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# 微塑料与铅复合污染对玉米种子萌发与生长的影响

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**摘要:** 为探明微塑料和重金属复合污染对作物种子萌发与生长的影响, 以玉米种子为对象, 探究了铅(Pb)和3种微塑料[聚乙烯(PE)、聚丙烯(PP)、聚氯乙烯(PVC)]不同单一及复合浓度暴露对玉米种子萌发及其生长的影响. 结果表明, Pb单一暴露对玉米种子发芽的抑制总体上随其浓度的升高而增强; 与CK相比, 500、1 000和1 500 mg·L<sup>-1</sup> PE暴露显著抑制玉米种子发芽, 100 mg·L<sup>-1</sup>和300 mg·L<sup>-1</sup>暴露影响不显著(第5 d除外); 所有PP浓度暴露均显著抑制玉米种子发芽; 相比PP和PE, PVC单一暴露对玉米发芽抑制较轻. Pb和3种微塑料复合暴露均显著抑制玉米种子发芽, 随着时间的增长, 抑制逐渐减弱. 玉米种子的发芽指数、发芽势和活力指数均随着Pb及3种微塑料单一暴露浓度升高而减小, 且在Pb和PE复合暴露下较CK显著减小, 但在Pb和PP、Pb和PVC复合暴露下均无显著变化; 3种微塑料中, PVC对玉米种子活力影响相对最轻. 10 mg·L<sup>-1</sup> Pb和100 mg·L<sup>-1</sup>的3种微塑料单一暴露均促进了玉米茎和根生长, 其他浓度多表现为抑制作用. 500 mg·L<sup>-1</sup> PE时, 10 mg·L<sup>-1</sup>和20 mg·L<sup>-1</sup> Pb暴露均促进玉米种子茎和根生长, 但PP和Pb复合暴露未产生显著抑制; PVC和Pb复合暴露下, 500 mg·L<sup>-1</sup> PVC和10 mg·L<sup>-1</sup> Pb对玉米茎和根生长抑制最强. 微塑料和Pb复合暴露对玉米种子的萌发及生长的影响基本表现为拮抗作用, 减缓了各自单一暴露对玉米种子的毒害作用.

**关键词:** 微塑料; 铅(Pb); 复合污染; 玉米; 种子萌发与生长

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## Effects of Combined Pollution of Microplastics and Lead on Maize Seed Germination and Growth

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**Abstract:** Microplastics are a new contaminant that are causing worldwide concern. However, an understanding of their impact on agricultural seed germination remains inadequate. To investigate the effects of combined microplastic and heavy metal contamination on crop seed germination and growth, the effects of exposure to different single and combined concentrations of lead (Pb) and three microplastics [polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC)] on maize seed germination and growth were investigated using maize seeds. The results showed that: the inhibition of maize seed germination by Pb single exposure generally increased with Pb concentration. Compared with that in CK, 500, 1 000, and 1 500 mg·L<sup>-1</sup> PE exposure significantly inhibited maize seed germination, but 100 and 300 mg·L<sup>-1</sup> exposure had no significant effect (except at d 5). All PP concentration exposures significantly inhibited maize seed germination, with higher concentrations resulting in stronger inhibition. Compared to that under PP and PE exposure, PVC single exposure inhibited maize germination less, and 500, 1 000, and 1 500 mg·L<sup>-1</sup> exposures produced a facilitative effect at the later stages of germination. The germination index, germination potential, and vigor index of maize seeds decreased with the increase in the single exposure concentration of lead and three types of microplastics, significantly decreased compared with that of CK under the combined exposure of Pb and PE, and did not change significantly under the combined exposure of PP and Pb or PVC and Pb. Among the three types of microplastics, PVC had the least effect on corn seed vigor. Both single exposures of 10 mg·L<sup>-1</sup> Pb and 100 mg·L<sup>-1</sup> of the three microplastics promoted maize stalk and root growth, whereas other concentrations showed mostly inhibitory effects. When the PE concentration was 500 mg·L<sup>-1</sup>, the 10 and 20 mg·L<sup>-1</sup> Pb exposures both promoted maize seed stalk and root growth; however, the combined PP and Pb exposures did not produce significant inhibition, whereas 500 mg·L<sup>-1</sup> PVC and 10 mg·L<sup>-1</sup> Pb showed the strongest inhibition of maize stalk and root growth under combined PVC and Pb exposures. The effects of combined exposure to microplastics and Pb on the germination and growth of maize seeds were essentially antagonistic, thus slowing down the toxic effects of their respective single exposures on maize seeds.

**Key words:** microplastics; lead (Pb); complex pollution; maize; seed germination and growth

随着塑料制品数量的不断增加,越来越多的塑料废弃物进入环境后,经光照、高温氧化、物理风化和生物降解等作用逐渐破裂、降解成更小的塑料碎片<sup>[1]</sup>,其中粒径小于5 mm的碎片称为微塑料<sup>[2]</sup>.微塑料因其粒径小、数目多且难降解等特点,常富集于水体、土壤和沉积物等环境介质中,并通过生物摄食等过程在食物链中发生积累,从而对人体健康产生潜在危害<sup>[3]</sup>.微塑料已成为人们普遍关注的新型污染物<sup>[4,5]</sup>.

微塑料不仅普遍存在于海洋、河流和湖泊等水

环境中,同时大量富集于农田等土壤环境<sup>[6]</sup>.农田土壤微塑料主要来自有机肥施用、农业覆膜生产、污水灌溉、地表径流和大气沉降等过程<sup>[7]</sup>.微塑料进入农田后,会改变土壤结构和质地,影响土壤理化

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性质和生物多样性,破坏土壤环境功能,并在作物体内发生富集,从而对食物安全构成潜在威胁<sup>[8~10]</sup>。此外,微塑料会干扰营养元素的循环过程,改变植物种子萌发及生长特性,进而影响农作物生长<sup>[11,12]</sup>。所以,开展微塑料对作物种子萌发及生长影响的研究意义重大<sup>[13]</sup>。

