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农田残留地膜累积生态效应研究进展

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摘要: 地膜覆盖是一项优良的现代农业生产技术,显著提高生产力,但随着使用年限的持续增加残留在土壤中的地膜不断累积,对土壤环境与生态健康构成巨大威胁。为系统了解残留地膜带来的生态环境影响,本文基于残留地膜污染特征,通过查阅国内外文献,初次引入累积生态效应概念,总结了残留地膜对土壤健康、动植物生长发育甚至人类健康产生影响的相关工作,并对目前研究中存在的问题和未来发展方向进行了探讨。结果表明:随着覆膜时间的增加土壤中地膜残留量不断增加,受耕作、老化与降解等因素的影响残留地膜的大小、形状和状态不断改变,产生的直接和间接累积生态效应也不断变化;残留地膜老化与降解过程会加重其累积生态效应,残留地膜类型不同、老化程度与降解过程不同产生累积生态效应的程度也不同;随着生物降解地膜使用量的增加,残留地膜累积生态效应的多样化增加,而残留生物降解膜累积生态效应的危害程度不亚于普通残留地膜;残留地膜的直接和间接累积生态效应都对人类健康构成威胁。总之,残留地膜累积生态效应是一个长期动态变化的过程。目前残留地膜累积生态效应的研究多以短期的、静态的效应研究为主,对长期系统性的研究不够深入,应在未来的研究中开展长期性、时空动态性的系统研究,并深化地膜残留累积生态效应机理与管控技术的研究,为农业可持续及人类可持续发展的研究提供理论支撑。

关键词: 微/纳米塑料;残留地膜;累积生态效应;潜在风险;农田土壤污染
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Review on Cumulative Ecological Effects of Mulching Film Residues in Farmland

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Abstract: Film mulching could increase productivity as an effective modern agricultural technology. However, with increasing time, more and more amounts of the mulching film are residual in the soil, posing a significant

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threat to the soil environment and health. To systematically understand the influences of mulching film residues (MFRs) on the environment, this paper first summarizes the characteristics of MFRs pollution. Then it provides a comprehensive overview of the effects of MFRs on soil health, plant and animal growth and development and human health. By reviewing domestic and foreign literature, we introduced a concept of cumulative ecological effects (CEEs) to indicate these complex and long-term effects. We also discussed the existing problems and directions of future research in the paper. Studies show that: (1) The amount of MFRs accumulation in the soil increases with time. Due to the influence of tillage, aging and degradation, the size, shape and state of the MFRs are constantly changing, and the accumulation amount of microplastics and pollutants released from the mulching film is increased, leading to the continuous change of CEEs. (2) The aging and degradation could make the CEEs much worse. The different mulching films, degrees of aging and degradation processes have different CEEs. (3) With the heavy usage of biodegradable mulching film, the diversity of the CEEs of MFRs increases. In comparison, the CEEs of the residual biodegradable film are as harmful as the ordinary mulching film. (4) Both direct and indirect CEEs of MFRs pose threats to human health. In brief, the CEEs of MFRs are a long-term and dynamic changing process, while relevant research still is needed because the current knowledge about the CEEs is from short-time and static studies. Therefore, it is necessary to carry out long-term and spatio-temporal systematic research in the future. Meanwhile, the mechanism and controlling methods of the CEEs of MFRs should be studied further. Hopefully, it can provide theoretical support for agriculture-sustainable and human-sustainable development.

Keywords: micro-/nano-plastics; mulching film residues (MFRs); cumulative ecological effects (CEEs); potential ecological risks; farmland soil contamination

某项活动发生在一段时间内单独的影响很小，但长时间累积却形成显著影响的现象称为累积效应[1-2]。当一项活动与过去、现在以及可预见的未来活动通过加和或交互协同作用叠加在一起对生态环境产生影响，这些影响随时间不断累积形成更深层的生态环境效应[3-5]，称为累积生态效应，也称为生态累积效应或累积环境效应[6]。累积生态效应已经在矿产资源开发、绿洲化过程、滨海湿地开发和水利水电工程等土地开发领域有一定程度的应用，其评价结果为协调区域经济发展与环境保护提供理论依据[5,7]。

长期以来地膜覆盖被认为是廉价且有益的农业生产技术，但在耕作、紫外线照射和生物降解等因素的影响下，残留在土壤中的地膜碎裂成不同尺度的宏观、微观和纳米塑料，致使土壤环境不断退化，而且难以修复[8-10]，从而产生一系列不可逆的负面效应[11-12]。随着在过去、现在及将来地膜的使用，土壤中地膜残留累积量和类型不断增加，伴随残膜老化及降解过程，持续对生态系统和生物个体造成危害，并随时间延长不断变化，符合累积生态效应的概念范畴。

