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沼液还田对土壤-作物系统重金属累积的影响：Meta分析

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摘要：为探讨沼液还田方式、还田时长和重金属带入量等对土壤-作物重金属累积的影响，明确重金属累积影响因素的重要性，对41篇文献和1 972对数据进行整合分析. 结果表明，单施沼液使土壤As、Cd、Cr、Cu、Zn和作物As、Cr的累积显著提高20.5%、15.2%、25.6%、18.7%、26.3%和14.6%、39.5%，对作物其它重金属累积作用不明显. 沼液与化肥混施可显著提高8.05%和4.70%的土壤Cr和Zn的累积且降低作物对As的累积. 相关分析表明，土壤As、Cd和Cr的累积速率与沼液还田时长和土壤有机质（SOM）含量呈极显著正相关（$P<0.01$），相关系数分别为0.30、0.15、0.13和0.22、0.27、0.22，而与土壤pH值呈极显著负相关（$P<0.01$），相关系数分别为0.16、0.13和0.11. 沼液还田带入的重金属会促进土壤As、Cd、Cr和作物As、Cd、Cr、Zn的累积，而土壤Cd、Cu和Zn的累积又会促进作物Cd、Cu和Zn的累积，其间相关系数分别为0.45、0.58和0.42. 因子重要性分析表明，沼液还田对土壤-作物系统中重金属累积的主要因素是还田时长、SOM和土壤pH值.

关键词：沼液；还田；土壤；作物；重金属
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Effect of Biogas Slurry Return to Field on Heavy Metal Accumulation in Soil-crop System: A Meta-analysis

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Abstract: To investigate the effects of biogas slurry return-to-field methods, the duration of biogas slurry return to field and the amount of heavy metals brought in from biogas slurry on the accumulation of heavy metals in soil-crop systems, and the importance of factors influencing heavy metal accumulation, 41 papers and 1 972 pairs of data were integrated and analyzed. The results showed that the application of biogas slurry alone significantly increased the accumulation of As, Cd, Cr, Cu, and Zn in soil and As and Cr in crops by 20.5%, 15.2%, 25.6%, 18.7%, and 26.3% and 14.6% and 39.5%, respectively, and it had no significant effect on the accumulation of other heavy metals in crops. The combined application of biogas slurry and chemical fertilizers significantly increased the accumulation of soil Cr and Zn by 8.05% and 4.70% and decreased the accumulation of As by crops. Correlation analysis showed that the accumulation rates of soil As, Cd, and Cr were highly significantly and positively correlated ($P<0.01$) with the duration of biogas slurry return to field and soil organic matter (SOM) content, with correlation coefficients of 0.30, 0.15, and 0.13 and 0.22, 0.27, and 0.22, respectively; they were highly significantly and negatively correlated ($P<0.01$) with soil pH, with correlation coefficients of 0.16, 0.13, and 0.11, respectively. The heavy metals brought in by biogas slurry return to field promoted the accumulation of As, Cd, and Cr in soil and As, Cd, Cr, and Zn in crops, whereas the accumulation of Cd, Cu, and Zn in soil promoted the accumulation of Cd, Cu, and Zn in crops, with correlation coefficients of 0.45, 0.58, and 0.42, respectively. The main factors of heavy metal accumulation in the soil-crop systems were the duration of biogas slurry return to field, SOM, and soil pH.

Key words: biogas slurry; return to field; soil; crops; heavy metals

沼气工程作为畜禽养殖业的配套设施，既可利用畜禽粪便产气提供大量能源，又可将其沼液、沼渣等副产物还田利用[1]. 沼液作为粪便厌氧发酵所得到的液态混合物，含有丰富的N、P等营养元素和氨基酸等微生物代谢产物[2,3]. 沼液还田不仅能改善土壤理化性质、提高土壤肥力、增加作物产量，还可以减少化肥的使用[4,5]. 然而，重金属在养殖过程中随着饲料的添加进入畜禽体内，再通过粪便排出，造成大量重金属（As、Cd、Cr、Cu和Zn等）富存于沼液中[4,6,7]. 许多研究报道了沼液还田会导致土壤中重金属含量的累积，进而增加土壤重金属污染风险[2,8,9]. 同时，沼液中含有大量溶解性有机质，长期施用沼液会降低土壤结合重金属的能力[10]，增强重金属在土壤和作物中的迁移性[11]，从而使得土壤重金属更容易被作物吸收利用，最后通过食物链进入人体造成健康危害[12,13]. 因此，沼液安全利用是可持续畜牧业养殖和循环农业的关键. 关于沼液

