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聚苯乙烯微塑料联合镉污染对土壤理化性质和生菜 (*Lactuca sativa*) 生理生态的影响

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摘要: 土壤中普遍存在微塑料和重金属等复合污染物, 二者极难降解且易形成复合污染, 改变土壤的理化性质, 并影响植物的生长与生理生态特征。为研究土壤微塑料与重金属的复合污染对土壤性质和植物生长的影响, 选取粒径 3 μm 的聚苯乙烯微塑料 (PS-MPs) 和重金属镉 (Cd), 设置不同 PS-MPs 暴露量 (0、10、50、100、200 和 400 $\text{mg}\cdot\text{kg}^{-1}$) 并联合 Cd 污染 (0、1.2 和 6.0 $\text{mg}\cdot\text{kg}^{-1}$) 条件下, 研究土壤的理化性质变化及其对生菜 (*Lactuca sativa*) 种子萌发、幼苗生长的影响。结果表明, 随着 PS-MPs 与 Cd 复合污染强度的增加, 土壤有机质 (SOM)、有效磷 (AP)、碱解氮 (AHN) 和速效钾 (AK) 等主要理化因子均显著降低, 在 PS-MPs 暴露量为 400 $\text{mg}\cdot\text{kg}^{-1}$ 时降到最低值; 同时, PS-MPs 联合 Cd 的污染也会显著降低生菜种子的萌发率, 但 PS-MPs 低暴露量 (10 $\text{mg}\cdot\text{kg}^{-1}$ 和 50 $\text{mg}\cdot\text{kg}^{-1}$) 会减缓 Cd (6.0 $\text{mg}\cdot\text{kg}^{-1}$) 污染对生菜种子萌发的抑制作用, 而 PS-MPs 高暴露量 (200 $\text{mg}\cdot\text{kg}^{-1}$ 和 400 $\text{mg}\cdot\text{kg}^{-1}$) 会加剧 Cd (6.0 $\text{mg}\cdot\text{kg}^{-1}$) 对生菜种子的抑制作用。受不同含量 Cd 污染后, 生菜幼苗鲜重、干重和株高等生长指标随 PS-MPs 暴露量增加均呈先升后降趋势; 叶绿素含量、超氧化物歧化酶 (SOD)、过氧化氢酶 (CAT) 和过氧化物酶 (POD) 等指标均呈下降趋势, 而丙二醛 (MDA) 含量总体呈上升趋势。土壤的主要理化指标与生菜幼苗的 MDA 呈显著负相关, 而与幼苗的其它各项指标则呈显著正相关。PS-MPs 和重金属 Cd 复合污染能通过改变土壤理化性质从而影响植物种子萌发及其幼苗生理生态特征, 研究结果对于评估土壤-植物系统中微塑料和重金属复合污染的生态效应能提供一定的参考借鉴。

关键词: 土壤; 微塑料 (MPs); 重金属; 复合污染; 生菜; 生长; 抗氧化酶

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Effects of Polystyrene Microplastics Combined with Cadmium Contamination on Soil Physicochemical Properties and Physiological Ecology of *Lactuca sativa*

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Abstract: Contaminants such as microplastics (MPs) and heavy metals are commonly found in soils, both of which are extremely difficult to degrade and can easily form compound contamination, altering the physicochemical properties of the soil and thus potentially changing the growth and physiological and ecological characteristics of plants. In order to study the effects of the combined contamination of soil MPs and heavy metals on soil properties and plant growth, polystyrene microplastics (PS-MPs) with a particle size of 3 μm and the heavy metal cadmium were selected in the study. The changes in the physicochemical properties of soil and their effects on lettuce (*Lactuca sativa*) seed germination and seedling growth were studied at various exposure concentrations of PS-MPs (0, 10, 50, 100, 200, and 400 $\text{mg}\cdot\text{kg}^{-1}$) and combined with different Cd contamination concentrations (0, 1.2, and 6.0 $\text{mg}\cdot\text{kg}^{-1}$), respectively. The results showed that soil organic matter (SOM), available phosphorus (AP), alkali-hydrolysable nitrogen (AHN), and available potassium (AK) showed significant decreases as the intensity of PS-MPs combined with Cd contamination increased. Simultaneously, PS-MPs combined with Cd contamination also significantly reduced the germination rate of lettuce seeds, but low concentrations of PS-MPs slowed down the effect of Cd (6.0 $\text{mg}\cdot\text{kg}^{-1}$) contamination on lettuce seeds, and high concentrations of PS-MPs enhanced the effect of Cd (6.0 $\text{mg}\cdot\text{kg}^{-1}$). The fresh weight, dry weight, and plant height of lettuce seedlings showed an increasing and then decreasing trend with increasing exposure to PS-MPs. Chlorophyll content, superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) showed a decreasing trend, whereas malondialdehyde (MDA) content showed an overall increasing trend under different Cd concentrations. The main physicochemical indicators of the soil were negatively correlated with MDA of lettuce seedlings, whereas other indicators of the seedlings were positively correlated. The combined contamination of PS-MPs and Cd could affect the germination of plant seeds and the physiological and ecological characteristics of seedlings by changing the physicochemical properties of the soil. Both exposure to single PS-MPs contaminants and the combination of PS-MPs with Cd inhibited the germination of lettuce seeds and affected the physiological activities of their seedlings, and the inhibition was significantly increased with increasing exposure. Low exposure to PS-MPs or the combination of PS-MPs with Cd contamination exhibited a promotive effect on lettuce seedling growth. High exposure to PS-MPs combined with Cd contamination exhibited significant ecological effects on lettuce seedlings, and high exposure to PS-MPs exacerbated the ecotoxicological effects of Cd contaminants on lettuce seedlings, and PS-MPs and Cd exhibited synergistic effects. The results can provide some reference for assessing the ecological effects of MPs and heavy metal pollution in soil-plant systems.

