH₂作为重要的氧化还原活性位点与可旋转键、芳香键、 π 堆积、阳离子- π 和盐桥等共同作用^[64,103],介导微环境中氧化还原反应、金属离子还原以及有机污染物还原降解等过程^[104,105].此外,DOM中丰富的非均质结合点位(图3)^[106,107],可影响重金属及有机污染物的化学形态^[108],迁移转化机制及生物可利用性^[109,110]. DOM和矿物反应造成的有机质分子在固液界面上的分馏是影响有机质稳定性、分子组成和反应特性的关键过程^[109,111].以羧基、羟基为主的酸性官能团发生质子解离后使有机质带有大量负电荷^[112~114],不仅能吸附重金属离子还可与土壤中带正电的金属氧化物(如针铁矿、赤铁矿、水铁矿等)形成复合体,进一步控制有机质在矿物表面的吸附分馏,同时决定DOM与质子和其他金属离子的结合能力^[115].关于DOM氧化还原和吸附络合功能虽已开展广泛的研究,然而长期以来多集中于宏观电子转移能力和吸附解吸能力的观测,缺乏在分子层面对非均质有机质功能特性的理解.

近年来的研究发现,土壤生态系统功能可能取决于堆肥种类、施用剂量及其两者之间相互作用^[97].2023

年,Ye等人^[107]开发了量化评估DOM质子络合位点种类、浓度及其与金属结合能力的统一建模方法.基于24种不同来源的土壤DOM的化学复杂性和Cu²⁺结合能力评估发现,羧基(-COOH)和酚羟基(Ar-OH)是主要的酸性官能团,对Cu²⁺吸附络合稳定具有重要作用.2025年,Ye等人^[116]进一步将智能预测与吸附解析动力学模型结合,预测DOM分子吸附络合位点及其对土壤中铜和镉的释放、吸附解析规律.发现含氧多酚类DOM分子可以像“分子胶水”牢牢锁住Cu²⁺,而脂类成分则加速Cd解离.2025年,Zhao等人^[64]基于维也纳SOM模型(Vienna soil organic matter modeler 2, VSOMM2)结合Schrödinger建模对施用不同来源堆肥的土壤DOM分子进行建模分析,系统评估了不同物料堆肥对土壤DOM分子氧化还原位点和分子间相互作用的影响(图3),发现施用牛粪堆肥显著增加了土壤DOM中吸电子的醌、Ar-COOH和Ar-SH的含量,其中20%(v/v)牛粪堆肥处理的土壤DOM表现出数量更多的吸电子位点.餐厨垃圾堆肥则显著提升了土壤DOM中供电子的Ar-OH和Ar-NH₂的水平,且随着堆肥添加比例的增加(5%~20%),土壤DOM中供电子位点含量显著提高.此外,两种堆肥的施用均不同程度地增强了土壤DOM的可旋转键、芳香键、 π - π 堆积、阳离子- π 和盐桥,且堆肥添加比例越高,分子间相互作用更复杂,进而促进了土壤氧化还原循环^[64].未来研究需结合分子动力学模拟和分子结构建模,从分子层面系统解析多源OSW堆肥对土壤DOM功能特性的影响机制.

5 总结与展望

SOM的本质经历了腐殖化理论,选择性保存理论到有机质连续体模型的发展.SOM的本质为微生物驱动的动态连续的整体.微生物碳泵理论的提出进一步深化了对SOM动态变化的理解,微生物通过体外修饰和体内周转的双重代谢途径共同调控SOM的激发效应与埋葬效应之间的平衡.而多源有机固废堆肥施用通过引入外源有机质并重塑微生物群落结构,显著影响这一平衡.基于已有研究发现,堆肥可通过3种核心路径驱动SOM更新,首先是SOM分子组成更新,堆肥可降低土壤中脂质等不稳定化合物含量并提升酚类等难降解有机质比例,进一步通过分子量分馏重构有机质连续体.其次是微生物群落调控,堆肥通过增强真菌和细菌互作网络复杂度,激活芳香碳降解功能菌,提升微生物碳泵效率,影响有机质微生物转化分子组装.最后是