目前,关于微塑料对作物种子萌发及生长影响的研究还处于初始阶段。De Silva 等<sup>[14]</sup>研究了聚乙烯微塑料(PE)对扁豆(*Lens culinaris*)种子萌发和生长的影响,首次证明了微塑料在作物种子萌发期间对其内部活动的阻碍作用,主要是由于微塑料颗粒对气孔的物理堵塞所致;Shi 等<sup>[15]</sup>研究发现,聚苯乙烯(PS)、聚乙烯(PE)和聚丙烯(PP)3种微塑料小于或等于 500 mg·L<sup>-1</sup> 暴露均可对番茄(*Lycopersicon esculentum* L.)种子萌发产生抑制作用,而1 000 mg·L<sup>-1</sup> 暴露抑制较轻;连加攀等<sup>[16]</sup>研究发现,乙烯-乙酸乙烯酯共聚合物(EVA)、低密度聚乙烯(LDPE)和聚甲基丙烯酸甲酯(PMMA)对小麦(*Triticum aestivum* L.)种子发芽和生长的影响程度与聚合物类型密切相关;吴佳妮等<sup>[17]</sup>研究发现,不同粒径的聚苯乙烯纳米塑料会对大豆(*Glycine max*)种子萌发产生不同作用(促进或抑制)。已开展的关于微塑料对作物种子萌发与生长影响的研究主要涉及小麦(*Triticum aestivum* L.)、大豆(*Glycine max*)、洋葱(*Allium cepa*)、水芹(*Lepidium sativum*)和黑麦草(*Lolium perenne* L.)等作物<sup>[18~21]</sup>,而针对

我国西北代表性农作物玉米(*Zea mays* L.)的研究很少。

土壤重金属污染是目前主要的环境问题之一。铅(Pb)是土壤中常见的重金属元素,主要通过大气沉降、含铅废水灌溉、尾矿排放和固体废物堆放等过程进入土壤,进而对土壤作物及生态系统产生危害<sup>[22]</sup>。重金属和微塑料在土壤中的复合污染时有发生<sup>[23,24]</sup>,而目前关于两者复合污染对作物种子萌发与生长影响的研究鲜见报道<sup>[25]</sup>。本文以玉米作为供试作物,探究 Pb 和 3 种微塑料[聚乙烯(PE)、聚丙烯(PP)、聚氯乙烯(PVC)]不同单一及复合浓度暴露对玉米种子萌发和生长的影响,通过揭示 Pb 与微塑料对作物的联合作用,旨在为微塑料和重金属污染生态风险评估和农田土壤污染的修复提供科学依据。

## 1 材料与方法

### 1.1 供试材料

供试玉米种子为五谷 704(国审玉 2012011,实测发芽率为 98.63%)。30% H<sub>2</sub>O<sub>2</sub> 和 Pb(NO<sub>3</sub>)<sub>2</sub> 均为分析纯。3 种常见微塑料(PE、PP 和 PVC)均购自于东莞市樟木头志研新材料经营部(过 100 目筛),其 SEM(FE-SEM, FEI Quanta 450)照片如图 1 所示,PE 颗粒表面较光滑,多孔且有裂缝;PP 表面有碎片类微小颗粒,且断裂褶曲变形;PVC 表面粗糙,有大小不一的泡状颗粒。

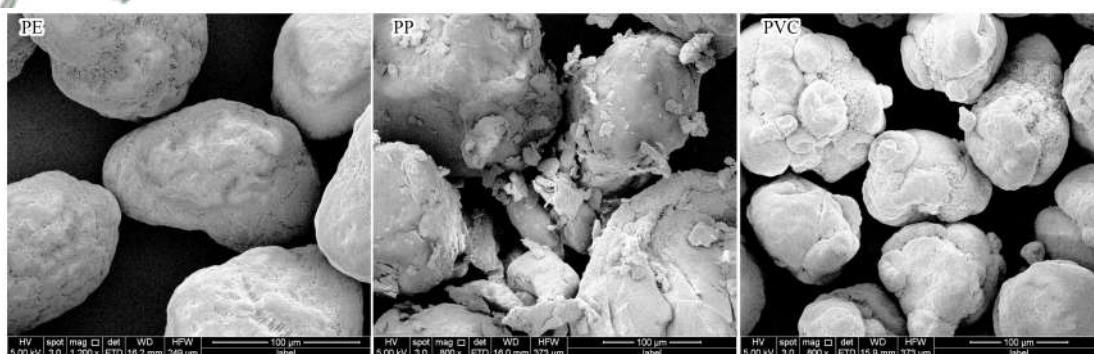


图 1 PE、PP 和 PVC 的 SEM 图

Fig. 1 SEM images of PE, PP, and PVC

### 1.2 实验设计

预实验:在培养皿中加入 5 mL 去离子水,封盖,在 25℃、12 000 lx 光照培养 12 h,20℃、无光照培养 12 h,交替连续培养 7 d。每天用称量法测定并计算培养皿中水的蒸发量。重复 3 次。得到每天(24 h)水的平均蒸发量为 0.45 mL。

单一暴露实验:设 5 个微塑料处理(100、300、500、1 000 和 1 500 mg·L<sup>-1</sup>)<sup>[16]</sup>和 5 个 Pb 浓度(10、20、50、100 和 150 mg·L<sup>-1</sup>)。选取健康饱满的玉米

种子,经 H<sub>2</sub>O<sub>2</sub> 溶液(1.0%)浸泡 30 min 后,水洗 3 次,在去离子水中浸泡 6 h,取 8 粒种子均匀摆放在加入了 20 g 土壤(取自宁夏师范学院校园 0~20 cm 表层土壤,过 20 目筛)的培养皿(直径为 9 cm)中,加入 5 mL 微塑料或 Pb 溶液,在与预实验相同条件下,将其置于生化培养箱中,培养 7 d,每隔 24 h 补充水分(0.45 mL)以使培养液浓度保持稳定,记录玉米种子萌发及生长情况。每个处理重复 3 次。

复合暴露实验:选 3 个微塑料浓度(100、300 和

500 mg·L<sup>-1</sup>) 和 2 个 Pb 浓度 (10 mg·L<sup>-1</sup> 和 20 mg·L<sup>-1</sup>) 进行复合暴露实验. 将 5 mL 微塑料和 Pb 的复合溶液加入培养皿中, 在与单一污染实验相同的条件下进行实验, 记录玉米种子萌发及生长情况. 每个处理 3 次重复.

空白实验 (CK): 相同条件下, 用等量去离子水进行玉米种子萌发实验.

### 1.3 指标测量及计算

种子吐出白色胚芽作为第 1 d; 当幼芽长度达到种子长度的一半, 幼根长度与种子长度相等时开始统计发芽数; 在第 3 d 计算发芽势, 第 7 d 计算发芽率<sup>[26]</sup>. 根和茎的长度用 1/10 cm 尺子进行人工测量. 相关指标的计算公式如下<sup>[23]</sup>:

发芽率 =  $t$  d 内发芽种子数 / 供试种子总数 × 100%

发芽势 = 3 d 内发芽种子数 / 供试种子总数 × 100%

$$\text{发芽指数} = \sum G_i / D_i$$

式中,  $G_i$  为  $t$  d 内的发芽种子数;  $D_i$  为对应的发芽天数.