Key words: soil; microplastics (MPs); heavy metals; complex contamination; lettuce; growth; antioxidant enzymes

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随着微塑料(microplastics, MPs)研究的不断深入,越来越多的研究发现海洋^[1]、淡水^[2]、土壤^[3]和大气^[4]等各种环境中均有微塑料存在,但相关研究更多集中于海洋生态系统^[5],对土壤生态系统影响方面的研究尚较少^[6]。据报道^[7],每年释放到陆地上的废塑料量比释放到海洋中的多4~23倍,且海洋环境中大量塑料颗粒来自陆地,通过沉积物转移或土壤侵蚀等方式进入^[8]。由此可见,微塑料污染对土壤的影响可能更严重。微塑料在土壤中极难降解^[9],易吸附携带有害污染物并改变土壤性质。如酸性土壤中微塑料污染会影响土壤理化性质和酶活性^[10],这种影响取决于微塑料类型及其污染水平;不同粒径聚苯乙烯微塑料(polystyrene, PS)通过改变土壤理化性质,进而潜在地改变植物生长^[11];有研究发现PS会影响黄瓜(*Cucumis sativus*)植株的总生物量、抗氧化和糖代谢系统^[12],且PS降解产生的苯环可能是影响叶绿素代谢和糖代谢的主要因素,微塑料不仅可以改变土壤理化性质,还直接或间接影响土壤中的植物生长。

此外,土壤中普遍存在严重的重金属污染问题。根据2014年《全国土壤污染调查公报》数据,镉(Cd)在全国土壤点位超标率最高,高达7.0%。2020年农用地土壤污染状况详查结果显示,影响农用地土壤环境质量的主要污染物是重金属,其中Cd为首要污染物。Cd进入植株体后,与养分共同竞争植物根系的吸收位点,干扰植物对养分的吸收或利用,从而影响植物的正常生长发育^[13,14]。Cd进入植株体后分布在不同部位^[15],通过食物链对生命健康产生威胁。已有研究表明,环境中MPs可以吸附重金属,并产生更强的毒性^[16]。然而,目前关于微塑料联合重金属污染的研究多集中于水生植物,针对二者复合污染胁迫土壤植物的研究尚较缺乏。

生菜(*Lactuca sativa*)是可直接食用的蔬菜,营养丰富,具有多种功效。有研究通过激光共聚焦显微镜和扫描电子显微镜观察发现,生菜不仅可吸收微塑料^[17],并能将其运输、积累和分布在茎叶之中。而在实际种植条件下,生菜受到MPs污染的同时,也会受土壤中重金属的毒害作用。基于此,本文以生菜作为供试植物,选用聚苯乙烯微塑料(polystyrene microplastics, PS-MPs)联合重金属Cd污染物,研究二者单一或复合污染下土壤理化性质的变化及其对生菜生理生态的影响,旨在为微塑料和重金属复合污染对土壤-植物系统的生态影响提供一定的基础数据。

1 材料与方法

1.1 供试材料与实验设计

现有研究发现粒径4.8 μm的MPs能在植物种子

囊孔隙中累积,并延迟种子萌发和根系生长^[18];还有研究通过设置10 mg·kg⁻¹和100 mg·kg⁻¹的暴露条件,也发现5 μm的PS-MPs可显著抑制陆生高等植物(小麦、蚕豆等)的根、茎伸长,破坏叶片的光合系统并抑制其抗氧化酶活性^[19,20]。据此,本文利用土壤培养条件,选取粒径3 μm的聚苯乙烯微球(购自纳瑞新材料有限公司),设置暴露量为0(空白对照)、10、50、100、200和400 mg·kg⁻¹,并参考国家《土壤环境质量标准》(GB 15618-2018),设置施加Cd污染物含量分别为0(空白对照)、1.2和6.0 mg·kg⁻¹,分别标记为C₀、C₁和C₂。

选取颗粒均匀饱满的玻璃生菜种子(购自欣欣然公司,实测发芽率为99.7%),采用3%的H₂O₂消毒30 min,用蒸馏水反复冲洗3次以去除种子表面残留H₂O₂,然后将其置于蒸馏水中浸泡12 h。将一部分种子置于含胁迫污染物的玻璃培养皿(直径9 cm,高3 cm)中进行土培,以测定发芽指标,每皿90 g土、10粒种子,共设3个平行;剩余种子置于含胁迫物的培养盆(口径18.0 cm,底径16.5 cm,高8 cm)中进行土培,以测定幼苗指标与土壤环境指标,每盆1.5 kg土、12粒种子并设3个平行。以上处理均置于人工气候箱中培养(光照/黑暗为12 h/12 h,日温/夜温为20℃/15℃;光照强度5 000 lx),每日浇水1次,保持土壤持水量70%左右。胁迫7 d后测定种子生长指标,45 d后测定幼苗生长指标与生理指标,并测定土壤理化性质。

1.2 指标测定方法

1.2.1 土壤理化指标

土壤有机质(soil organic matter, SOM)测定采用重铬酸钾氧化-外加热法^[21];有效磷(available phosphorous, AP)含量测定采用盐酸-氟化铵法^[22];速效钾(available kalium, AK)含量测定采用四苯硼钠比浊法^[23];碱解氮(alkali-hydrolyzable nitrogen, AHN)含量测定采用碱解扩散法^[24]。

1.2.2 植物种子发芽指标

在种子发芽第3 d和第7 d时,记录种子发芽数,并在第7 d时将生菜幼苗置于103℃烘箱中烘干24 h至恒重,采用电子天平测定苗干质量。参考连加攀等^[25]的方法计算种子发芽率(germination rate, GR)、发芽势(germination vigor, GV)、发芽指数(germination index, GI)和活力指数(vigor index, VI)等萌发指标,计算公式如下:

$$GI = \sum G_i / D_i \quad (1)$$

$$GV = (a/n) \times 100\% \quad (2)$$

$$VI = GI \times m \quad (3)$$

$$GR = (b/n) \times 100\% \quad (4)$$

式中, G_t 为 t 天内的发芽数; D_t 为对应的发芽天数; a 为 3 d 内供试种子发芽数; n 为供试种子总数; m 为苗干质量; b 为 7 d 内发芽种子数。

1.2.3 植物幼苗指标

参考刘幸红等^[26]的方法测定生菜鲜重、干重和株高; 叶绿素 a 含量(C_a)、叶绿素 b 含量(C_b)、叶绿素总量(total chlorophyll, C_t)和叶绿素 a 与叶绿素 b 含量比(C_a/C_b)等指标测定采用分光光度法^[27]; 超氧化物歧化酶(superoxide dismutase, SOD)活性测定采用氮蓝四唑法, 过氧化物酶(peroxidase, POD)活性测定采用愈创木酚法, 过氧化氢酶(catalase, CAT)活性测定采用紫外吸收法^[28]; 丙二醛(malondialdehyde, MDA)含量测定采用硫代巴比妥酸法^[29]。

1.3 数据处理与统计分析

数据处理采用 Excel 2019 软件; 数据统计分析采用 SPSS 21.0 软件; 采用单因素方差分析(one-way, ANOVA)和 Duncan 法对数据进行差异性比较, 结果采用均值±标准误差表示; 采用冗余分析(redundancy analysis, RDA)对数据进行相关分析; 采用 Origin 2022 软件进行制图。