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还田方式对于土壤和作物重金属累积影响的报道发现,沼液与化肥混施提高了作物中的 Cu 累积[14],相比于沼液单施,沼液与化肥混施降低了作物中重金属 As、Cu 和 Zn 的累积[15]. 高杰云等[16]研究发现,与沼液单施相比,沼液与化肥混施增强了土壤重金属 Cr 的累积,而有研究却显示出与之相反的现象[17]. 一项为期 8a 的田间试验发现长期施用沼肥显著增强了稻田土壤和作物中重金属 Cd 的累积[18],也有学者发现长期沼液灌溉没有对土壤重金属 Cd 含量的累积造成影响,却导致了作物中重金属 Cd 的含量提高[1]. 对于沼液短期灌溉下的稻田土壤和作物的研究发现,其重金属含量并无显著差异[19],但有研究显示沼液短期灌溉下土壤和作物中重金属 Cd 和 Zn 含量显著增加,其含量平均值超过了我国污染限制[20]. 另外,Wan 等[21]发现施用禽粪便提高了水稻土中 Cd 和 Pb 的含量,降低了水稻籽粒中 Cd 和 Pb 的含量. 施用沼液对于不同土地利用类型下所种植的作物重金属含量影响也有差异,有研究报道沼液施用下的小麦籽粒中 Cd 含量显著增加,而水稻籽粒中 Cd 含量并无显著变化[1]. 目前存在许多关于沼液还田对土壤和作物重金属累积影响的报道,但关于沼液还田方式、土地利用类型、还田时长、土壤性质和重金属带入量等因素对于土壤-作物重金属累积影响仍不清楚.

为此,本文拟对沼液还田下土壤-作物系统中重金属含量已发表数据进行整合分析,探究沼液还田方式、还田时长、土地利用类型、土壤性质和重金属带入量对土壤和作物重金属含量变化的影响,同时分析重金属带入量、土壤重金属含量和作物重金属含量变化的相关关系,最后通过因子重要性分析明确土壤和作物重金属累积的重要影响因素,以期为沼液还田安全利用提供参考依据.

1 材料与方法

1.1 数据收集

通过"中国知网"与"Web of Science"两个数据库检索了截至 2022 年 4 月发表的经同行评议相关论文. 在搜索文献时,研究使用了以下关键词:沼液(biogas slurry; anaerobic digest)、土壤(soil)、作物(crop)、重金属(heavy metal; As、Cd、Cr、Cu 和 Zn). 纳入整合分析中的研究必须满足以下标准:①数据来自大田试验且研究区域内没有工业污染. ②试验处理至少应包含单施沼液、混施沼液与化肥和不施肥(CK)等 3 种情形. ③各处理应有明确的施氮量或沼液重金属量. ④舍弃无作物,或无土壤 pH 值、有机质的研究. ⑤表层土壤和作物中 As、Cd、Cu、Cr 和 Zn 含量中至少有一个目标变量被量化. ⑥同一地点和同一年限中所观测到的数据只纳入一次,避免数据叠加和权重加大.

数据提取时采用 GetData 2.2 软件用来识别图片中的数值; 由于部分研究没有报道变量的标准差(standard deviation, SD),将给定值的 10% 作为 SD[22],对应于数据库中各自给定的 SD 均值. 基于以上标准,总共筛选出 41 篇经同行评议文献以及 1 972个相关数据对用于整合分析,其中 8 篇来自 Web of Science,33 篇来自中国知网.

1.2 数据分析

通过还田方式、还田时长(土壤施用沼液开始至研究结束所用时间)和重金属带入量(沼液还田带入土壤的重金属量)对沼液还田下土壤和作物重金属累积的影响进行评估,为了满足最大程度的组内均质化,还田方式分为沼液单施和沼液与化肥混施,土地利用方式分为旱地和水田. 沼液还田对变量(X)的影响通过自然对数进行量化,以表示响应比(lnRR),其计算公式如下[23]:

$$\mathrm{ES} = \ln\mathrm{RR} = \ln(X_e / X_c) \quad (1)$$

式中, X_e 和 X_c 分别表示变量 X 的处理组和对照组(不施肥)的均值. 为了更好地显示变量的响应大小,将响应比值转化为百分数形式[(RR - 1) × 100%][22],其中,百分数为正值时表示在沼液施用条件下目标变量增加,反之减小.