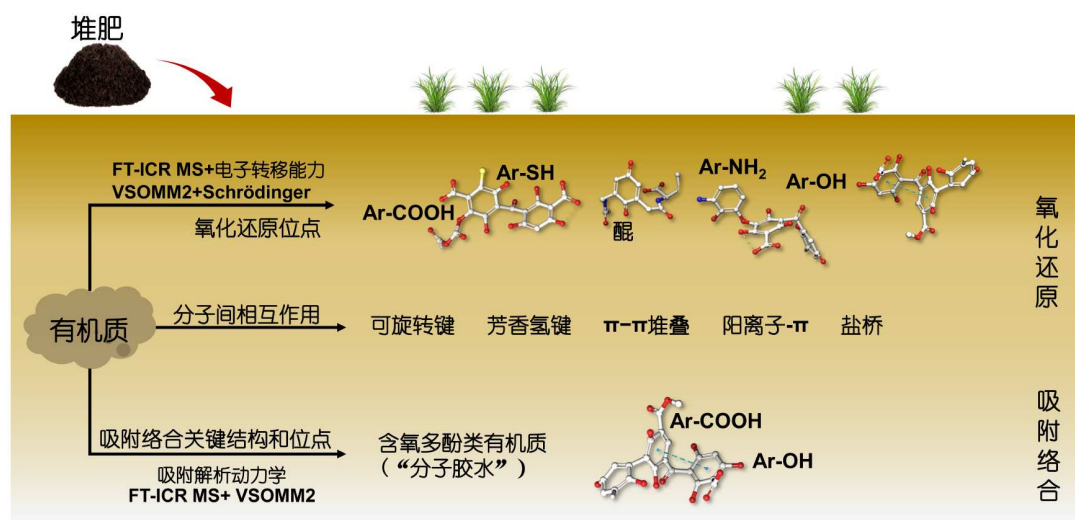


图3 多源有机固废堆肥-土壤利用溶解性有机质环境行为

Figure 3 Environmental behavior of dissolved organic matter in soil amended with composts from multiple organic solid waste sources

功能位点更新,堆肥改变土壤DOM氧化还原活性位点(醌、Ar-OH等)和分子间相互作用(π 堆叠,盐桥等)的丰度、化学形态和空间构型,强化有机质电子转移与吸附络合能力。

然而,研究方法的局限性及长期性、系统性研究的缺乏,现有研究中多源有机固废堆肥对SOM的“更新效应”认识不足,并且对多源有机固废堆肥品质与土壤动态需求的匹配认识不清。存在的主要问题及未来研究包括以下几个方面:

(1) 堆肥-土壤利用研究多集中于宏观有机质含量及组成的观测,并将有机质看作一个整体考虑。然而,受到所研究的堆肥种类的限制,对不同物料堆肥施用SOM的动态变化认识不清。以微生物碳泵理论为指导,从有机质连续体角度全面解析不同物料堆肥施用对SOM组成的影响,包括代谢产物(如胞外酶、胞外聚合物等)、微生物残体(如壳聚糖、胞壁酸、几丁质等)及微生物生物量(细菌和真菌)的动态变化及其对温度的响应是未来研究的重点。

(2) 分子量是DOM的内在属性,显著影响DOM生物地球化学循环。当前DOM物质组成研究主要集中于200~800 Da范围。然而,DOM是一个从数百到数万Da的连续分布体系,包含大量异质化合物。分子量级的局限性阻碍了我们对整体DOM的认知。基于分子分级透析并结合质谱分析,在更广泛的分子量范围内揭示堆肥-土壤利用对DOM分子结构和功能特性的影响极为

重要。

(3) DOM微生物转化直接影响土壤碳循环。目前,DOM分子与微生物群落互作机制的研究主要通过分析特定DOM物质组分与微生物群落的相互作用网络来识别关键物种并试图解释其转化途径。未来研究应基于元群落生态学中的生态位理论与中性理论进一步解析多源OSW堆肥-土壤利用DOM分子的动态变化和微生物转化组装机制。此外,考虑到全球变暖的影响,进一步深入探究温度胁迫下热敏感菌群响应机制及其对微生物碳泵的影响,对于全面了解堆肥对SOM分子动态变化的影响尤为重要。

(4) DOM氧化还原和吸附络合功能特性虽已开展了广泛的研究,然而长期以来多集中于宏观电子转移能力和吸附解吸能力的观测,并且通常将有机质作为一个整体考虑,缺乏在分子层面对非均质有机质功能特性的理解。借助分子动力学模拟和分子结构建模,从分子层面解析DOM结构变化导致的功能特性的改变将为指导堆肥产品的大规模土壤利用和反向预测堆肥品质提升提供理论依据和预测工具。