1.4 质量保证与质量控制

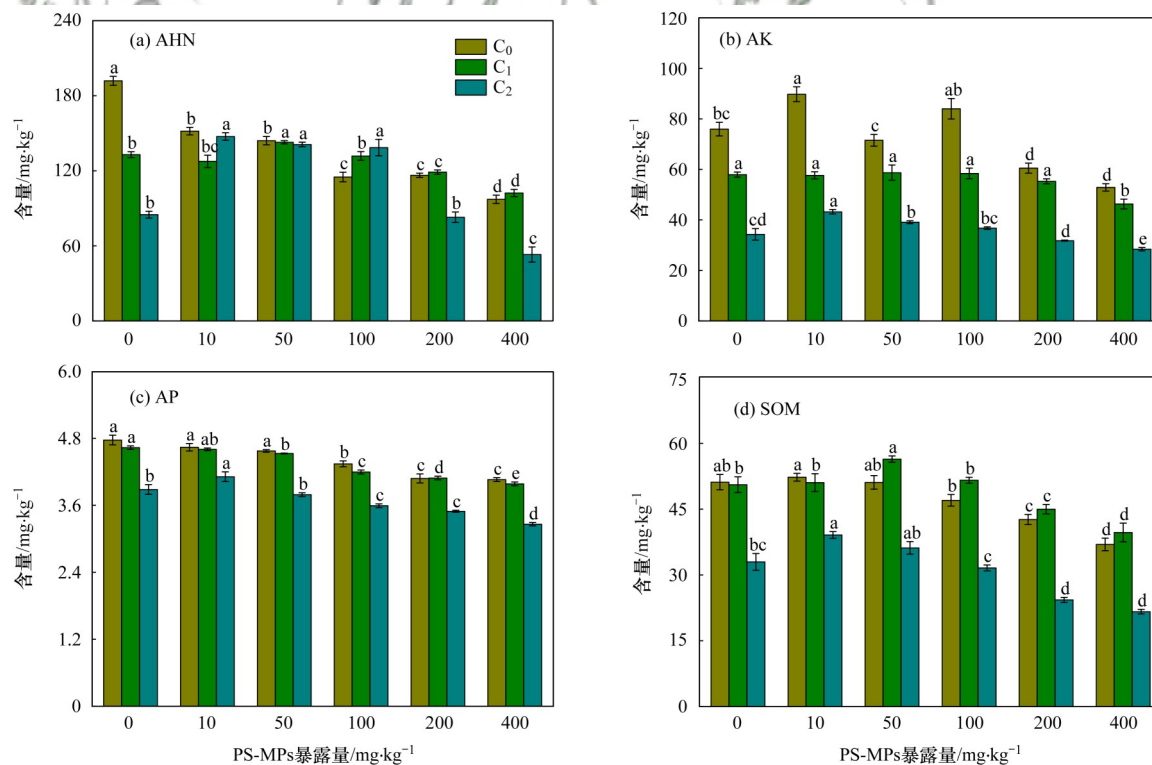
为确保实验过程的质量保证和质量控制, 在实验操作和数据分析全程执行严格的控制方案, 包括: 检查并消除所有的潜在污染, 尽量减少或避免外来

微塑料污染的可能性, 全程避免使用塑料制品; 所有实验步骤均使用乳胶手套和棉质实验服; 玻璃实验用品在使用前进行清洁、干燥; 供试植物在培养箱中生长以减少空气中微塑料污染; 测定指标时避免样品间交叉污染; 确保试剂、量具的准确度与仪器的精确度。

2 结果与分析

2.1 PS-MPs 联合 Cd 污染下土壤理化性质的变化

如图 1 所示, 土壤理化性质在 PS-MPs 联合 Cd (C_0 、 C_1 和 C_2) 污染条件下均有不同程度变化。Cd 在 C_0 条件下, AHN 含量随 PS-MPs 暴露量增加呈下降趋势, AK、AP 和 SOM 含量在 PS-MPs 暴露量为 200~400 $\text{mg} \cdot \text{kg}^{-1}$ 下显著降低, 并在 400 $\text{mg} \cdot \text{kg}^{-1}$ 时降到最低, 与 0 $\text{mg} \cdot \text{kg}^{-1}$ 相比分别降低了 49.9%、43.7%、14.5% 和 27.8%。 C_1 条件下, AHN 和 SOM 在 PS-MPs 暴露量 200~400 $\text{mg} \cdot \text{kg}^{-1}$ 范围内均显著降低, 分别降低了 23.1% 和 21.5%; AK 与 AP 在 PS-MPs 暴露量为 400 $\text{mg} \cdot \text{kg}^{-1}$ 时降到最低, 分别降低了 25.2% 和 14.0%。 C_2 条件下, AHN 和 AK 在 PS-MPs 暴露量为 400 $\text{mg} \cdot \text{kg}^{-1}$ 时降到最低, 分别降低了 37.5% 和 20.8%; AP 和 SOM 在 PS-MPs 暴露量为 10 $\text{mg} \cdot \text{kg}^{-1}$ 时升高, 分别升高了 5.9% 和 9.7%, 200~400 $\text{mg} \cdot \text{kg}^{-1}$ 范围内显著降低, 在 400 $\text{mg} \cdot \text{kg}^{-1}$ 时降到最低, 分别降低了 16.0% 和 34.4%。



不同小写字母表示差异显著 ($P < 0.05$)

图1 PS-MPs和Cd复合污染下土壤理化性质的变化

Fig. 1 Changes in soil physicochemical properties under combined contamination with PS-MPs and Cd