活力指数 = 发芽指数 × 茎长度

微塑料和 Pb 对玉米种子的联合作用判断<sup>[27]</sup>:

$$\Delta I = (I_{\text{MPs+Pb}} - I_{\text{CK}}) - (I_{\text{MPs}} - I_{\text{CK}}) - (I_{\text{Pb}} - I_{\text{CK}})$$

式中,  $I_{\text{MPs+Pb}}$ 、 $I_{\text{Pb}}$ 、 $I_{\text{MPs}}$  和  $I_{\text{CK}}$  分别为微塑料与 Pb 复合、Pb 单独、微塑料单独和空白处理时玉米种子萌发及生长指标. 若  $\Delta I = 0$ , 无交互作用;  $\Delta I > 0$ , 拮抗

作用;  $\Delta I < 0$ , 协同作用.

### 1.4 数据处理与分析

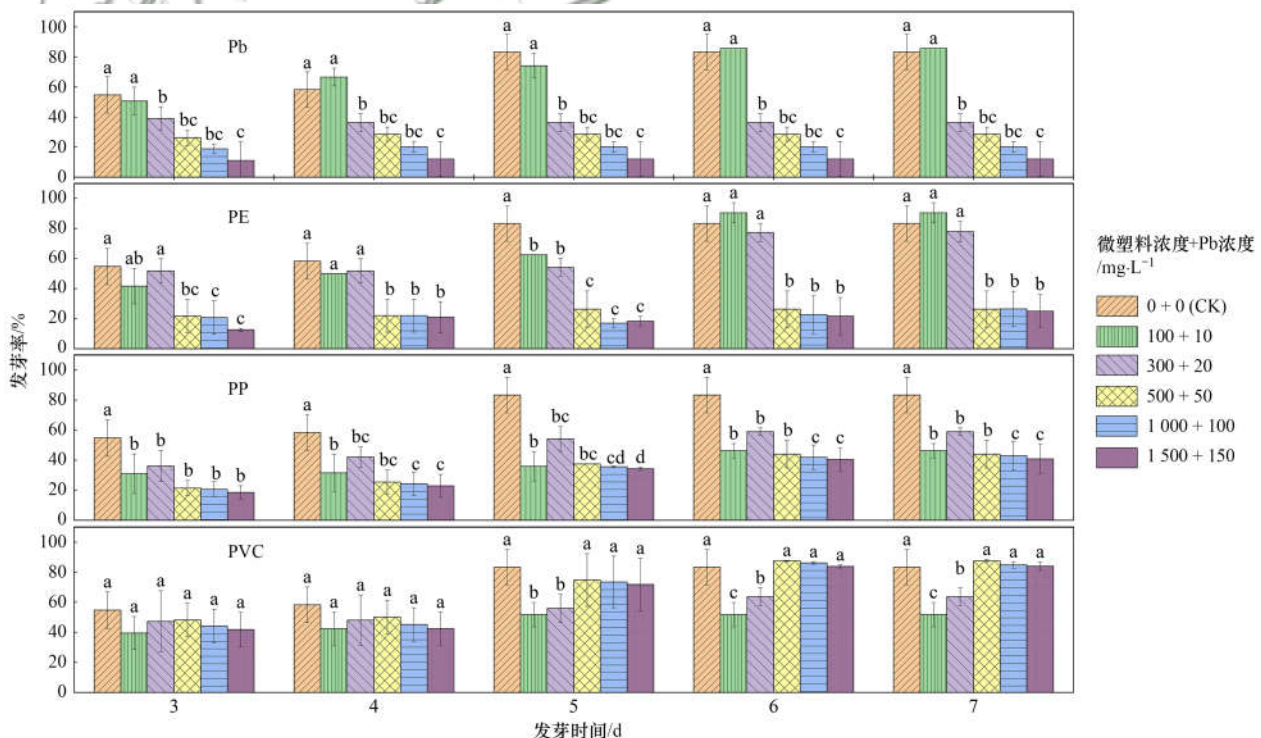
数据均以平均值 ± 标准偏差 (Mean ± SD) 表示, 分别用 SPSS22.0 和 Origin2021 进行统计分析和制图, 用 SPSS22.0 进行单因素方差分析和多重比较 (Duncan 检验, 95% 置信水平).

## 2 结果与分析

### 2.1 单一暴露对玉米种子发芽率的影响

发芽率的大小能直观体现作物种子在污染胁迫下发芽的能力. Pb 单一暴露下, 玉米种子的发芽率为 11.12% ~ 85.71%, 且总体上随着 Pb 浓度的升高而减小 (图 2). 10 mg·L<sup>-1</sup> Pb 暴露下, 玉米发芽率在第 4、6 和 7 d 均高于 CK, 但差异不显著; 其他 Pb 浓度暴露下, 玉米发芽率均显著低于 CK, 且 Pb 浓度越高, 发芽率越小, 说明 Pb 单一暴露浓度越高, 其对玉米种子发芽的抑制作用越明显.

PE、PP 和 PVC 暴露下, 玉米种子的发芽率分别为 86.75% ~ 96.73%、86.72% ~ 96.76% 和 86.71% ~ 96.74%, 说明供试的微塑料浓度范围暴露下, 大部分玉米种子均可以发芽, 但发芽率的变化趋势因微塑料类型不同各异 (图 2). 玉米每天的发芽率在 100 mg·L<sup>-1</sup> 和 300 mg·L<sup>-1</sup> PE 暴露下均较 CK 变化不显著 (第 5 d 除外), 但在 500、1 000 和 1 500 mg·L<sup>-1</sup> 暴露下均显著降低, 说明 PE 对玉米种子的



不同小写字母表示同一时间不同处理间具有显著性差异 ( $P < 0.05$ ), 下同

图 2 Pb 和微塑料不同单一浓度暴露下玉米发芽率变化

Fig. 2 Changes in maize germination rate under different single concentrations of lead and microplastics

发芽影响在 100 mg·L<sup>-1</sup>和 300 mg·L<sup>-1</sup>暴露时轻微,但随着暴露浓度升高,变为较强的抑制作用. 所有 PP 浓度暴露下,玉米种子发芽率均显著小于 CK, 300 mg·L<sup>-1</sup> PP 暴露下的玉米发芽率最高,1 500 mg·L<sup>-1</sup>下最低. PVC 暴露时,500 mg·L<sup>-1</sup>暴露下玉米每天的发芽率均为最高,为 86. 71%~88. 64%;在发芽后期(第 6、7 d),玉米发芽率在 100 mg·L<sup>-1</sup>和 300 mg·L<sup>-1</sup> PVC 暴露下均显著低于 CK,而 500、1 000和1 500 mg·L<sup>-1</sup>暴露下均高于 CK,对玉米种子发芽产生一定的促进作用. 总体上看,相比 PP 和 PE,PVC 对玉米种子发芽抑制较轻.