采用 Metawin 2.1 软件进行随机效应 Meta 分析,加权平均效应值和偏差矫正的 95% 置信区间(CI)是通过 bootstrapping 过程产生的. 经过5 000次迭代[23],得到效应值 95% 置信区间. 计算公式如下:

$$\omega = \left[\frac{S_e^2}{n_e \times X_e^2} + \frac{S_c^2}{n_c \times X_c^2}\right]^{-1} \quad (2)$$

$$\mathrm{meanES} = \left(\sum_{i=1}^{j} \omega_i \times \mathrm{ES}_i\right) \Big/ \sum_{i=1}^{j} \omega_i \quad (3)$$

$$S(\mathrm{meanES}) = \left(\sqrt{\sum_{i=1}^{j} \omega_i}\right)^{-1} \quad (4)$$

$$95\%\,\mathrm{CI} = \mathrm{meanES} \pm 1.96 S(\mathrm{meanES}) \quad (5)$$

式中, S_e 和 S_c 分别表示处理组的标准差和对照组的标准差; n_e 和 n_c 分别表示处理组和对照组样本量; ω 表示权重; meanES 表示权重响应比; S(meanES)为 meanES 的标准误.

如果 95% 置信区间没有与 0 相交,则认为沼液还田对目标变量(X)促进或抑制效果显著. 通过分类随机效应分析比较了沼液还田方式对土壤和作物重金属含量影响的效应大小. 经卡方检验 $P < 0.05$,

则认为各组间变量的效应值均数有显著差异. 同时运用 SPSS 26 软件分析沼液重金属带入量、土壤重金属和作物重金属变化效应值的相关性. 运用 Origin 2018 软件在沼液还田时长对土壤重金属变化效应值进行线性拟合.

1.3　重金属影响因子重要性分析

依据袋装决策树算法以及多元无序回归理论，利用 Matlab 2016 软件实现土壤和作物(蔬菜、谷物)重金属累积的影响因子重要性分析. 影响因子的重要性程度越高,其数值越大. 模型拟合度(R^2)越高表示重要性分析结果越可靠. 其表达公式如下：

$$y = k_0 + k_1x_1 + k_2x_2 + \cdots + k_7x_7 \tag{6}$$

式中，x_1、x_2、x_3、x_4、x_5、x_6 和 x_7 分别表示施肥方式、作物种类、土地利用方式、土壤 pH、沼液还田时长、SOM 和重金属带入量，k_1、k_2、k_3、k_4、k_5、k_6 和 k_7 分别为对应变量系数，k_0 为常数项. 其中,将土地利用方式(水田和旱地)、施肥方式(单施和混施)和作物类型(蔬菜和谷物)进行赋值,利用袋装决策树算法将变量与效应值进行多元回归拟合.

2　结果与讨论

2.1　还田方式和土地利用类型对土壤-作物重金属累积的影响

沼液还田方式对土壤中 5 种重金属含量的影响均达到了显著水平[$P < 0.05$,图 1(a)]. 沼液单施明显促进了土壤重金属的累积,这与之前研究的结果一致[18,24~26]. 土壤 As、Cd、Cr、Cu 和 Zn 含量分别提高了 20.5%、15.2%、25.6%、18.7% 和 26.3%,这可能是由于沼液中的大量重金属导致. 沼液混施使土壤中 Cr 和 Zn 含量分别提高 8.05% 和 4.70%,而 As、Cd 和 Cu 含量变化具有异质性,说明相对于沼液单施,沼液混施能够在一定程度上降低土壤对重金属的累积. 同样,施肥方式对于作物中 As 和 Cr 的含量的影响显著[$P < 0.01$,图 1(c)]. 沼液单施对作物中 As 和 Cr 的累积分别提高 14.6% 和 39.5%. 有研究显示,在不同的蔬菜系统中,沼液灌溉使其 Cr 含量超过参考标准,其中苋菜中 As 含量最高[27],表明沼液灌溉会促进作物对 As 和 Cr 的吸收和累积,这与分析结果一致. 而沼液混施对作物 As 的累积具有一定抑制作用,效应均值为 -26.1%. 这是因为沼液与化肥混施会提高土壤中有效磷的含量[28],而土壤有效磷磷能有效地抑制作物对 As 的累积和吸收,减弱 As 对作物的毒性[29]. 其次,磷与 As 在作物细胞中的竞争吸附行为会降低作物对 As 的吸收和转运能力[30].