2.2 PS-MPs联合Cd污染对生菜种子萌发指标的影响

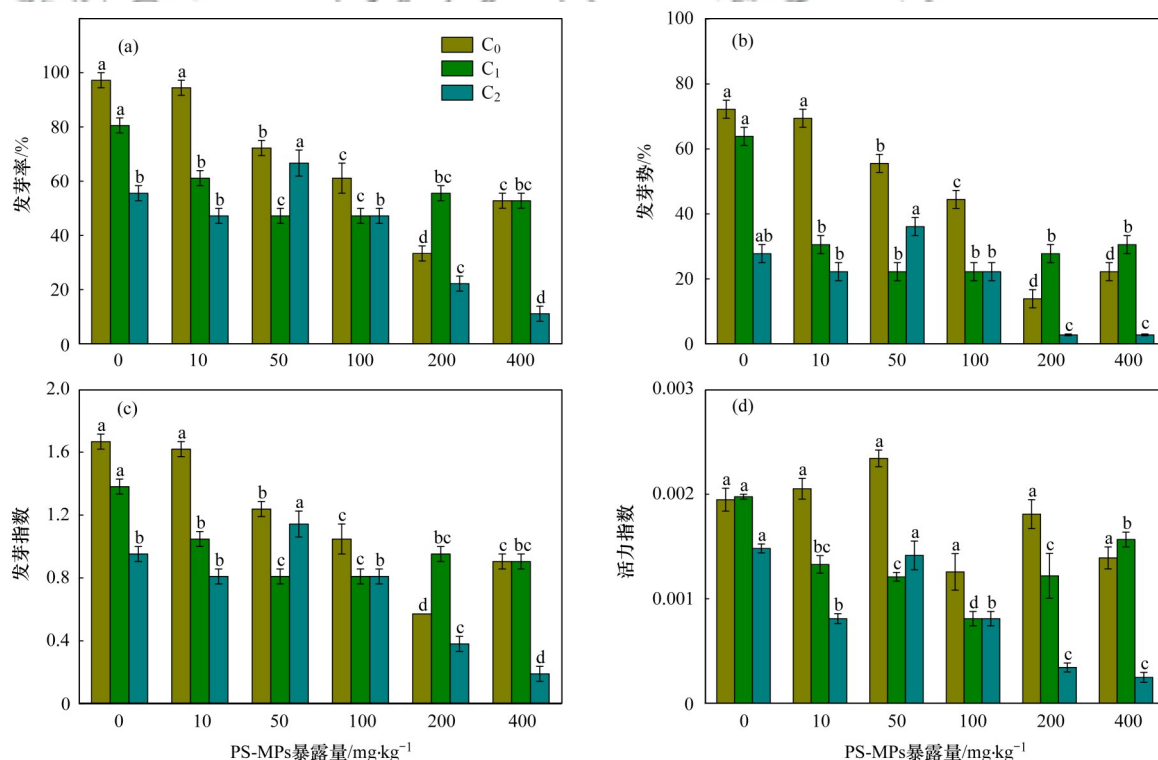
如图2所示,不同含量PS-MPs与Cd(C_0 、 C_1 和 C_2)联合处理对生菜种子发芽的影响有一定差异。Cd在 C_0 条件下,PS-MPs暴露量为50~400 $\text{mg}\cdot\text{kg}^{-1}$ 时种子发芽率、发芽势和发芽指数均显著降低,并在200 $\text{mg}\cdot\text{kg}^{-1}$ 时降到最低,与0 $\text{mg}\cdot\text{kg}^{-1}$ 相比分别降低了65.7%、80.8%和65.7%。 C_1 条件下,不同PS添加下的种子发芽率、发芽势、发芽指数和活力指数等指标均受明显抑制,表明 $\omega(\text{Cd})$ 为1.2 $\text{mg}\cdot\text{kg}^{-1}$ 时,PS-MPs会加剧Cd对种子萌发的抑制作用。 C_2 条件下,PS-MPs暴露量为50 $\text{mg}\cdot\text{kg}^{-1}$ 时种子发芽率和发芽指数均上升到最高,但在PS-MPs暴露量为200~400 $\text{mg}\cdot\text{kg}^{-1}$ 时显著降低,并在400 $\text{mg}\cdot\text{kg}^{-1}$ 时降到最低,均降低了80.0%。表明 $\omega(\text{Cd})$ 为6 $\text{mg}\cdot\text{kg}^{-1}$ 时,PS-MPs暴露量为50 $\text{mg}\cdot\text{kg}^{-1}$ 时能削弱Cd对种子萌发的抑制,在PS-MPs暴露量为200~400 $\text{mg}\cdot\text{kg}^{-1}$ 范围内会加剧Cd对种子萌发的抑制作用。

2.3 PS-MPs联合Cd污染对生菜幼苗生长及其生理指标的影响

如图3所示,PS-MPs联合Cd(C_0 、 C_1 和 C_2)污染条件下,随着PS-MPs暴露量增加,生菜幼苗干重(DW)、鲜重(FW)与株高(PH)等生长指标总体呈先升后降趋势。Cd在 C_0 条件下,PS-MPs暴露量为10~100 $\text{mg}\cdot\text{kg}^{-1}$ 下生菜的干重和鲜重显著升高;PS-MPs

暴露量为200~400 $\text{mg}\cdot\text{kg}^{-1}$ 时干重和鲜重呈下降趋势,并在400 $\text{mg}\cdot\text{kg}^{-1}$ 时均降到最低,与0 $\text{mg}\cdot\text{kg}^{-1}$ 相比降低了28.7%和22.3%。 C_1 条件下,PS-MPs暴露量在10~50 $\text{mg}\cdot\text{kg}^{-1}$ 时,幼苗的干重和鲜重均显著升高;400 $\text{mg}\cdot\text{kg}^{-1}$ 时均显著降低,与0 $\text{mg}\cdot\text{kg}^{-1}$ 相比降低了30.5%和44.8%;随PS-MPs含量增加,株高受到的抑制逐渐增强。 C_2 条件下,植物干重和鲜重与株高变化趋势与 C_1 处理下大体一致。表明不同Cd浓度污染下,PS-MPs暴露量低时能促进生菜幼苗生长,而PS-MPs暴露量高时会加剧Cd对幼苗生长的抑制作用。

图4所示,Cd在 C_0 条件下,当PS-MPs暴露量为50~400 $\text{mg}\cdot\text{kg}^{-1}$ 时,生菜叶绿素指标 C_a 、 C_b 和 C_t 持续降低,在400 $\text{mg}\cdot\text{kg}^{-1}$ 时降到最低,与0 $\text{mg}\cdot\text{kg}^{-1}$ 相比分别降低了21.5%、19.1%和20.9%。 C_1 条件下,PS-MPs暴露量在10~400 $\text{mg}\cdot\text{kg}^{-1}$ 时, C_a 、 C_t 和 C_a/C_b 均显著降低,在400 $\text{mg}\cdot\text{kg}^{-1}$ 时降到最低,分别降低了47.7%、39.1%和39.5%;而叶绿素 C_b 在PS-MPs暴露量为50~200 $\text{mg}\cdot\text{kg}^{-1}$ 范围内显著升高,在10 $\text{mg}\cdot\text{kg}^{-1}$ 和400 $\text{mg}\cdot\text{kg}^{-1}$ 时显著降低,分别降低了7.8%和13.8%。 C_2 条件下,叶绿素 C_b 在PS-MPs暴露量为100~400 $\text{mg}\cdot\text{kg}^{-1}$ 范围内显著下降,在400 $\text{mg}\cdot\text{kg}^{-1}$ 时降到最低,降低了35.6%; C_a 、 C_t/C_b 和 C_t 随PS-MPs暴露量增加而呈下降趋势,均在400 $\text{mg}\cdot\text{kg}^{-1}$ 时显著降低,分别降低了63.7%、43.5%和54.5%。总体结果表明,PS-MPs暴露量高会加剧Cd污染对生菜幼苗叶绿素的抑制影响。