2.2 单一暴露对玉米种子活力的影响

发芽势、发芽指数、活力指数等指标大小变化能反映污染物对作物种子活力的影响程度. 玉

米种子的发芽指数、发芽势和活力指数均随着 Pb 浓度的升高而降低,除 10 mg·L<sup>-1</sup>外,其余 Pb 浓度暴露下的 3 个指标均较 CK 显著减小(表 1). 微塑料单一暴露对玉米种子发芽势的影响总体上表现为抑制作用. PE 暴露下,3 个指标总体上随着 PE 浓度的升高而减小,但 100 mg·L<sup>-1</sup>和 300 mg·L<sup>-1</sup> PE 暴露下较 CK 变化不显著,在 >300 mg·L<sup>-1</sup>暴露下变化显著. 3 个指标总体上随着 PP 暴露浓度的升高显著降低,且最大值均出现在 300 mg·L<sup>-1</sup>暴露时. 所有 PVC 浓度暴露下,玉米种子发芽指数和发芽势较 CK 均无显著变化,1 000 mg·L<sup>-1</sup>和 1 500 mg·L<sup>-1</sup>PVC 暴露下的活力指数较 CK 显著降低. 相比 PE 和 PP,PVC 对玉米种子活力影响较轻.

表 1 Pb 和微塑料不同单一浓度暴露下玉米种子发芽特性的变化

| Table 1 Changes in germination characteristics of maize seeds exposed to different single concentrations of lead and microplastics |                       |       |             |               |              |
|------------------------------------------------------------------------------------------------------------------------------------|-----------------------|-------|-------------|---------------|--------------|
| 处理                                                                                                                                 | 浓度/mg·L <sup>-1</sup> | 发芽指数  | 发芽势/%       | 活力指数          |              |
| Pb                                                                                                                                 | CK                    | 0     | 6.0 ± 1.3a  | 54.8 ± 14.9a  | 22.5 ± 9.0a  |
|                                                                                                                                    |                       | 10    | 5.8 ± 0.6a  | 50.6 ± 11.3a  | 18.5 ± 5.5a  |
|                                                                                                                                    |                       | 20    | 3.2 ± 0.7b  | 39.1 ± 9.2ab  | 7.3 ± 1.7b   |
|                                                                                                                                    |                       | 50    | 2.4 ± 0.5bc | 26.3 ± 6.2bc  | 5.0 ± 1.7b   |
|                                                                                                                                    |                       | 100   | 1.7 ± 0.4bc | 18.9 ± 3.8bc  | 3.2 ± 1.0b   |
|                                                                                                                                    |                       | 150   | 1.0 ± 1.3c  | 11.1 ± 15.2c  | 1.8 ± 2.1b   |
| PE                                                                                                                                 | CK                    | 0     | 6.0 ± 1.3a  | 54.8 ± 14.9a  | 22.5 ± 9.0a  |
|                                                                                                                                    |                       | 100   | 5.4 ± 0.5a  | 41.7 ± 14.4ab | 22.7 ± 4.8a  |
|                                                                                                                                    |                       | 300   | 5.2 ± 0.7a  | 51.8 ± 9.9a   | 20.5 ± 4.8a  |
|                                                                                                                                    |                       | 500   | 2.1 ± 1.2b  | 21.8 ± 13.6bc | 4.5 ± 3.0b   |
|                                                                                                                                    |                       | 1 000 | 1.9 ± 1.1b  | 20.8 ± 13.6bc | 3.6 ± 2.5b   |
|                                                                                                                                    |                       | 1 500 | 1.6 ± 0.7b  | 12.6 ± 1.2c   | 2.7 ± 1.5b   |
| PP                                                                                                                                 | CK                    | 0     | 6.0 ± 1.3a  | 54.8 ± 14.9a  | 22.5 ± 9.0a  |
|                                                                                                                                    |                       | 100   | 3.2 ± 1.0b  | 31.0 ± 16.2b  | 13.1 ± 3.8b  |
|                                                                                                                                    |                       | 300   | 4.1 ± 0.7b  | 36.1 ± 12.7ab | 11.3 ± 1.2b  |
|                                                                                                                                    |                       | 500   | 2.8 ± 0.1bc | 21.4 ± 6.2b   | 6.3 ± 0.3b   |
|                                                                                                                                    |                       | 1 000 | 2.7 ± 0.5bc | 20.6 ± 6.3b   | 10.4 ± 2.2b  |
|                                                                                                                                    |                       | 1 500 | 2.5 ± 0.5c  | 18.5 ± 5.4b   | 8.7 ± 1.4b   |
| PVC                                                                                                                                | CK                    | 0     | 6.0 ± 1.3a  | 54.8 ± 14.9a  | 22.5 ± 9.0a  |
|                                                                                                                                    |                       | 100   | 3.7 ± 1.0a  | 34.5 ± 13.5a  | 16.0 ± 4.6ab |
|                                                                                                                                    |                       | 300   | 4.4 ± 1.4a  | 42.3 ± 25.0a  | 15.0 ± 4.1ab |
|                                                                                                                                    |                       | 500   | 5.3 ± 0.9a  | 41.2 ± 13.7a  | 12.0 ± 3.0b  |
|                                                                                                                                    |                       | 1 000 | 5.1 ± 0.9a  | 39.2 ± 13.7a  | 10.0 ± 2.1b  |
|                                                                                                                                    |                       | 1 500 | 5.0 ± 0.8a  | 37.9 ± 14.1a  | 8.9 ± 1.6b   |

1) 同一类型微塑料同列数据中不同小写字母表示处理间差异显著(P < 0.05),下同

2.3 单一暴露对玉米种子生长的影响

Pb 和微塑料单一暴露对玉米种子根、芽生长的影响随着各自浓度不同而不同(图 3). 总体上看,10 mg·L<sup>-1</sup>Pb 和 100 mg·L<sup>-1</sup>的 3 种微塑料暴露下玉米种子茎、根长均大于 CK,但随着各自浓度的升高,玉米茎长和根长逐渐变小. 这说明浓度越高,Pb 和微塑料单一暴露对玉米种子的生长抑制越强. 当暴露浓度最大时,Pb、PE、PP 及 PVC 对玉米茎生长

抑制率分别为 50.36%、55.67%、4.24% 和 49.48%,对根生长抑制率分别达到 21.61%、45.17%、49.25% 和 39.84%.