土地利用类型对土壤重金属累积影响显著[$P < 0.05$,图 1(b)]. 水田中 As、Cd 和 Cr 累积效应值分别为 28.1%、20.7% 和 32.9%,而旱地效应值分别为 14.4%、10.6% 和 19.5%,这说明与旱地相比,沼液的施用对于水田土壤 As、Cd 和 Cr 累积效应更为明显. 这主要是在淹水条件下,土壤氧化还原电位下降,在厌氧微生物和有机质、铁锰氧化物等的作用下,使得土壤对重金属的固定能力增强[21,31,32],从而使得土壤重金属的累积效应增强. 土地利用类型对于沼液还田过程中土壤 Cu 和 Zn 含量的变化具有异质性. 而其对于作物中 Cu 和 Zn 含量的变化具有显著差异[$P < 0.01$,图 1(d)]. 沼液还田使旱地作物中 Zn 含量提高了 28.6%,高于水田(17.3%),而水田作物中,Cu 含量提高了 81.9%,远高于旱地(24.5%). 有研究显示,沼液长期灌溉的小麦中 Zn 含量的增加高于水稻中 Zn 含量的增加,而 Cu 在水稻中含量的增加高于小麦中 Cu 的增加[1],这与本研究的结果一致.

2.2　沼液还田时长和土壤有机质、pH 值对土壤重金属累积的影响

沼液还田时长对于土壤 As、Cd 和 Cr 含量均具有显著影响[$P < 0.01$,图 2(a)、图 2(d)和图 2(g)]. 其中,As、Cd 和 Cr 的累积效应值随着沼液还田时长的增加呈现递增趋势,表明沼液还田时长的增加会提高土壤中这 3 种金属的累积量. 有研究显示,长期施用沼液会导致土壤中重金属的累积[18], Duan 等[24]研究也发现施用沼液第 2 年土壤中的重金属比第 1 年显著增加,这与分析结果一致.

土壤有机质(SOM)含量对于土壤 As、Cd 和 Cr 累积具有显著影响[$P < 0.01$,图 2(b)、图 2(e)和图 2(h)]. SOM 含量与土壤 As、Cd 和 Cr 累积效应具有正相关性,表明 SOM 含量越大,土壤 As、Cd 和 Cr 的累积量越高,这与先前所报道的结论一致[33,34]. 这是因为土壤中含有的有机质可以通过吸附和与腐殖质形成了稳定的复合物从而增强了土壤对重金属的吸附能力[27,35,36]. 而对于 Cu 和 Zn 而言,SOM 含量对其在土壤中的累积并不显著,且相关性较低[图 2(k)和图 2(n)],这可能是因为 SOM 是以可交换性形式保留重金属的能力的主要贡献者,随着 SOM 含量的提高,作物对土壤重金属的利用率也随之增加[37],作物对 Cu 和 Zn 的大量吸收与土壤固定和吸附 Cu 和 Zn 的行为共同作用所导致.

土壤 pH 值对土壤 As、Cd、Cr、Cu 和 Zn 含量累积均有着显著影响[$P < 0.05$,图 2(c)、图 2(f)、图 2(i)、图 2(l)和图 2(o)]. 土壤中的 As、Cd 和 Cr 含量累积变化效应值与土壤 pH 值具有负相关性(相关系数分别为 0.16、0.13 和 0.11),表明在一定