不同小写字母表示差异显著($P < 0.05$)

图2 PS-MPs和Cd复合污染下生菜种子萌发指标的变化

Fig. 2 Changes in lettuce seed germination indicators under combined contamination with PS-MPs and Cd

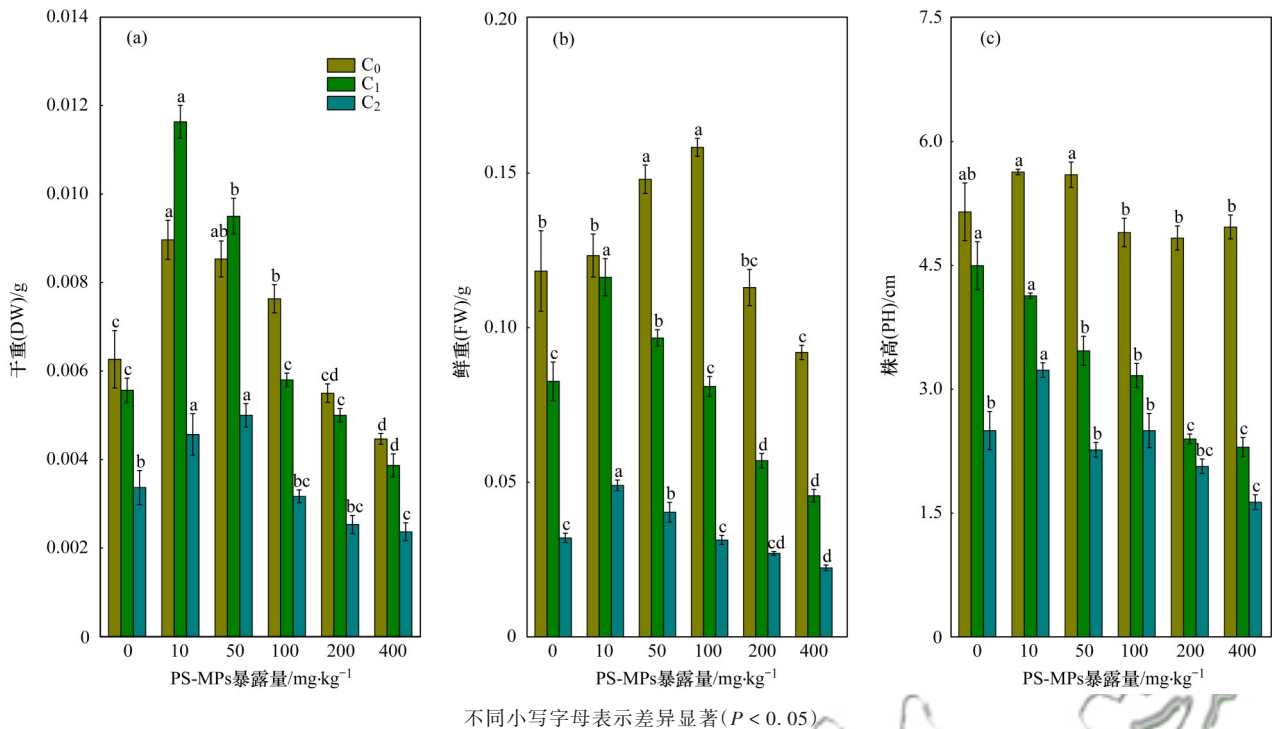


图3 PS-MPs和Cd复合污染下幼苗生长指标的变化

Fig. 3 Changes in lettuce seedling growth indexes under combined contamination with PS-MPs and Cd