2.4 复合暴露对玉米发芽率的影响

基于单一暴露结果,复合暴露实验选取的微塑料浓度为:100 mg·L<sup>-1</sup>(对玉米种子的发芽起促进作用)、300 mg·L<sup>-1</sup>(较弱的抑制作用)和 500 mg·L<sup>-1</sup>(较强的抑制作用);Pb 浓度为:10 mg·L<sup>-1</sup>

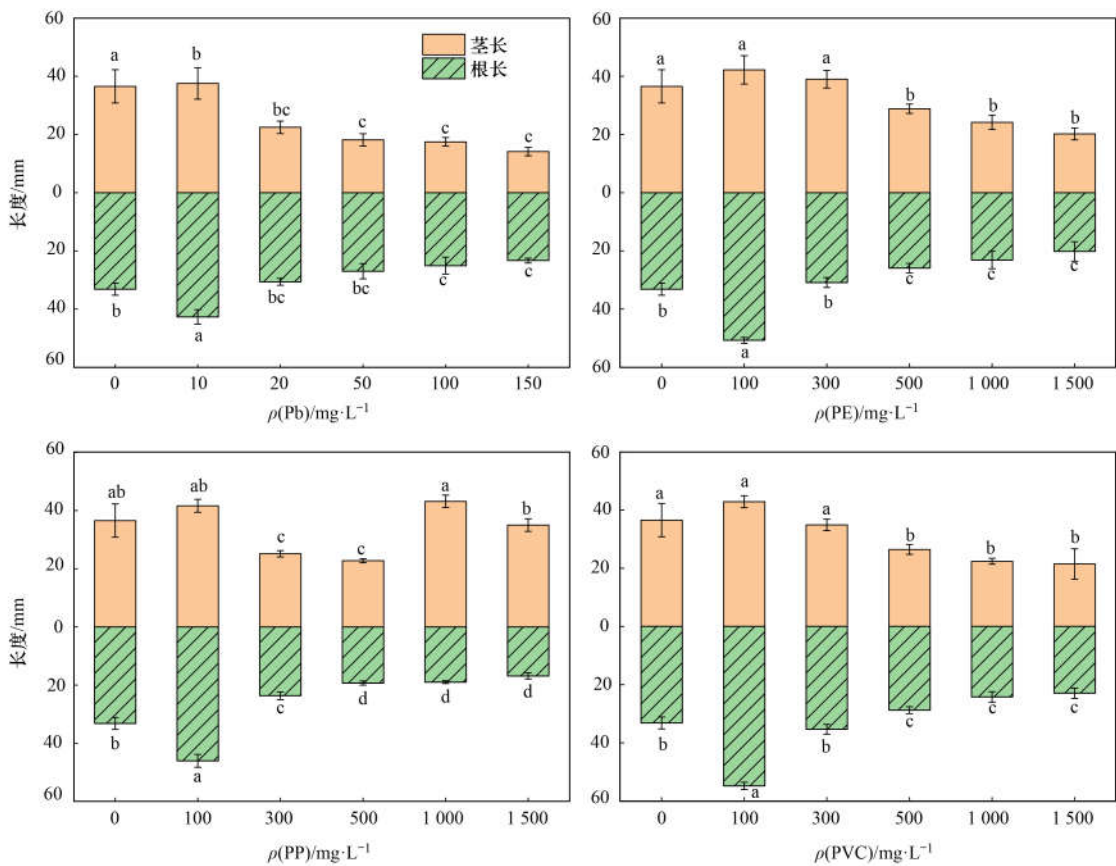


图 3 Pb 和微塑料不同单一浓度暴露下玉米种子茎长和根长变化

Fig. 3 Changes in stem and root length of maize seeds exposed to different concentrations of lead and microplastics

(促进作用)和  $20 \text{ mg} \cdot \text{L}^{-1}$  (抑制作用).

所有复合暴露下,玉米种子发芽率均小于 CK,但随着发芽时间增长,发芽率均有所增加(图 4).这说明 3 种微塑料和 Pb 的复合暴露均抑制了玉米种

子发芽,但这种抑制作用随着时间增长逐渐减弱.总体上看,同一 Pb 浓度下,玉米发芽率随着 PE 和 PP 浓度增加而增加,但随着 PVC 浓度增加而减少. PE + Pb 暴露时,玉米每天发芽率在  $\text{PE}(300 \text{ mg} \cdot \text{L}^{-1}) +$

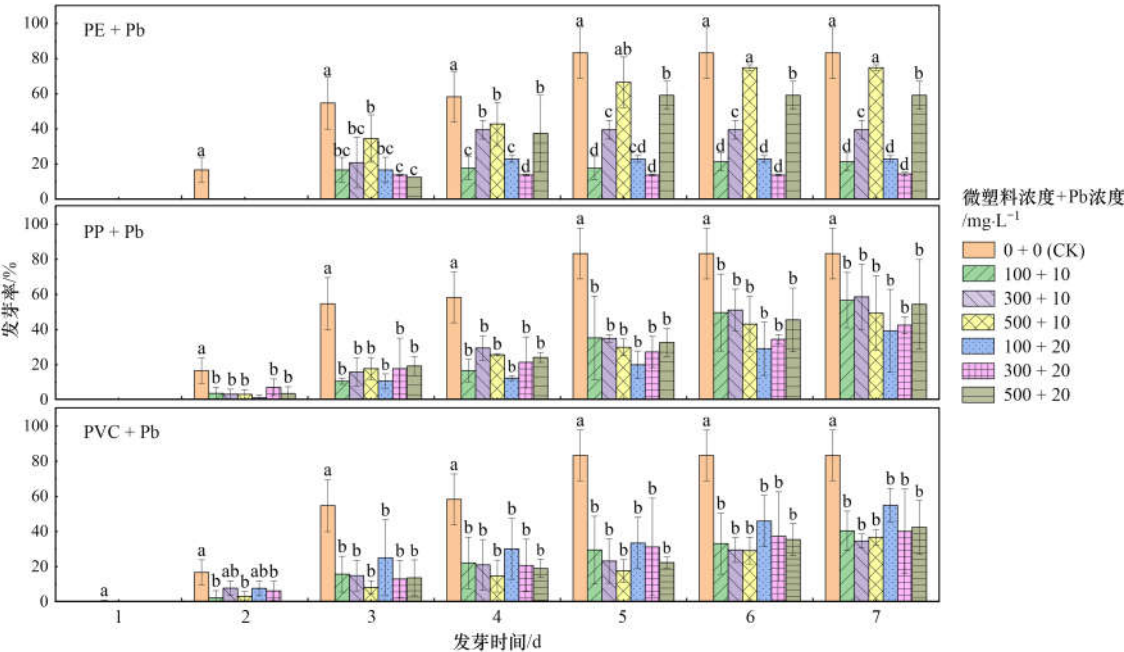


图 4 Pb 和微塑料不同复合浓度暴露下玉米发芽率的变化

Fig. 4 Changes in maize germination rate under different combined concentrations of lead and microplastics