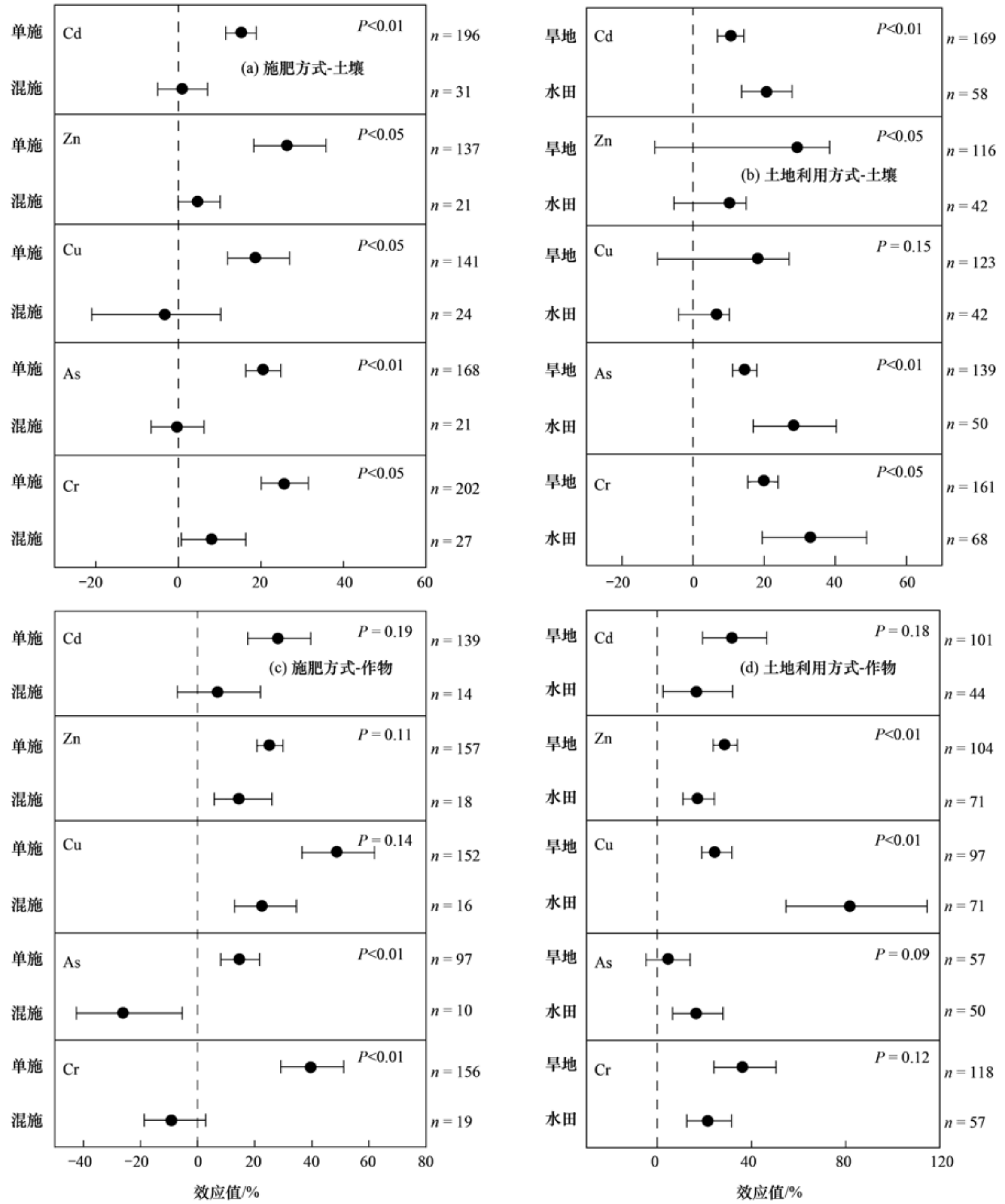


图 1 还田方式和土地利用方式对土壤重金属累积的影响

Fig. 1 Effects of methods of biogas slurry return to field and land use practices on soil heavy metal accumulation

pH 值范围内,土壤 pH 值越大,土壤重金属相对累积量越低. 一方面可能是因为随着 pH 值的提高,土壤对于重金属的保持和固定能力随之提高[37],前人研究发现,土壤中 As、Cd 和 Cr 的含量与 pH 值呈正相关[27],因此土壤受到外界影响的(大气沉降和灌溉水等)差异性降低; 另外,在一定条件下,随着土壤 pH 值的提高,土壤中的溶解性有机质含量也会随之增加[38],与之结合的土壤重金属的流动性和迁移性增强,使植物更容易从土壤中吸收重金属. 而 As、Cd 和 Cr 在其综合作用下导致累积量减小. 尽管土壤 pH 值与土壤 Cu 和 Zn 的累积相关系数较低,分别为 0.03 和 0.07,但仍显现负相关趋势.