为了更好地理解残留地膜不断累积对生态环境产生的影响，本文根据目前已有的研究结果，初次对农田残留地膜累积生态效应进行较为全面的阐述，以期为农田土壤健康和农业生态系统可持续管理提供理论支撑。

1 农田残留地膜污染现状及累积生态效应(Pollution status and cumulative ecological effects of mulching film residues in farmland)

1.1 农田残留地膜污染现状及影响因素

塑料地膜具有保温、保墒和除草等优点，可扩大作物适种区域、延长农产品的供应季节，在水热不协调地区被广泛应用[13-14]。地膜覆盖可提高粮食产量25% ~42%[11]，显著提高生产力，已成为农业生产的重要物质资料之一。据统计，全球每年农业塑料薄膜使用量约有 7.40×10^6 t，其中地膜使用量为 2.00×10^6 t，并呈持续增长态势[10,15]。由于回收率低大量地膜残留在农田土壤中并不断累积。普通地膜主要成分为聚乙烯(PE)或聚氯乙烯(PVC)[15-16]，稳定性高，半衰期长，可在土壤中残存数百年，造成持久性污染[17]。为缓解普通地膜残留造成的污染，多种类型的生物降解地膜不断研发和应用，目前以聚乳酸(PLA)等天然生物质材料为主的生物降解地膜，以聚丁二酸丁二醇酯(PBS)、聚己二酸/对苯二甲酸丁二醇酯(PBAT)和聚羟基烷酸酯(PHA)等石油材料为主的添加型降解地膜已经开始应用于农业生产[18-20]。

1.1.1　残留地膜污染特征

残留地膜对农田土壤造成污染的研究主要集中在地膜使用量多的区域,如中国和印度为主的亚洲地区,尤其中国对残留地膜污染的研究比较深入[20-22]。残留地膜包括大尺寸的地膜碎片(≥5 mm)和小尺寸的地膜微塑料(MPs, <5 mm)[23-24]、纳米塑料(NPs, <1 μm)[25-26]。而目前地膜残留量的研究主要是对大尺寸地膜碎片的统计。

研究显示,土壤中地膜残留量从几 $kg \cdot hm^{-2}$ 到几百 $kg \cdot hm^{-2}$ 不等,地膜残留污染主要集中在地膜使用量多的干旱半干旱地区[27-28],其中,中国西北地区是地膜残留污染最严重的地区,地膜残留量平均在 136.7 ~ 259.1 $kg \cdot hm^{-2}$[24],局部地区高达 502.2 $kg \cdot hm^{-2}$[29]。残留地膜在土壤中的垂直分布也表现出明显的差异性,随土壤深度的增加而残留量降低,主要集中在 0 ~ 30 cm 的土壤表层中,其中 0 ~ 10 cm 内地膜残留量占总残留量的 60% ~ 75%[21,28,30]。受耕作、风化、光照、热解和微生物等因素的影响,土壤中的残留地膜不断老化或降解破碎成更小尺寸的碎片、微纳米塑料[23-26]。研究发现残留时间越长,地膜碎片面积越小[30-31],越容易向深层土壤迁移,导致深层土壤污染加重[32]。

1.1.2　地膜残留量的影响因素

影响地膜残留量的因素很多,如覆膜年限、回收情况、作物种类、地膜厚度、使用量及土壤质地等都会直接或间接影响地膜残留量和分布特性[27,29-35],且各影响因素的贡献率在不同区域差异显著[30,34-35]。研究发现,农民意识薄弱、回收措施不佳和无政策管控等原因导致地膜回收率低,是地膜残留的重要原因[33]。另外,覆膜年限也是影响地膜残留累积量的重要因素之一,覆盖年限越长地膜残留量越大,累积效应越明显[36],Zhang 等[29]研究发现新疆覆盖>20 年的棉田地膜残留量高达 210.3 $kg \cdot hm^{-2}$,比覆盖 10 年的农田高 150.4%。

根据当前的生产和使用模式,Geyer 等[37]预估 2050 年塑料废弃物全球回收利用量将达到 90 多亿 t,焚化总量达到 120 多亿 t,填埋或者丢到自然环境中的塑料总量达到 120 多亿 t。地膜是农业发展必不可少的农用物资,地膜覆盖技术会持续使用,土壤中地膜残留量会持续增加,虽然使用可降解地膜、增加地膜厚度和提高回收率等是解决残留地膜污染的潜在途径,但目前正处于研究阶段,不能立竿见影地彻底解决地膜残留问题。残留地膜污染应是一个长期面对的问题,而目前地膜残留量的研究多是土壤中实际残留量的调查统计,缺少对未来地膜残留量的预测。