Pb(20 mg·L<sup>-1</sup>) 暴露下为最小(13.76%~14.42%)(第3 d 除外);在 PE(500 mg·L<sup>-1</sup>) + Pb(10 mg·L<sup>-1</sup>) 下最大(34.52%~74.90%)。相比其他 PE + Pb 暴露,PP(100 mg·L<sup>-1</sup>) + Pb(20 mg·L<sup>-1</sup>) 暴露下的发芽率最小(1.21%~39.33%),PP(300 mg·L<sup>-1</sup>) + Pb(10 mg·L<sup>-1</sup>) 处理下达到最大(3.27%~58.67%)(第2、3 d 除外)。PVC + Pb 暴露时,PVC(500 mg·L<sup>-1</sup>) + Pb(10 mg·L<sup>-1</sup>) 暴露下玉米种子发芽率最小(3.12%~36.73%)(第2、7 d 除外),PVC(100 mg·L<sup>-1</sup>) + Pb(20 mg·L<sup>-1</sup>) 暴露下最大(7.63%~54.93%)。10 mg·L<sup>-1</sup> Pb 与 PVC 复合暴露下玉米发

芽率普遍低于 20 mg·L<sup>-1</sup> Pb 时复合暴露。

2.5 复合暴露对玉米种子活力的影响

3 种微塑料和 Pb 复合暴露下,玉米种子发芽指数、发芽势和活力指数随着微塑料类型不同而呈现不同的变化趋势(表2)。与 CK 相比,Pb + PE 暴露对发芽指数、发芽势和活力指数均发生显著变化,3 个指标在 10 mg·L<sup>-1</sup> Pb 处理下均随着 PE 浓度增加而增大,在 20 mg·L<sup>-1</sup> Pb 处理下随 PE 浓度增加先减后增。PP + Pb 和 PVC + Pb 暴露下,3 个指标均较 CK 无显著变化,且随着 PP 和 PVC 浓度增加总体上呈现升高趋势。

表2 Pb 和微塑料不同复合浓度暴露下玉米种子发芽特性的变化

| Table 2 Changes in germination characteristics of maize seeds exposed to different combined concentrations of lead and microplastics |                       |               |                 |                  |
|--------------------------------------------------------------------------------------------------------------------------------------|-----------------------|---------------|-----------------|------------------|
| 处理                                                                                                                                   | 浓度/mg·L <sup>-1</sup> | 发芽指数          | 发芽势/%           | 活力指数             |
| CK                                                                                                                                   | 0                     | 4.34 ± 0.91ab | 54.76 ± 14.87a  | 162.49 ± 65.09bc |
|                                                                                                                                      | 100 + 10              | 1.61 ± 0.50e  | 16.67 ± 7.22bc  | 35.60 ± 17.70de  |
|                                                                                                                                      | 300 + 10              | 2.96 ± 0.41cd | 20.83 ± 14.43bc | 117.59 ± 26.89cd |
|                                                                                                                                      | 500 + 10              | 4.70 ± 0.67a  | 34.52 ± 13.52b  | 351.45 ± 46.74a  |
|                                                                                                                                      | 100 + 20              | 1.84 ± 0.31de | 16.67 ± 7.22bc  | 42.44 ± 10.77de  |
|                                                                                                                                      | 300 + 20              | 1.21 ± 0.04e  | 13.76 ± 0.45c   | 17.46 ± 1.38e    |
|                                                                                                                                      | 500 + 20              | 3.49 ± 0.76bc | 12.50 ± 0.00c   | 210.73 ± 69.52b  |
| PP + Pb                                                                                                                              | 0                     | 4.34 ± 0.91a  | 54.76 ± 14.87a  | 162.49 ± 65.09a  |
|                                                                                                                                      | 100 + 10              | 3.67 ± 1.37a  | 46.02 ± 46.02a  | 153.38 ± 81.69a  |
|                                                                                                                                      | 300 + 10              | 4.13 ± 2.37a  | 54.17 ± 40.18a  | 247.90 ± 185.04a |
|                                                                                                                                      | 500 + 10              | 4.16 ± 2.42a  | 58.33 ± 38.19a  | 229.08 ± 200.20a |
|                                                                                                                                      | 100 + 20              | 3.03 ± 1.70a  | 37.50 ± 25.00a  | 142.32 ± 116.88a |
|                                                                                                                                      | 300 + 20              | 4.73 ± 0.97a  | 52.67 ± 25.25a  | 171.46 ± 116.02a |
|                                                                                                                                      | 500 + 20              | 4.16 ± 1.70a  | 58.33 ± 28.87a  | 243.03 ± 194.74a |
| PVC + Pb                                                                                                                             | 0                     | 4.34 ± 0.91a  | 54.76 ± 14.87a  | 162.49 ± 65.09a  |
|                                                                                                                                      | 100 + 10              | 4.34 ± 2.07a  | 58.33 ± 38.19a  | 155.88 ± 115.82a |
|                                                                                                                                      | 300 + 10              | 4.57 ± 0.98a  | 58.33 ± 28.87a  | 132.93 ± 66.42a  |
|                                                                                                                                      | 500 + 10              | 4.00 ± 2.39a  | 54.17 ± 43.90a  | 118.71 ± 100.31a |
|                                                                                                                                      | 100 + 20              | 5.35 ± 1.44a  | 66.67 ± 28.87a  | 240.81 ± 58.10a  |
|                                                                                                                                      | 300 + 20              | 5.77 ± 1.17a  | 75.00 ± 43.30a  | 148.56 ± 100.77a |
|                                                                                                                                      | 500 + 20              | 5.37 ± 2.33a  | 76.00 ± 41.30a  | 248.77 ± 165.96a |

2.6 复合暴露对玉米种子生长的影响

玉米种子茎长和根长在 10 mg·L<sup>-1</sup> Pb 暴露时均随着 PE 浓度增加而增大,在 20 mg·L<sup>-1</sup> Pb 暴露下随着 PE 浓度增大先减小后增大(图5)。当 PE 浓度为 500 mg·L<sup>-1</sup> 时,两种 Pb 浓度暴露均显著促进玉米茎和根的生长。相比其他 PP + Pb 暴露,PP(300 mg·L<sup>-1</sup>) + Pb(10 mg·L<sup>-1</sup>) 暴露下玉米根和茎长均达到最大,分别为 60.20 mm 和 57.7 mm。Pb + PVC 暴露下,除 PVC(100 mg·L<sup>-1</sup>) + Pb(20 mg·L<sup>-1</sup>) 与 PVC(500 mg·L<sup>-1</sup>) + Pb(20 mg·L<sup>-1</sup>) 处理,其他处理暴露均抑制了玉米茎的生长;PVC(500 mg·L<sup>-1</sup>) + Pb(10 mg·L<sup>-1</sup>) 暴露下,玉米茎长和根均为最小,分别为 22.82 mm 和 15.78 mm。