2.3 沼液重金属带入量对土壤-作物系统重金属累积的影响

沼液中含有大量重金属,还田过程中会附带其进入土壤,导致土壤重金属含量提高[27]. 有研究证实,这与带入土壤的重金属的量相关[39,40],通过对沼液还田量和沼液中含有的对应重金属含量计算得出沼液重金属带入量. 分析结果显示,重金属带入量与土壤 As、Cd 和 Cr 含量的变化呈现出显著正相关

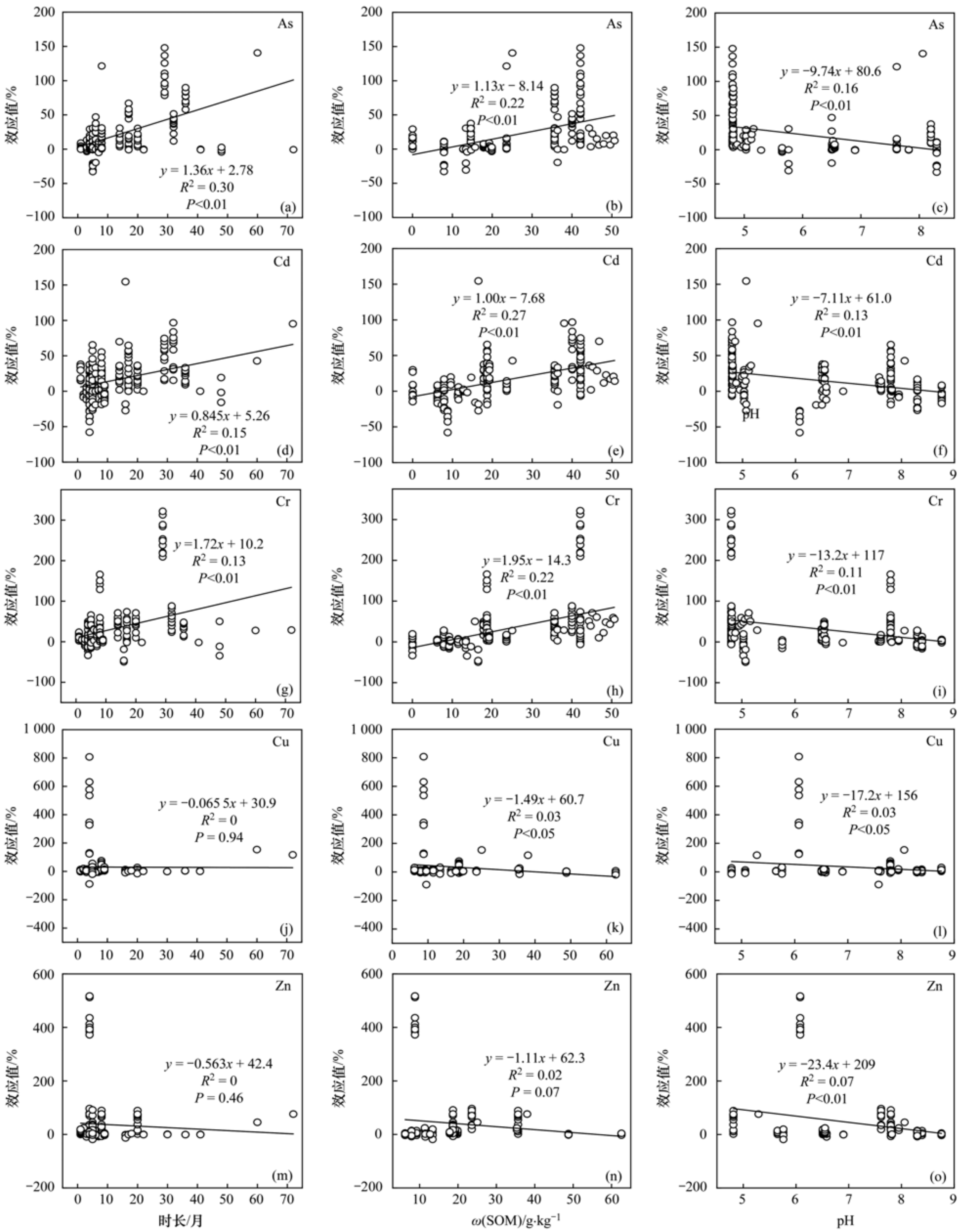
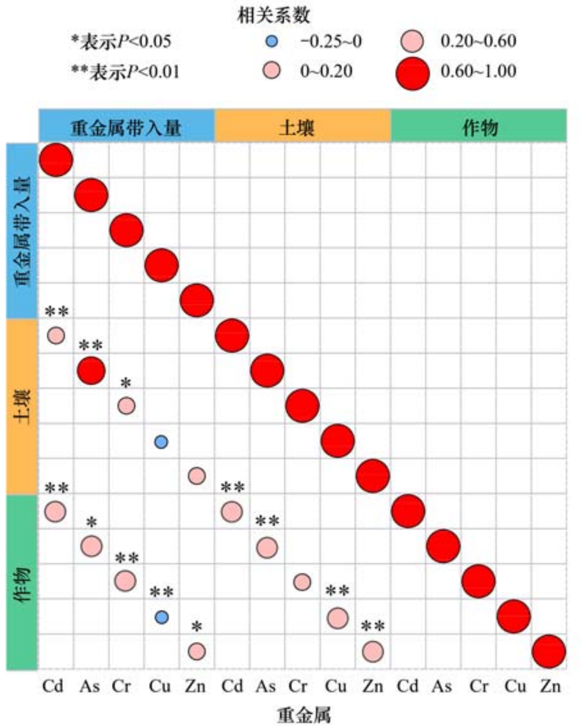