1.2　残留地膜累积生态效应

根据是否受老化或降解过程影响而产生的生态效应,可将残留地膜累积生态效应分为直接和间接累积生态效应(图 1)。直接累积生态效应指残留地膜碎片或地膜微塑料不受老化或降解过程影响,直接对土壤理化性质、土壤动物及酶活性和作物生长发育产生的累积生态效应。而间接累积生态效应指残留地膜碎片或地膜微塑料在降解与老化过程中或降解后产生的累积生态效应,残留地膜老化或降解过程中向土壤中释放有机物和重金属,老化或降解的地膜碎片及其微/纳米塑料可以作为环境污染物的载体,聚合重金属、抗生素和有机污染物等,出现“塑料圈”效应[38],对农业生态系统功能和可持续发展构成严重的潜在威胁[11],并且通过迁移或食物链给动植物及人类健康带来风险[39],造成间接累积生态效应。

2　农田残留地膜的直接累积生态效应(Direct cumulative ecological effects of mulching film residues in farmland)

2.1　影响土壤理化性质

2.1.1　改变土壤物理性质

残留地膜会破坏耕层土壤结构,改变土壤容重,改变孔隙率,影响土壤通透性[40-41]。残留地膜对土壤容重影响的研究存在明显差异,多数研究结果表明随地膜残留量增加,土壤容重增加[42-43],但胡琦等[44]和 Fu 等[45]研究发现土壤容重随地膜残留量增加,容重呈逐渐降低的趋势,主要原因可能是实验选用的残留地膜面积大小与研究方法不一致。残留地膜对土壤物理结构最显著的影响是阻断土壤毛管,降低土壤渗透性能,影响土壤水分的垂直渗透和水平运移,研究表明随着地膜残留量增加,深层土壤含水量降低[46],土壤蓄水保墒能力削弱[47]。李玉环等[48]研究发现随着地膜残留量的增加,0 ~ 60 cm 剖面土壤体积含水率逐渐减少,其中 0 ~ 20 cm 土壤体积含水率减少幅度最大。

2.1.2　影响土壤水盐运移

残留地膜改变土壤空隙和阻断土壤毛管导致土壤水分运移受抑制。Wen 等[49]和牛文全等[50]研究发现随地膜残留量的增加,湿润锋运移距离、湿润体和土壤饱和导水率均呈减小趋势,且地膜残留量和