3 讨论

3.1 单一暴露对玉米种子发芽及生长的影响

玉米是西北主要的经济作物之一,其大部分种植采用覆膜方式,玉米种子发芽与生长势必会受到土壤中微塑料的影响<sup>[28]</sup>。发芽率、发芽势、发芽指数及活力指数是种子发芽实验的重要指标,常用于反映作物种子的质量和发芽能力<sup>[29,30]</sup>。Pb 对作物种子发芽及生长影响的研究已有大量报道,于雄胜等<sup>[31]</sup>研究发现,谷子的发芽势、发芽率和发芽指数均与 Pb 暴露浓度呈显著负相关;段代祥等<sup>[32]</sup>研究表明,绿豆种子的发芽率、发芽势、根长及芽长均随着 Pb 浓度(10~200 mg·kg<sup>-1</sup>) 增加而降低。本研

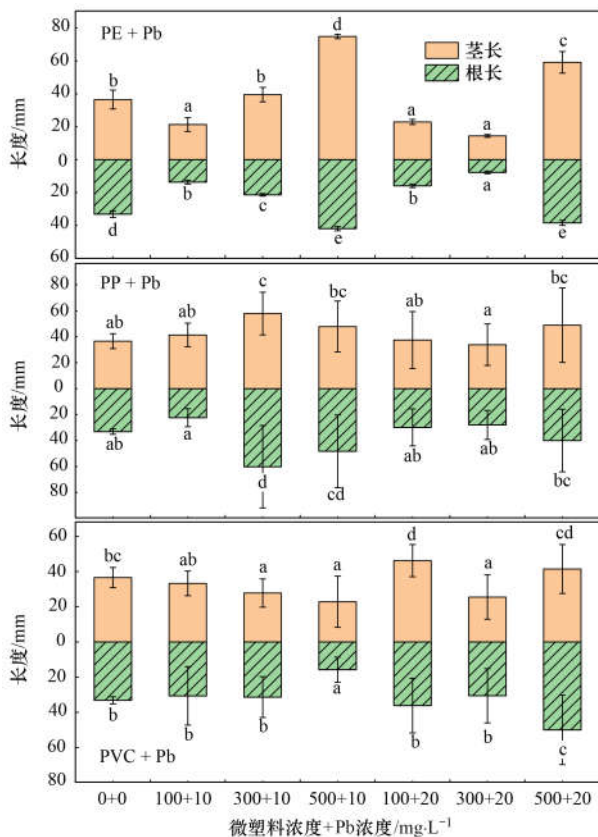


图5 Pb和微塑料不同复合浓度暴露下玉米种子茎长和根长的变化

Fig. 5 Changes in stem length and root length of maize seeds exposed to different concentrations of lead and microplastics

究中,玉米种子的发芽率总体上随着Pb浓度的增加而减小,这与以上研究结果相同.此外,本研究中Pb暴露对玉米种子发芽和生长的影响表现出“低促高抑”的规律( $10 \text{ mg} \cdot \text{kg}^{-1}$ 促进,  $> 10 \text{ mg} \cdot \text{kg}^{-1}$ 抑制),这与杨玲等<sup>[33]</sup>研究Pb、Zn胁迫对早熟禾和狗牙根种子萌发出苗影响的结果相似.

微塑料对植物种子萌发生长的影响与微塑料聚合物类型密切相关<sup>[34,35]</sup>.张彦等<sup>[18]</sup>通过盆栽试验,探究了PP、PE和可降解塑料(PLA)对小麦种子发芽及生长的影响,结果发现,3种微塑料均降低了小麦种子发芽率,且降低程度随着微塑料类型、粒径和浓度不同而不同,对小麦种子生长指标的影响因微塑料类型不同而各异.本研究中,不同的微塑料类型对玉米种子萌发及生长的影响程度不同,这不仅是由于不同聚合物微塑料表面粗糙程度不同(图1),而且是因为不同类型微塑料颗粒表面所带电荷也不同(带正电荷较多颗粒比不带或者带负电荷的颗粒更易附着于表面),最终使得作物种子根部对微塑料的吸附和吸收能力有较大差别<sup>[36,37]</sup>.

此外,在本研究中,较高浓度(500、1 000和1 500  $\text{mg} \cdot \text{L}^{-1}$ )PVC暴露对玉米发芽产生一定的促进作用,可能是由于PVC在高浓度时,易发生团聚

作用,表面积减小,减弱了玉米种子对其的吸附和吸收<sup>[6]</sup>.微塑料对玉米种子发芽和生长的抑制作用随着萌发时间的增长逐渐减弱或者消失(PVC),这可能是因为作物种子萌芽初期急需大量水分,而微塑料颗粒短时间内大量吸附于种子的表面,阻滞了种子对水分的吸收,但随着暴露时间增长,植物吸取的水分逐渐充足,微塑料对种子的抑制也逐渐消失<sup>[38]</sup>.

### 3.2 复合暴露对玉米种子发芽及生长的影响

微塑料能吸附环境中的重金属离子,通过自身的迁移优势,加大重金属进入生物体内并发生累积的概率,从而对生物造成更大毒害<sup>[39]</sup>;不同类型的微塑料颗粒带电性、表面的官能团及其它特性的差异性,使得其对重金属的吸附行为因微塑料类型不同而不同<sup>[40,41]</sup>.本实验基于单一暴露实验的结果,选取的100、300和500  $\text{mg} \cdot \text{L}^{-1}$ 这3种微塑料浓度,10  $\text{mg} \cdot \text{L}^{-1}$ 和20  $\text{mg} \cdot \text{L}^{-1}$ 这2种Pb浓度,进行复合暴露实验,同时采用生长净变化量法判定了微塑料和Pb联合作用(表3).结果表明,微塑料聚合物类型、浓度以及Pb离子浓度不同,微塑料和Pb对玉米种子的萌发及生长产生的交互作用不同,但绝大部分复合暴露均表现为拮抗作用.这说明,Pb和微塑料复合暴露减缓了其各自单一暴露对玉米的毒害作用,这可能是由于重金属离子被吸附在微塑料上,或在微塑料表面发生聚集,减小了其与玉米种子接触的程度,从而降低两者的生物可利用性<sup>[27,42]</sup>.而PE(100  $\text{mg} \cdot \text{L}^{-1}$ ) + Pb(10  $\text{mg} \cdot \text{L}^{-1}$ )和PP(300  $\text{mg} \cdot \text{L}^{-1}$ ) + Pb(20  $\text{mg} \cdot \text{L}^{-1}$ )暴露对玉米种子萌发和生长均产生协同作用,主要是因为微塑料通过吸附作用也能使Pb离子发生富集,增加了作物的摄入浓度,加重了污染物毒性效应,从而表现出协同危害<sup>[43,44]</sup>.