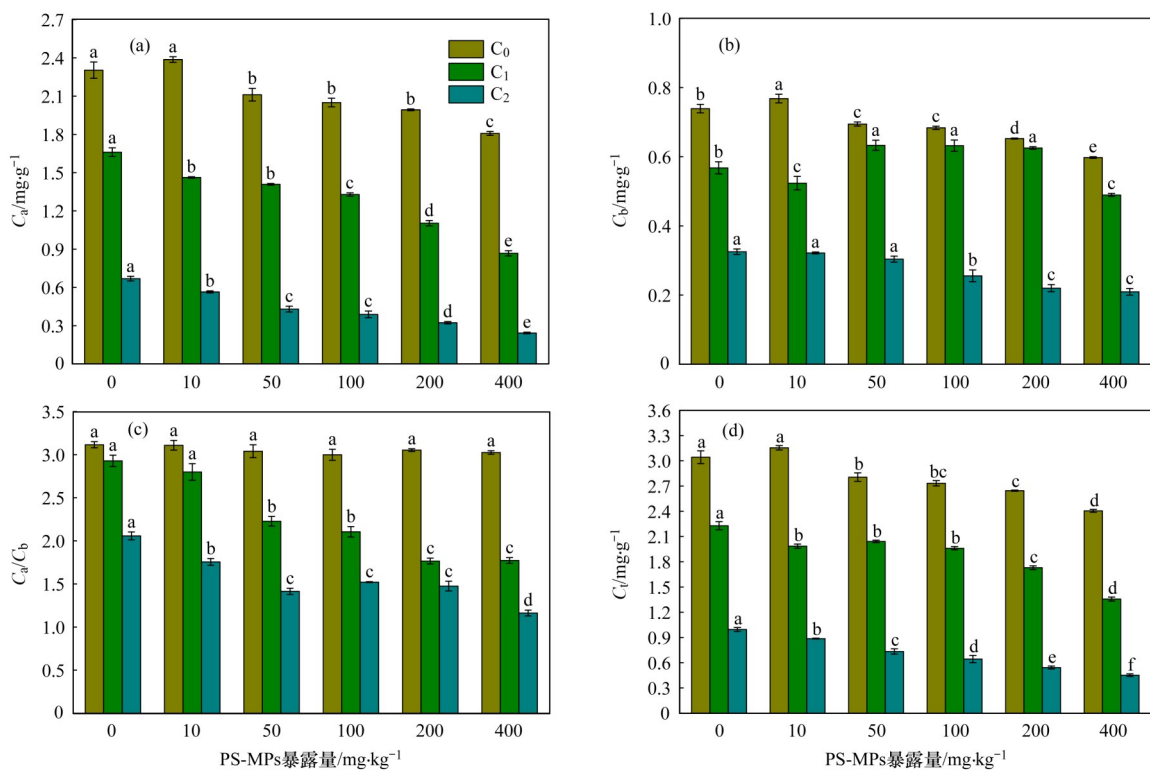


图4 PS-MPs和Cd复合污染下幼苗叶绿素指标的变化

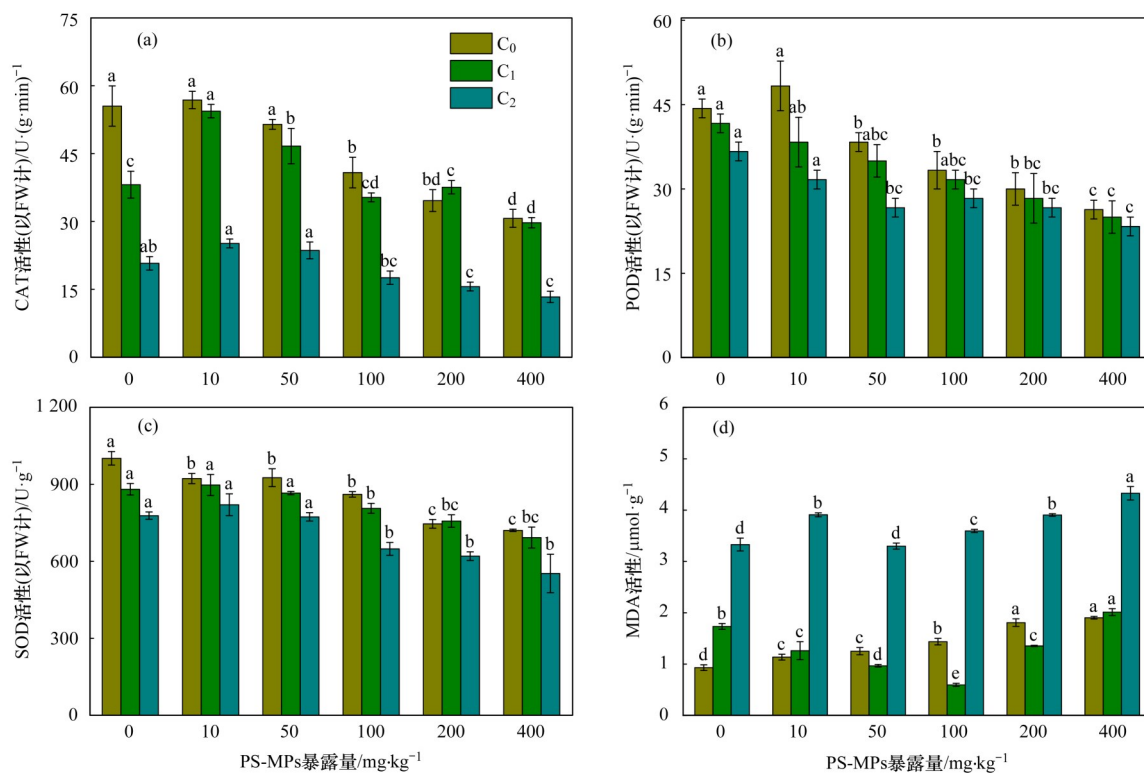
Fig. 4 Changes in chlorophyll indicators of lettuce seedlings under combined contamination with PS-MPs and Cd

图5所示,生菜幼苗的抗氧化酶活性与MDA含量在PS-MPs联合Cd污染条件下均有变化。Cd在C₀条件下,CAT在PS-MPs暴露量为100~400 mg·kg⁻¹时显著降低,POD在PS-MPs暴露量为50~400 mg·kg⁻¹时显著

降低,SOD活性随着PS-MPs含量增加显著降低,均在400 mg·kg⁻¹时降到最低,分别下降了44.7%、40.6%和28.0%;MDA含量呈上升趋势,在400 mg·kg⁻¹时升到最高值,上升了104.5%。C₁条件下,CAT、POD和

SOD 在 PS-MPs 暴露量为 $200\sim 400\text{ mg}\cdot\text{kg}^{-1}$ 时显著降低,均在 $400\text{ mg}\cdot\text{kg}^{-1}$ 时显著降低,分别降低了 22.1%、40.0% 和 21.4%;MDA 随 PS-MPs 暴露量增加呈先降后升趋势,在 $400\text{ mg}\cdot\text{kg}^{-1}$ 时升到最高,上升了 16.1%。

C_2 条件下, CAT、POD 和 SOD 在 PS-MPs 暴露量为 $100\sim 400\text{ mg}\cdot\text{kg}^{-1}$ 时显著降低,均在 $400\text{ mg}\cdot\text{kg}^{-1}$ 时降到最低,分别下降了 35.8%、36.4% 和 21.4%;MDA 含量持续升高,在 $400\text{ mg}\cdot\text{kg}^{-1}$ 时升到最高值,上升了 30.0%。



不同小写字母表示差异显著 ($P < 0.05$)

图5 PS-MPs和Cd复合污染下幼苗生理指标的变化

Fig. 5 Changes in physiological indicators of lettuce seedlings under combined contamination with PS-MPs and Cd

2.4 生菜幼苗生长指标与土壤环境间的关系

如图6,不同 PS-MPs 暴露量联合不同 Cd 污染 (C_0 、 C_1 和 C_2) 条件下,各环境因子与生菜幼苗各生理指标间存在一定相关性,排序轴 1 和排序轴 2 对幼苗指标的累计解释量分别达 66.64%、69.56% 和 67.28%。Cd 在 C_0 条件下幼苗 MDA 与 AK、SOM、AP 和 AHN 呈显著负相关,且相关性大小表现为: $\text{AP} > \text{AHN} > \text{SOM} > \text{AK}$;幼苗其它指标与土壤指标呈正相关,且相关性大小表现为: $\text{SOM} > \text{AK} > \text{AP} > \text{AHN}$ 。 C_1 条件下幼苗 MDA 与土壤指标呈显著负相关,且相关性大小表现为: $\text{SOM} > \text{AHN} > \text{AK} > \text{AP}$;其它指标与土壤指标呈显著正相关,且相关性大小表现为: $\text{AP} > \text{SOM} > \text{AHN} > \text{AK}$ 。 C_2 条件下幼苗 MDA 与土壤指标呈显著负相关,且相关性大小表现为: $\text{SOM} > \text{AHN} = \text{AP} > \text{AK}$;其它指标与土壤指标呈显著正相关,且相关性大小表现为: $\text{AP} > \text{SOM} > \text{AK} > \text{AHN}$ 。