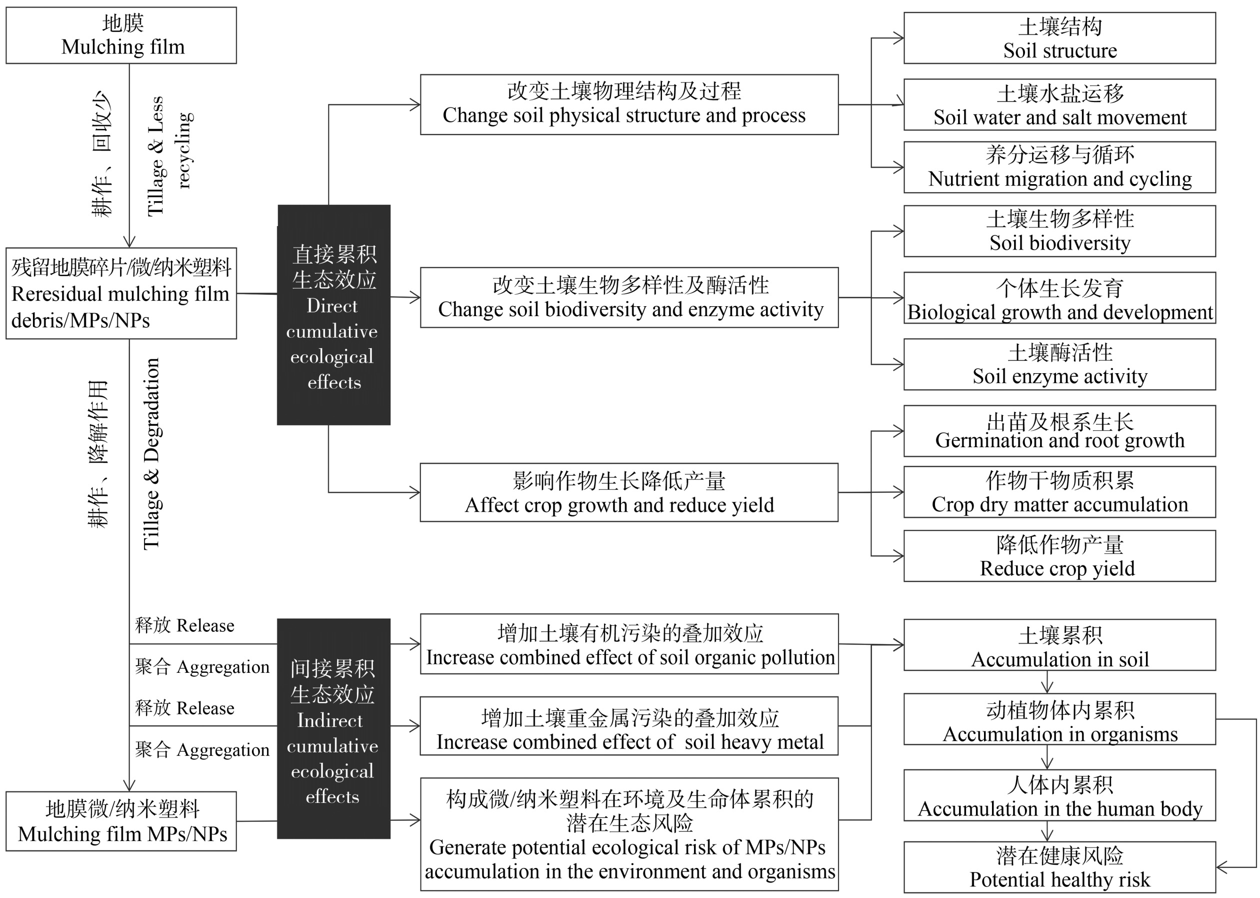

图1 残留地膜累积生态效应

Fig. 1 Cumulative ecological effects of mulching film residues

均匀性会影响土壤累积入渗量和蒸发量,地膜残留量越大、分布越不均匀,土壤下渗和蒸发速率的变异系数越大,土壤中产生的优先流几率和程度越大[44,51]。李元桥等[52]研究发现当土壤中地膜残留量达到720 kg·hm^{-2}时土壤大孔隙比例增加,土壤优势流明显。受蒸散发的影响,残膜量越大农田的无效耗水量越大,导致土壤水分的利用率降低[53]。除残留量外,残膜面积大小也会显著的影响土壤水分运移[54],一般情况下,面积越大阻碍作用越明显,但面积大小对水分运移的影响程度缺少深入研究。受水分运移的影响残膜也会影响土壤盐分运移,研究表明地膜残留量增加,土壤盐渍化程度增加[48],尤其是在残留地膜污染严重的干旱半干旱地区。

2.1.3 影响土壤养分含量、迁移及利用

氮磷钾是土壤中的基本元素,是动植物及微生物生长发育必备的养分,残留地膜影响土壤中养分含量、运移和利用率。高维常等[55]研究表明地膜残留会明显减弱硝态氮和铵态氮的迁移。残留地膜通过影响土壤微生物的活性而影响土壤中有机肥料的养分释放和分解,造成碱解氮、有效磷和速效钾下降[56],从而影响肥料的利用效率,不同类型和不同尺寸的残留地膜碎片及其微/纳米塑料影响土壤养分有效性不同。黄艳等[57]研究发现生物可降解膜和PE地膜的残留碎片均显著降低土壤的碱解氮、有效磷以及速效钾的含量。而Yan等[58]发现PVC微/纳米塑料通过影响微生物介导的无机磷溶解和有机磷矿化来增加酸性红壤中有效磷含量。Li和Liu[59]通过短期试验研究发现PE微/纳米塑料短期内可显著降低土壤速效磷含量,残留地膜对土壤养分含量、迁移及利用的长效影响机理需要进一步研究。

2.2 改变土壤生物多样性及酶活性

2.2.1 影响生物生长发育

残留地膜破坏土壤结构,降低土壤中的空气循环和交换能力,严重影响土壤生物的生理生化过

程[41],引起组织损伤、生长代谢抑制、氧化应激和免疫反应、神经毒性、高死亡率等不良反应[60]。研究发现残留地膜对土壤动物和微生物的影响具有相关性,如被吞噬的地膜碎片及微/纳米塑料可引起蚯蚓、线虫等土壤动物的肠道损伤,肠道微生物群落的改变,增加土壤动物免疫应激反应,影响土壤动物生长发育,甚至影响子代繁殖[61-62]。张书武等[63]研究表明 PE 微塑料和生物降解微塑料均会诱导蚯蚓发生氧化应激反应,生物降解微塑料比 PE 微塑料对蚯蚓的毒性更强,基于这一点残留生物降解膜及其微塑料是否也会对土壤生物产生负效应需要进一步研究。