总体上看,同一Pb浓度暴露下,100  $\text{mg} \cdot \text{L}^{-1}$ 和300  $\text{mg} \cdot \text{L}^{-1}$ 的PP和PE暴露对玉米种子均表现为协同作用,500  $\text{mg} \cdot \text{L}^{-1}$ 暴露均表现为拮抗作用.与以上结果相似,DONG等<sup>[45]</sup>研究发现,较低浓度(40  $\text{mg} \cdot \text{L}^{-1}$ )聚苯乙烯减缓了重金属对水稻生长的毒害,而较高浓度(100  $\text{mg} \cdot \text{L}^{-1}$ )强化了重金属对水稻生长的抑制.然而,微塑料和Pb复合暴露对玉米种子萌发和生长的影响不仅与微塑料类型和暴露浓度有关,还与微塑料粒径大小、实际耕作方式及气候等因素相关,其机制复杂且尚未明确,还需进一步深入研究.

## 4 结论

(1) Pb对玉米种子发芽的抑制作用随着其暴露

表 3 微塑料和 Pb 暴露对玉米种子发芽及生长的交互作用

Table 3 Interaction between micro plastics and lead exposure on maize seed germination and growth

| $\rho(\text{Pb})$<br>/ $\text{mg}\cdot\text{L}^{-1}$ | 微塑料类型, 浓度<br>/ $\text{mg}\cdot\text{L}^{-1}$ | 第 7 d 发芽率 | 发芽势 | 发芽指数 | 根长 | 茎长 | 活力指数 |
|------------------------------------------------------|----------------------------------------------|-----------|-----|------|----|----|------|
| 10                                                   | PE,100                                       | 协同        | 协同  | 协同   | 协同 | 协同 | 协同   |
|                                                      | PE,300                                       | 协同        | 协同  | 协同   | 协同 | 拮抗 | 拮抗   |
|                                                      | PE,500                                       | 拮抗        | 拮抗  | 拮抗   | 拮抗 | 拮抗 | 拮抗   |
|                                                      | PP,100                                       | 拮抗        | 拮抗  | 拮抗   | 协同 | 拮抗 | 拮抗   |
|                                                      | PP,300                                       | 协同        | 拮抗  | 拮抗   | 拮抗 | 拮抗 | 拮抗   |
|                                                      | PP,500                                       | 拮抗        | 拮抗  | 拮抗   | 拮抗 | 拮抗 | 拮抗   |
|                                                      | PVC,100                                      | 协同        | 拮抗  | 拮抗   | 协同 | 协同 | 拮抗   |
|                                                      | PVC,300                                      | 协同        | 拮抗  | 拮抗   | 协同 | 协同 | 拮抗   |
|                                                      | PVC,500                                      | 协同        | 拮抗  | 拮抗   | 协同 | 拮抗 | 拮抗   |
| 20                                                   | PE,100                                       | 协同        | 协同  | 拮抗   | 协同 | 协同 | 协同   |
|                                                      | PE,300                                       | 协同        | 协同  | 协同   | 协同 | 协同 | 协同   |
|                                                      | PE,500                                       | 拮抗        | 拮抗  | 拮抗   | 拮抗 | 拮抗 | 拮抗   |
|                                                      | PP,100                                       | 拮抗        | 拮抗  | 拮抗   | 协同 | 拮抗 | 拮抗   |
|                                                      | PP,300                                       | 拮抗        | 拮抗  | 拮抗   | 拮抗 | 拮抗 | 拮抗   |
|                                                      | PP,500                                       | 拮抗        | 拮抗  | 拮抗   | 拮抗 | 拮抗 | 拮抗   |
|                                                      | PVC,100                                      | 拮抗        | 拮抗  | 拮抗   | 协同 | 拮抗 | 拮抗   |
|                                                      | PVC,300                                      | 拮抗        | 拮抗  | 拮抗   | 协同 | 拮抗 | 拮抗   |
|                                                      | PVC,500                                      | 拮抗        | 拮抗  | 拮抗   | 协同 | 协同 | 协同   |

浓度升高而增强. 大部分玉米种子在微塑料单一暴露下均可发芽.  $100\text{ mg}\cdot\text{L}^{-1}$ 和 $300\text{ mg}\cdot\text{L}^{-1}$ PE 暴露对玉米种子的发芽影响不显著, 而 $500$ 、 $1\,000$ 和 $1\,500\text{ mg}\cdot\text{L}^{-1}$ 暴露显著抑制玉米种子的发芽. 所有 PP 浓度暴露对玉米种子发芽均产生显著的抑制作用. 总体上看, 相比 PP 和 PE, PVC 单一暴露对玉米种子发芽抑制较轻. 3 种微塑料和 Pb 的复合暴露均抑制了玉米种子发芽, 且这种抑制作用随着时间增长逐渐减弱.

(2) 总体上看, 玉米种子的发芽指数、发芽势和活力指数均随着 Pb 及 3 种微塑料暴露浓度升高而降低. 相比 PE 和 PP, PVC 对玉米种子活力影响相对较轻. Pb 和 PE 复合暴露下, 玉米种子发芽指数、发芽势和活力指数显著减小, 在 PP 和 Pb、PVC 和 Pb 复合暴露下无显著变化.

(3)  $10\text{ mg}\cdot\text{L}^{-1}$  Pb 和  $100\text{ mg}\cdot\text{L}^{-1}$  的 3 种微塑料单一暴露对玉米种子根和茎生长产生促进作用, 其他浓度暴露产生抑制作用(浓度越高, 抑制越强). 当 PE 浓度为  $500\text{ mg}\cdot\text{L}^{-1}$  时, 2 种 Pb 暴露均显著促进玉米茎和根的生长. PVC 和 Pb 复合暴露下, PVC ( $500\text{ mg}\cdot\text{L}^{-1}$ ) + Pb ( $10\text{ mg}\cdot\text{L}^{-1}$ ) 处理对玉米种子根和茎生长的抑制作用最大. 大多微塑料与 Pb 复合暴露处理对玉米种子的萌发及生长影响均表现为拮抗作用.

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