3 讨论

土壤理化性质的变化对植物生长和生理等活动均有重要影响,研究土壤理化性质的变化极其关键。

本研究发现不同 PS-MPs 暴露量及其联合 Cd 污染 ($1.2\text{ mg}\cdot\text{kg}^{-1}$) 会显著降低土壤中的 AK、SOM、AP 和 AHN 等含量,而 $400\text{ mg}\cdot\text{kg}^{-1}$ 的 PS-MPs 暴露量联合 Cd 污染 ($6\text{ mg}\cdot\text{kg}^{-1}$) 也显著降低土壤各理化指标含量。上述结果表明,一定量的 PS-MPs + Cd 复合污染会对土壤理化性质产生不利影响,这与已有研究的结果较一致^[30, 31],可能与土壤酶活性有一定关联^[32],具体机制有待深入研究。

本研究还发现土壤 SOM、AP、AK 和 AHN 等指标含量与生菜叶片的 MDA 含量呈显著负相关,与其它幼苗指标呈正相关,表明土壤理化性质在 MPs 和重金属复合污染下会影响生菜幼苗的生长,与其他研究结果较一致^[33, 34]。其中, SOM 和 AP 与幼苗指标的相关性最显著,可能是因为 SOM 含量降低对土壤孔隙度、通气性和结构等产生负面影响,会阻碍植物根系吸收养分与水分,从而影响生菜幼苗的生长和生理生态;土壤中的 AP、AK 和 AHN 等含量的降低会导致植物能够吸收的土壤养分减少,从而无法维持其正常生长。以上结果表明,微塑料与重金属复合污染会直接影响土壤理化性质,从而间接影响植物的

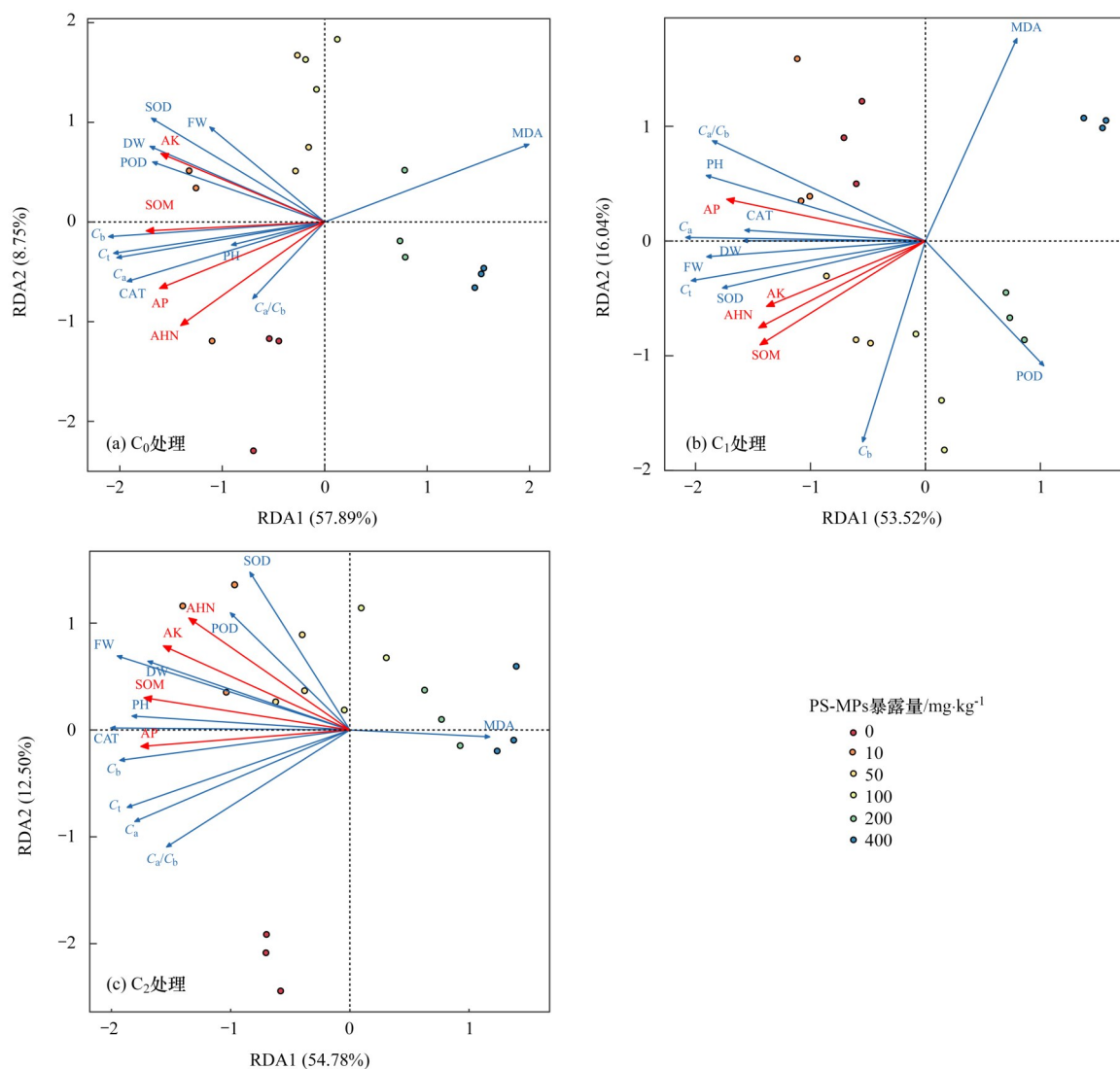


图6 生菜幼苗指标与土壤环境指标间的冗余分析

Fig. 6 Redundancy analysis (RDA) between lettuce seedling indicators and soil environment indicators