2.2.2　改变物种多样性

残留地膜对土壤微生物活性及其丰富度具有显著效应,改变微生物群落结构[45],会严重影响土壤生物多样性[64],随地膜残留量的增加土壤通气性降低,土壤中好氧微生物数量减少,厌氧型微生物急剧增加[65]。张丹等[66]研究表明低含量的残留地膜可通过保水作用提高土壤微生物活性及其丰富度,而当地膜残留量超过 450 $kg \cdot hm^{-2}$ 时,土壤微生物群落丰度、生物量显著下降[64]。地膜残留时间也是影响细菌群落分布特征的重要因素[67],赵雪[68]研究发现土壤中的微生物数量随地膜覆盖年限的增加而减少,其中放线菌数量变化最为显著。残留的普通地膜和生物降解膜对土壤微生物多样性的影响不同。Hu 等[67]的研究表明生物降解膜微/纳米塑料能促进作物有益细菌的增长,而普通地膜微/纳米塑料持续残留会富集作物潜在的致病菌。Liu 等[69]的研究结果表明,与普通地膜残留相比,生物降解膜残留可促进优势菌群、抑制劣势菌群的生长发育,但整体上降低微生物的种类。土壤动物对普通地膜和生物降解膜的响应随时间变化而不同,残留地膜碎片及地膜微/纳米塑料对土壤生物丰度和多样性的影响短期难以显现,有随时间增加的趋势[70]。

2.2.3　影响土壤酶活性

残留地膜通过影响微生物群落特性和生理特征,进而影响土壤酶活性[71],如降低土壤脲酶、磷酸酶和转化酶等酶的活性,影响土壤的综合肥力[67]。有研究表明不同地膜残留量下酶的活性不同,随着地膜残留量的增加,酶的活性呈现降低趋势,张丹等[66]的研究表明地膜残留量为 300 ~ 450 $kg \cdot hm^{-2}$ 时,土壤中 α-葡萄糖苷酶、α-葡萄糖苷酶、纤维素酶、木聚糖酶以及几丁质酶活性普遍较高,当地膜残留量为 600 $kg \cdot hm^{-2}$ 时这些酶活性显著降低,而产生这一现象的机理研究较少。此外,生物降解膜与普通地膜对土壤生物代谢和酶活性的影响也不相同,Liu 等[69]的研究表明生物降解膜会促进土壤生物代谢物丰度的增加,黄艳等[57]用盆栽实验研究发现残留的可降解地膜对土壤酶活性的负效应大于 PE 地膜残留。

2.3　影响作物生长降低产量

残留地膜影响种子萌发,束缚根系生长,影响土壤养分含量和有效性,降低作物对水分和养分的吸收,影响作物生长发育[72],地膜残留量越大对作物生长发育的抑制作用越显著[11,73],残留地膜对不同作物的影响程度不同,且对同一作物不同生长期的影响也不同。在作物出苗和幼苗期,随着地膜残留量的增加,作物出苗率降低,幼苗死亡率升高,根系生长受抑制,研究发现高剂量的地膜残留量对玉米和棉花出苗、根系生长有显著负效应[74-76]。残留地膜对作物生长期和成熟期的影响大于作物幼苗期,Chen 等[77]通过田间试验研究发现,玉米在穗期阶段对残留地膜的敏感性高于幼苗期和拔节期,茎、叶和穗的干物质随着残膜量的增加而减少,水分利用效率降低。Hu 等[78]研究发现,棉花的干物质含量受残留地膜影响的程度在棉铃期显著于苗期。随地膜残留量的增加,作物物质交换、水分和养分吸收能力降低,超过一定阈值后会影响作物干物质积累,降低作物产量和质量[78-79]。随着地膜残留量增加,小麦、玉米和棉花等重要粮食与经济作物产量降低[77-78,80],Zhang 等[11]通过全球数据的整合分析发现每增加 100 $kg \cdot hm^{-2}$ 地膜残留量,作物产量平均降低 3%。

总体来说,残留地膜影响作物生长发育,降低作物干物质积累,造成作物减产,从而影响粮食安全[11]。残留地膜污染对作物生长发育的影响除与地膜残留量有关外,还与地膜聚合物成分、尺度大小、作物类型及生长阶段等因素有关[73],目前的研究主要以残留量的研究居多,对于其他因素的研究较少,且缺乏机理性研究和时空动态监测,不能有效指导作物生产。此外,作物生长发育与土壤动物、微生物息息相关,而地膜残留对植物-微生物联合效应的研究较少[45]。

3　农田残留地膜的间接累积生态效应(Indirect cumulative ecological effects of mulching film residues in farmland)