图 2　沼液还田时长、SOM 和土壤 pH 值对土壤重金属累积的影响

Fig. 2　Effects of duration of biogas slurry return to field, SOM, and soil pH on the accumulation of heavy metals in soil

($P < 0.05$，图 3)，相关系数分别为 0.60、0.20 和 0.17，说明沼液 As、Cd 和 Cr 带入量的增加会促进土壤 As、Cd 和 Cr 的累积. 而沼液还田时长的增加会导致沼液重金属带入量的增加，这与上述还田时长的增加与土壤中 As、Cd 和 Cr 累积量呈正相关性的结论一致；对于土壤 Cu 和 Zn 影响并不显著($P = 0.54$，$P = 0.17$)，这同样与上述分析结果一致. 可能由于 Cu 和 Zn 是作物所必须的营养元素[41]，土壤中沼液重金属的输入与作物的大量吸收相互作用，对土壤中 Cu 和 Zn 的累积产生了一定的影响.



计算相关系数时,土壤和作物中重金属累积程度均用响应比表示

图 3　沼液重金属带入量对土壤-作物系统重金属累积的影响

Fig. 3　Effects of the amount of heavy metals brought in from biogas slurry on the accumulation of heavy metals in soil-crop systems

沼液重金属(As、Cd、Cr、Cu 和 Zn)带入量对作物中对应重金属含量均具有显著影响($P<0.05$,图 3). 随着沼液还田量的增加,沼液 As、Cd、Cr 和 Zn 带入量提高,作物中对应的重金属含量增加效应也随之提高,相关系数分别为 0.27、0.28、0.32 和 0.19,说明沼液中 As、Cd、Cr 和 Zn 带入量的增大会促进作物中对应重金属的累积. 这可能是因为沼液重金属带入量的增加的同时为土壤提供了大量无机氮源,加速了土壤中有机质矿化作用[42],使吸附在土壤的重金属重新释放,导致重金属有效态的提高,这会使作物更容易从土壤中吸收重金属,加速在其体内的累积,从而有利于作物从土壤中提取重金属. 沼液也会向土壤提供有机化学物质,从而影响重金属的活性,促进作物对重金属的吸收,有研究表明土壤重金属有效态与作物中重金属含量呈正相关[37,43,44]. 而沼液重金属带入量与作物中 Cu 含量变化效应值相关系数为 −0.24,表明沼液还田量的增加导致沼液重金属带入量提高的同时,会对作物中 Cu 含量累积效应起到一定的抑制作用. 有研究显示,沼液施用会使土壤-水稻系统中 As、Cd 和 Zn 的迁移活性显著提高,而 Cu 显著降低[24]. 可能是由于 Cu 更倾向于和稳定部分有机物结合,大部分到达土壤中的 Cu 都会被土壤中的有机物保留,流动性低,生物有效性低[45~49].

As、Cd、Cu 和 Zn 在土壤中含量的变化量和作物中含量的变化量呈极显著正相关($P<0.01$,图 3),相关系数降序排列为:Cu(0.58) > Cd(0.45) > Zn(0.42) > As(0.28). 有研究显示,施用沼肥会使土壤 As、Cd、Cu 和 Zn 的累积量提高,进一步提高了作物中的重金属累积量[24]. Tang 等[1] 和 Zhou 等[50] 的研究也显示出同样的规律; 而土壤-作物系统中 Cr 的变化效应值相关性并不显著,可能是相较于另外 4 种重金属,Cr 在土壤-作物系统中的累积因子低[51,52],Cr 的迁移能力低所致[37,53].