生长。

发芽率、发芽势、发芽指数和活力指数是衡量植物种子发芽能力的重要指标。本文结果表明,单因素 PS-MPs 或其联合 Cd 的不同暴露量对生菜种子萌发具有不同抑制作用,这与吴佳妮等^[35]研究的结果一致。有研究认为^[18], PS-MPs 抑制生菜种子发芽是由于 MPs 会粘附在种皮表面并对种子囊孔隙产生物理堵塞,抑制种子吸收水分及营养成分进而延缓萌发。但也有研究发现, MPs 不会显著降低植物种子发芽率^[36],甚至会促进发芽^[37],这可能与 MPs 种类、粒径、暴露量及其所带电荷等因素有关^[38, 39]。此外,微塑料能够通过富集金属离子增大毒性效应并损害种子某些组织^[40],如 PS-MPs 联合 Cd ($1.2 \text{ mg} \cdot \text{kg}^{-1}$) 和 PS-MPs ($200 \sim 400 \text{ mg} \cdot \text{kg}^{-1}$) 联合 Cd ($6 \text{ mg} \cdot \text{kg}^{-1}$) 暴露下均加剧抑制种子萌发,这与王泽正等^[37]研究的结果一致。本文还发现 $50 \text{ mg} \cdot \text{kg}^{-1}$ PS-MPs 会减缓 Cd (6

$\text{mg} \cdot \text{kg}^{-1}$) 对种子萌发的抑制,这可能是 MPs 在一定暴露量范围内发生团聚并吸附 Cd,导致土壤中游离态微塑料和重金属含量减少,削弱重金属的生物可利用性,从而降低污染物与种子的可接触性,减缓发芽抑制^[41, 42]。在不同环境条件下,不同暴露量微塑料对重金属的吸附能力不同^[43],因此,微塑料联合重金属污染对种子萌发产生不同程度的抑制作用与二者的暴露量均有直接关系。

生物量能够直观反映外界因子对植物生长发育的影响。本文发现低暴露量 PS-MPs 与 Cd 的复合污染能显著升高生菜幼苗的鲜重和干重,促进植物生长发育,表明低暴露量 MPs 可提高植物幼苗的抗逆能力,并在一定程度上缓解 Cd 污染对生菜幼苗的毒害,这与周颖等^[44]研究的结果一致。 MPs 通过降低土壤容重,减小植物根系的渗透阻力、增加土壤孔隙率和改善土壤通气性,从而促进植物生长和增加生物

量^[45, 46]. 高暴露量 PS-MPs 及其 Cd 复合污染下幼苗的鲜重、干重显著降低, 表明生菜在逆境条件下通过减少生物量的积累, 以应对外界伤害, 这与已有研究的结果相一致^[47], 郭丽丽等^[48]认为植物在逆境时具有调节生物量分配模式的能力, 为适应胁迫环境需要维持细胞正常功能, 需消耗其体内能量, 最后导致植物生长受到抑制^[49].

叶绿素在光合作用的光吸收中起关键作用, 是植物进行光合作用的主要色素. 有研究认为 MPs 通过降低光合作用主要产物——可溶性糖, 影响植株光合作用, 进而降低植物生物量^[12]. 本研究也发现, 随着 PS-MPs 暴露量增加, 生菜幼苗叶片的叶绿素含量降低, 表明土壤中 PS-MPs 不利于叶绿素积累, 且高含量 MPs 抑制效果更强, 这和 Li 等^[12]认为 PS-MPs 降解产生的苯环可能是影响叶绿素代谢的主要因素的研究结果相似. 叶绿素 a 起转化光能的作用, 存在于类囊体膜上, 其含量降低导致植物 C_l 和 C_a/C_b 下降, 进而抑制光合作用和光能利用^[49]. 在 Cd 污染条件下, C_a 和 C_a/C_b 和 C_l 随着 PS-MPs 暴露量增加变化趋势一致, 说明幼苗类囊体可能受到破坏并引起叶绿素含量和光能转化率下降, 导致叶绿素含量降低, 从而影响植物生长. 这和 Dong 等^[47]研究的结果相似. 本研究还发现, 一定暴露量范围内 PS-MPs 暴露会导致 C_b 升高, 但叶绿素总量 C_l 呈现降低趋势. 综合以上分析, 认为 C_a 是影响植物利用光能和叶绿素含量的主要因素; 而 PS-MPs 联合 Cd 污染可能通过影响植物叶片光能的转化并影响叶绿素含量.

外界胁迫会引起植物体内活性氧自由基 (reactive oxygen species, ROS) 积累, 导致细胞膜脂过氧化, 产生过量 MDA, 造成细胞膜系统受到破坏. 本研究单一 PS-MPs 暴露或 Cd ($6 \text{ mg} \cdot \text{kg}^{-1}$) 胁迫下, MDA 含量呈上升趋势, 表明生菜幼苗体内积累了大量 ROS, 膜系统受害程度较严重; PS-MPs 联合 Cd ($1.2 \text{ mg} \cdot \text{kg}^{-1}$) 处理下, MDA 含量先降后升, 说明一定暴露量 MPs 或能减轻 Cd ($1.2 \text{ mg} \cdot \text{kg}^{-1}$) 对幼苗的氧化损伤, 这与已有研究的结果较相似^[50, 51]. 生菜幼苗体内的抗氧化酶活性整体呈抑制现象, 活性均显著低于对照组, 且表现出随 PS-MPs 暴露量增高而降低的趋势, 表明 Cd 对幼苗的毒害作用会随 PS-MPs 暴露量增加而加剧, 导致幼苗无法启动抗氧化酶系统进行自我调节. 这与 Jia 等^[52]研究认为土壤中 MPs 有利于重金属进入植株体内, 加剧植物受害的结果较一致. 刘玲等^[53]研究表明, 水稻 (*Oryza sativa*) 抗氧化酶活性在低暴露量 MPs 和重金属胁迫下会升高, 供试植物具有一定耐受性, 这与本文研究的结果不同, 可能是本实验植物种子发芽阶段幼苗耐受性减弱, MPs 加剧了

Cd 对叶片抗氧化酶活性的抑制作用. 总体上, 微塑料与重金属复合污染会抑制植物抗氧化系统的活性, 诱导胁迫反应, 影响植物正常生理代谢与生长.

4 结论

(1) PS 微塑料与重金属 Cd 的复合污染会直接影响土壤理化性质的变化, 并间接影响植物的生长.

(2) 单一 PS-MPs 暴露或 PS-MPs 联合 Cd 污染均能抑制生菜种子的萌发并影响其幼苗的生理活动, 且表现为随着暴露量增加, 抑制作用显著增强.

(3) 低暴露量 PS-MPs 或其联合 Cd 的复合污染对生菜幼苗的生长表现为促进作用, 但高含量胁迫下则表现出显著的抑制作用.

(4) 高含量 Cd 联合 PS-MPs 污染对生菜幼苗会产生显著的生态效应; 高暴露量 PS-MPs 会加剧 Cd 对幼苗的生态毒理效应, 二者表现为协同作用.

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