相比于直接累积生态效应,受老化和降解过程

影响的残留地膜间接累积生态效应可能产生更大的潜在危害,通过累积与叠加效应对土壤环境造成更严重的污染,通过迁移或食物链对生物有机体的健康构成威胁[81]。

3.1 构成微/纳米塑料在环境及生命体累积的潜在生态风险

3.1.1 增加土壤及其他环境中微/纳米塑料污染量

土壤中微/纳米塑料的危害已经引起极大关注,Ren 等[82]和 Li 等[83]的研究表明地膜是农田土壤中微/纳米塑料的主要来源,占比达到 30% 以上,严重的地区达到 60% 以上。Huang 等[84]通过分析中国 19 个省的 384 份土壤样品证实地膜覆盖是土壤环境中大塑料和微/纳米塑料污染的重要来源。地膜微/纳米塑料含量随覆膜年限的增加而增加[85],Li 等[86]研究发现干旱区覆盖期从 5 年增加到 30 年时土壤中 PE 微/纳米塑料的浓度从 91.20 mg·kg^{-1} 增加到 308.50 mg·kg^{-1}。

微/纳米塑料除在土壤内部迁移外,还会通过侵蚀、地表径流等方式向土体外的其他水体迁移[87],Ren 等[82]通过测算发现海洋中 10% ~30% 的微/纳米塑料来源于残留的地膜,de Souza Machado 等[88]的研究表明随着农膜和含有微/纳米塑料的农业化学品使用量的增加,农田土壤中的微/纳米塑料累积量已超过海洋环境中微/纳米塑料的积累量。除微塑料的迁移污染外还会携带其他污染源,研究表明土壤中微/纳米塑料是地下水污染的主要污染源载体[89],此外,可降解生物膜可在短时间内高度降解、甚至完全矿化,分裂成可降解膜的微/纳米塑料[90],和普通地膜微/纳米塑料一样容易在土壤-水体中迁移,而 2 种类型的微/纳米塑料在土壤-水体中的迁移和带来的生态风险目前仍然存在很多未知。

3.1.2 促进动植物体内微/纳米塑料的累积

研究表明微/纳米塑料可在植物和动物体中累积。微/纳米塑料可通过蒸腾作用吸收和转运至植物其他器官[91],Li 等[92]的研究表明微/纳米塑料可从小麦和生菜根部转移至可食用部分,而且 Oliveri Conti 等[93]研究发现市场销售的胡萝卜、生菜、西兰花、土豆、苹果和梨等水果和蔬菜中存在微/纳米塑料。土壤中微/纳米塑料被蚯蚓、虫类等动物取食后,可通过食物链在更高级的动物体中累积,引发病毒性伤害,如其他土壤动物、鸟类。Huerta Lwanga 等[94]的研究表明微/纳米塑料在长期覆膜土壤中的密度为 0.87 个·g^{-1},在蚯蚓粪中密度为 14.8 个·g^{-1},在鸡粪中密度为 129.8 个·g^{-1}。

3.1.3 对人类健康构成威胁

微/纳米塑料已经在人体血液和器官中被发现[95-96],Yang 等[96]在胎儿丘脑中发现非地膜成分的聚苯乙烯(PS)纳米颗粒,对胎儿大脑发育产生负面影响,进而有引发自闭症、抑郁症、精神分裂症、阿尔茨海默病和帕金森病等疾病的可能性,但是地膜微/纳米塑料是否会引发这几种疾病需要进一步研究。目前关于地膜微/纳米塑料通过食物链传递对动植物甚至人体健康潜在风险的研究较少,应扩大研究范围、增加样本量以评估地膜微/纳米塑料所有潜在风险的可能性及其累积生态效应。另外,目前已有研究结果表明微/纳米塑料是病原体和抗生素的载体,Li 等[97]研究发现地膜残留微/纳米塑料导致土壤中动物寄生虫、人类病原体和植物病原体的丰度增加,增加真菌感染流行病传播的几率,对土壤健康、粮食安全及全球人类健康构成潜在威胁[98-99],但目前针对这一方面的研究较少,尤其是在气候变化背景下,缺少微/纳米塑料对病原体、真菌感染流行病传播贡献率的研究。

3.2 增加土壤中地膜添加剂污染的生态风险

传统地膜除包括 PE 聚合物或 PVC 聚合物外,为保证地膜的性能生产时添加增塑剂、抗氧化剂、热稳定剂、润滑剂和着色剂等添加剂[16,100]。这些添加剂中包含邻苯二甲酸酯类(PAEs)、卤系化合物、芳香胺类和烷基酚等多种有机污染物,Pb、Cd、Zn、Ba 和 Sn 等重金属盐类[16,100],在地膜降解过程中这些物质释放出来,进入土壤导致土壤污染。研究表明土壤中重金属含量与地膜残留量呈正相关,尤其 Cd 含量超标显著[101]。