(5) 解析不同粒级团聚体中微生物和有机质的协同演化特征,并融合机器学习与量子化学计算(如VSOMM2模型)来预测堆肥-土壤系统中DOM分子功能位点对重金属或新污染物赋存形态的调控阈值是未来研究的热点。

上述研究通过解析以微生物碳泵为核心的有机质

分子转化机制、土壤碳库循环、功能分子位点识别与量化, 以期为定向调控堆肥-土壤利用有机质激发和埋葬效应及功能位点形成提供依据, 最终为“双碳”目标下土壤减污降碳协同提供理论指导。

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Summary for “多源有机固废堆肥对土壤有机质连续体的更新效应”

Renewal effects of multi-source organic solid waste compost on soil organic matter continuum

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Conventional agriculture relies heavily on nitrogen-based chemical fertilizer (CF) to facilitate agricultural productivity, which contributes little to soil organic carbon and leads to ecosystem degradation. Compost, which is rich in active microorganisms and microbial residues, contributes to enhanced environmental sustainability by improving soil nutrient availability, stimulating microbial activity, promoting carbon sequestration, and reducing reliance on CF. Soil organic matter (SOM) plays a pivotal role in sustaining agricultural productivity, regulating ecosystem functions, and mitigating climate change. Compost has been proven to increase the content of SOM and modulate the microbial community. The ecological value of compost is primarily determined by its biochemical properties, with the heterogeneity and complexity of organic constituents across various organic solid waste (OSW) sources contributing to the distinct biochemical profiles of compost products. However, composts derived from different OSW are often treated as generic products. The systematic mechanisms by which compost derived from multisource OSW replenishes SOM remain insufficiently understood, limiting the development of precision composting technologies and targeted soil management strategies. Therefore, developing a deeper understanding of how composts derived from various types of biowaste contribute to the renewal of SOM and its ecological functions is essential for guiding scientific fertilization strategies aimed at improving soil quality—which we refer to as a “soil demand-oriented, compost quality-based utilization strategy”.

The conceptual understanding of SOM has evolved through humification theory, the theory of selective preservation, and the continuum model. The proposed microbial carbon pump theory has further improved our understanding of the dynamic changes in SOM. Microorganisms regulate the balance between the priming effect and the burial effect of SOM through dual metabolic pathways: extracellular modification and intracellular turnover. On the basis of the SOM continuum model, this study systematically elucidated how multisource OSW composts alter SOM by reshaping molecular composition, microbial dynamics, and functional site renewal. The first process involves molecular composition renewal, whereby compost modulates the levels of labile compounds, such as lipids, and recalcitrant substances, such as phenolic compounds, in the soil, thereby reconstructing the SOM continuum through molecular weight fractionation. The second process is microbial community regulation, where compost enhances the complexity of fungal–bacterial interaction networks, activates aromatic carbon-degrading functional bacteria, and alters microbial carbon pump efficiency and the molecular assembly mechanisms of SOM. The third process is functional molecular site renewal, in which compost changes the abundance, chemical forms, and spatial configuration of redox and proton complexation sites in SOM; thus, regulating π – π conjugation systems and electron cloud density, ultimately affecting soil biogeochemical cycles. Future research should comprehensively assess the effects of multisource OSW compost on the molecular composition, structure, function, and assembly mechanisms of SOM from an organic matter continuum perspective, as well as their temperature responses. Molecular weight is an intrinsic characteristic of SOM and plays a significant role in influencing its biogeochemical cycling. The integration of molecular fractionation dialysis with mass spectrometry analysis is crucial for elucidating the effects of compost application on the molecular composition and functional properties of SOM across a broad range of molecular weights. By integrating molecular dynamics simulations with molecular structure modeling, this approach enables the analysis of functional characteristic changes induced by structural variations in SOM at the molecular level, thereby providing a theoretical foundation and predictive tools for guiding the utilization of compost soil and forecasting improvements in compost quality. In particular, quantifying the molecular dynamics and stability thresholds of the SOM continuum under long-term, multisource OSW compost application with the microbial carbon pump as the core is necessary to provide a basis for evaluating the carbon sequestration potential of different types of compost and matching soil demands.

organic solid waste, compost soil application, organic matter continuum, microbial carbon pump

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