从沼液 Cd 带入量与土壤 Cd 含量变化效应到土壤 Cd 含量变化效应与作物 Cd 含量变化效应的相关系数呈现出增加的趋势,说明作物 Cd 累积效应受土壤 Cd 含量变化更为敏感,Cu 和 Zn 也是如此,而 As 和 Cr 没有表现出同样的规律.

2.4　重金属累积影响因子重要性分析

为了解土壤和作物中重金属累积的影响因素重要性,对土壤和作物累积重金属的影响因素进行因子重要性程度分析(表 1). 沼液还田量和重金属带入量决定了土壤中重金属的累积量[2,54],沼液还田时间增加,还田量提高,重金属带入量也随之提高. 在沼液还田过程中会影响 SOM 含量和土壤 pH 值[39,55],二者是影响土壤中的重金属固定和迁移的关键因素[27,34,37]. 结果表明,SOM 对土壤重金属 Cd、Cu 和 Zn 累积的影响最大,沼液还田时长对土壤 As 和 Cr 的累积影响最大. 其次,影响土壤 As 和 Zn 累积的因素重要性依次为土壤 pH 值和重金属带入量,影响土壤 Cu 的依次为土壤 pH 值和沼液还田时长,影响土壤 Cd 的依次为重金属带入量和土壤 pH 值,影响土壤 Cr 的依次为 SOM 和土壤 pH 值. 对作物重金属 As 和 Cu 的累积影响最大的是土壤 pH 值,对作物 Cd、Cr 和 Zn 的累积影响最大的是沼液还田时长. 长期大量施用沼液可能导致土壤重金属大量累积[2],显著提高作物重金属累积量[24]. 有研究也报道了沼肥施用时间增加导致土壤和作物重金属含量增加这一现象[56,57]. 通过研究太湖流域沼液灌溉下的土壤和作物中重金属含量发现,SOM 和土壤 pH 值与土壤重金属累积有着显著的相关性,对作物中重金属含量进行主成分分析,发现 SOM 和土壤 pH 值对其重金属含量的影响贡献率达 71.7%,其他研究也证实了 SOM 和土壤 pH 值对于土壤和作物重金属累积的影响[58],而长期施用沼液会影响 SOM 含量和土壤 pH 值[59~61]. 因此,沼液还田时长、SOM、土壤 pH 值和重金属带入量对土壤和作物中重金属的累积影响至关重要.

表 1　土壤-作物系统中重金属累积影响因子重要性分析

Table 1　Analysis of the importance of factors influencing heavy metal accumulation in soil-crop systems

项目	As		Cd		Cr		Cu		Zn	
	土壤	作物	土壤	作物	土壤	作物	土壤	作物	土壤	作物
施肥方式	0.29	0.42	0.33	0.35	0.14	0.25	0.15	0.03	0.26	−0.05
作物种类	0.61	0.60	0.53	0.39	0.48	0.50	0.19	0.26	0.37	0.70
土地利用方式	0.66	0.25	0.59	0.23	0.51	0.37	0.16	0.41	0.17	0.78
土壤 pH	1.04	0.82	1.04	0.57	0.94	0.92	0.96	0.97	0.82	0.81
沼液还田时长	1.41	0.36	0.72	1.24	1.40	1.48	0.50	0.73	0.47	1.61
SOM	0.74	0.74	1.91	1.03	1.31	0.89	0.99	0.95	0.90	0.67
重金属带入量	0.75	0.64	1.51	1.03	0.71	1.09	0.40	0.76	0.68	0.71
模型拟合度	0.83	0.83	0.83	0.82	0.89	0.83	0.88	0.90	0.94	0.74

3　结论

(1)沼液还田方式会影响土壤和作物重金属的累积,沼液化肥混施相比沼液单施减缓了土壤-作物系统中重金属的累积.

(2)沼液还田时长直接和间接地影响了土壤-作物系统重金属的累积.还田时长对土壤-作物系统中重金属 As、Cd 和 Cr 的直接影响更为明显,而对土壤-作物系统中重金属 Cu 和 Zn 的间接影响更为明显.

(3)SOM、沼液还田时长、土壤 pH 值和重金属带入量是影响土壤-作物系统中重金属累积的重要因素.土壤重金属累积主要受 SOM 和沼液还田时长影响,作物重金属累积主要受土壤 pH 值和沼液还田时长影响.

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