作为增塑剂主要成分的 PAEs 是土壤中 PAEs 的主要来源[102-103],覆膜时间越长土壤中 PAEs 检出率越高[100]。研究表明 PAEs 可在土壤动物、微生物、植物及人类体内累积,对土壤微生物及酶活性、动植物的生长发育产生毒害作用,对人类健康构成严重威胁[104-106],其抑制和毒害作用随着 PAEs 浓度的增加而加重。已有研究发现在冬瓜、雪菜、莴苣、油菜、黄瓜、大葱、白菜和玉米籽粒等常见蔬菜和作物中发现含有 PAEs[16],动物及人类通过采食这些含有 PAEs 的蔬菜或作物,造成体内蓄积 PAEs,从而威胁健康[107]。目前土壤中的 PAEs 累积剂量远小于对动物和人体的作用剂量,有学者认为土壤中 PAEs 对人体健康没有风险[108],但是随着地膜残留累积量的

增加,释放出的 PAEs 含量在未来持续增加,是否能达到对动物和人体产生影响的剂量需要深入研究。目前对地膜残留释放出的 PAEs 引起的危害有较为系统的研究,但是对地膜残留释放出的其他污染物质的研究较少。

与 PE 或 PVC 地膜的添加剂不同,生物降解膜一般添加改性剂、扩链剂、生物基增塑剂、成核剂和稳定剂等,生物基增塑剂主要有柠檬酸酯类、PEG/PPG 醚酯类和植物油基类等种类[109-110]。研究表明生物降解膜典型有机添加剂对秀丽线虫具有致死性和生长发育毒性,毒性强弱与添加剂种类和化学结构有关[110]。生物降解膜的添加剂在作物生长期及收获后期不断释放至土壤中,对土壤生物、作物生长发育产生毒害作用[111],关于这方面的研究相对较少,应增加相关研究。

3.3　增加土壤中污染物质产生复合污染的生态风险

3.3.1　与土壤中有机污染物形成复合污染

土壤中有机氯农药、多环芳烃(PAHs)、多氯联苯(PCBs)和多溴二苯醚(PBDEs)等一系列疏水有机化学物质可与地膜微/纳米塑料通过吸附、聚集、积累、转化和解吸等相互作用形成复合污染,通过拮抗、协同或增效作用影响有机污染物对土壤动物、植物的毒害作用[112-114]。Hu 等[115]研究发现 PAHs 与 PE 微/纳米塑料复合后具有极高的生物可及性,对人体存在致癌风险。残留地膜碎片及其微/纳米塑料与土壤环境中有机污染物的相互作用受聚合物成分、尺寸、颜色、官能团及老化程度影响[114]。一般情况下老化程度越高,地膜微塑料对有机污染物吸附作用越强,Wu 等[116]的研究表明老化塑料地膜和全新可降解地膜增强了土壤对吡虫啉和丙炔氟草胺 2 种农药的吸附强度,且吸附强度随着地膜微/纳米塑料的老化而增强,而 Wang 等[117]研究发现老化促进了 PE、PVC 和 PLA 地膜微塑料对四环素的吸附,且原始微塑料与老化微塑料对四环素的吸附机制不同。

目前地膜微/纳米塑料与有机污染物相互作用的临界条件、机理及影响因素尚不清楚,应增加这方面的研究。此外,还应深入研究地膜微/纳米塑料与有机污染物对土壤生物的复合毒性,以全面了解拮抗或协同作用的发生条件,并在分子水平上研究毒性影响机制[113]。

3.3.2　与土壤中重金属形成复合污染

残留地膜碎片及微纳米塑料形成的“塑料圈”可促进土壤中重金属的累积[118],作为载体通过吸附、共沉降及解析作用与土壤中的重金属元素形成复合污染,改变重金属元素的生物有效性,影响植物生长和微生物群落结构,对农田土壤健康和人类健康构成潜在的威胁[119]。残留地膜碎片及微/纳米塑料对重金属的复合效应受其地膜类型、老化程度和残留量影响,老化程度越高对重金属的吸附能力越强[120-121],浓度越高重金属的生物有效性越强[122]。研究发现白色 PE 地膜和黑色 PE 地膜的添加剂不同,导致地膜对不同形态的砷吸附效果不同,黑色 PE 地膜比白色 PE 地膜对 4 种砷形态的吸附效果更强[123]。Wang 等[124-125]研究发现 PE 地膜和可降解的 PLA 微塑料均可增加土壤中 Cd 的生物有效性,Abbasi 等[120]发现地膜微/纳米塑料作为载体将 Cd、Zn 和 Pb 迁移至小麦根际,更有利于向植物体中转移,Moreno 等[126]研究发现覆膜种植的白菜比未覆膜的白菜中重金属积累量高 90%,造成粮食安全问题。

然而,Yu 等[127]的研究表明微/纳米塑料通过物理吸附和共沉降作用降低重金属的交换态、碳酸盐结合态和铁锰氧化物结合态,增加有机结合态,降低重金属在土壤中的生物有效性和迁移率,从而降低重金属对作物的毒性,与他人研究结果不一致,地膜微/纳米塑料对土壤中重金属污染的影响需深入研究。此外,廖苑辰等[128]利用非地膜成分的 PS 微/纳米塑料和 Cd 的复合污染对蚯蚓的生长、生理代谢及 DNA 损伤的影响程度高于单一 Cd 污染的影响程度,但是地膜微/纳米塑料与重金属复合污染的潜在风险研究比较少,应增加此方面的研究。

4　总结与展望(Summary and prospect)

地膜是农业生产必不可少的农业物资,地膜残留后会产生直接和间接累积生态效应。受累积量、地膜成分组成和老化与降解等因素的影响,残留地膜会改变土壤理化性质,加剧土壤地膜微/纳米塑料、有机物和重金属污染的危害,影响土壤生物多样性及酶活性,影响农业生产,对粮食安全造成影响,对生物体和人类健康产生威胁[11,81,129-130]。随着研究的不断深入,发现残留地膜累积生态效应主要有以下特点,但相关研究依然存在一些不足,需要进一步加强。

(1)地膜残留量和累积生态效应不断发生动态变化

随着覆膜时间增加土壤中地膜残留量不断增加,直接累积生态效应不断改变。经过长时间的耕作、老化与降解,残留地膜的大小和形状不断改变,

地膜微/纳米塑料累积量和释放的污染物质量增加,残留地膜间接累积生态效应也随之增加,说明残留地膜累积生态效应是长期存在的,且不断变化的动态过程。

关于地膜残留量的研究,目前多是对当前土壤中地膜残留累积量的调查研究,缺少对未来地膜残留量预测的研究,且缺乏普适性较强的评估模型。关于残留地膜生态效应的研究,目前主要以短期的、静态的模拟试验为主,部分研究中残留地膜碎片及微塑料的添加量远高于农田中地膜残留量,造成残留地膜的试验浓度和自然环境浓度之间的不可比性[129-130]。除残留量外,地膜组成成分、尺度大小等因素都会影响地膜残留累积生态效应,针对这些方面的研究不够深入,不能有效揭示残留地膜对农田生态系统影响的时空动态变化过程,应开展残留地膜累积生态效应的长期研究,以揭示地膜残留污染产生的长远影响[129,131]。

(2)老化和降解过程会加重残留地膜累积生态效应

残留地膜老化、降解成尺寸更小的地膜碎片及微/纳米塑料,老化与降解过程中向土壤中释放PAEs等有机物和重金属,残留地膜老化和降解程度可改变残留地膜碎片及其微/纳米塑料的环境行为,与土壤环境中的有机污染物和重金属形成复合污染。不同类型的地膜老化与降解机制显著不同,老化程度与降解过程不同,产生生态效应的程度不同[129,131-132],对土壤健康、动植物生长发育及人体健康存在的潜在风险不同[81,129]。目前对老化与降解过程产生机制和影响因素研究较少,对残留地膜产生间接累积效应的时间也不明确,今后应注重地膜残留老化、降解机制及影响因素的研究,有助于更清晰地了解残留地膜累积生态效应。

(3)生物降解地膜增加残留地膜累积生态效应的多样化

为缓解普通地膜残留对土壤可持续利用的影响,可降解地膜的使用量不断增加,残留地膜累积量和类型均在发生变化。研究表明残留生物降解膜累积生态效应的危害程度不亚于普通地膜残留,甚至危害性更高。相对于累积生态效应的危害种类来说,当前残留降解地膜累积生态效应的研究较少。今后应探明可降解地膜带来的负效应并在生产过程中加以改善,为农业生态系统可持续发展提供有利的支撑[130]。

(4)残留地膜直接或间接对人类构成威胁

无论是直接还是间接累积生态效应,残留地膜对人类产生的危害不断被发现。宏观层面,直接累积生态效应改变土壤理化性质,影响作物生长,降低农业产量,影响全球消除饥饿目标的实现[11]。微观角度,残留地膜加重土壤微塑料、有机物与重金属污染及其复合污染,通过迁移增加水体、大气等其他环境污染的风险,在食物链效应下对动植物甚至人体健康产生影响,引发多种疾病甚至影响子代生命的孕育,对人类可持续构成潜在威胁[81,114,129-130]。但是当前对地膜微塑料、有机物与重金属污染及其复合污染的机理性和深入性研究较少,且为单一因素的研究,缺少复合因素联合效应的研究,建议今后深入研究地膜残留污染潜在生态风险及其科学管控措施。

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