

食品中微纳米塑料的来源及潜在威胁

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摘要:塑料广泛应用于包装、储存、加工等食品领域,在延长食品保质期、降低物料损耗、促进食品流通等层面发挥着至关重要的作用。但这些与食品直接或间接接触的塑料制品会经物理和化学作用等多种方式产生微纳米塑料,并通过生物富集等途径累积于人体,现已成为威胁食品安全与人类生命健康的“新污染物”之一。文章对食品中微纳米塑料的产生渠道、释放方式、潜在健康威胁、防控与治理技术等方面的研究进展进行了详细总结,并对未来进一步保障食品安全与生命健康进行了展望。

关键词:微纳米塑料;生物富集;食品接触材料;理化作用;食品安全;生命健康

Sources and potential risks of micro- and nanoplastics in foods

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Abstract: Plastics are widely used in food packaging, storage, processing, and other food-related applications, playing a vital role in extending food shelf life, reducing material loss, and promoting food circulation. However, these plastic products that come into direct or indirect contact with foods can release micro- and nanoplastics through various physical and chemical processes. These micro- and nanoplastics can accumulate in the human body through bioaccumulation and other pathways and have become one of the emerging contaminants threatening food safety and human health. This review provides a comprehensive summary of the research progress on the generation pathways, release mechanisms, potential health threats, and prevention, control, and remediation technologies of micro- and nanoplastics in foods. Finally, future perspectives are presented for further safeguarding food safety and human health.

Keywords: micro- and nanoplastics; bioaccumulation; food contact material; physicochemical action; food safety; life health

自 1862 年诞生以来,塑料作为一类轻质、耐用、低成本的多功能材料极大地促进了人类经济社会的高速发展。在食品行业中,塑料包装占据重要地位,在保持食品外观品质、延长食品货架期、促进食品流通和销售等全链条中发挥着关键作用。塑料保鲜膜能将果蔬损耗率显著降低^[1],让食材跨越千里仍保持新鲜品质^[2];轻量化塑料包装能够大幅减少运输质量,显著降低能耗和碳排放,在绿色物流中扮演关键角色。此外,塑料制品也广泛用作

盛放食品的各类容器和用具、餐具、炊具等^[3-7],比如餐桌上的果盘、外卖里的一次性包装盒餐具、厨房里的不粘锅涂层等皆由塑料制成。从田间到餐桌,塑料包装和制品堪称现代食品体系的“安全屏障”。

然而,这些与食品直接或间接接触的塑料包装或制品正悄然转变为一种威胁食品安全和人类生命健康的“新污染物”——微纳米塑料。微塑料(microplastics)的定义于 2004 年被提出,指粒径小于 5 mm 的塑料颗粒、碎片

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或纤维^[8-9];其中,粒径小于 1 μm 的微塑料后来被称为纳米塑料(nanoplastics)^[10]。当前,全球每年塑料总产量超过 4 亿 t^[11],其中食品接触塑料是最大的应用领域,保守估计至少占总量的 30%~40%,也就是每年 1.2 亿~1.6 亿 t 的规模。尽管国内外对于食品级塑料都有非常严格的使用和回收标准,它们在加工、包装、运输和储存食品的各个环节中难免会产生微纳米塑料而掉落或沾染在食品上,这已成为食品中微纳米塑料的重要来源之一。此外,使用后随意丢弃的各种塑料制品在自然环境条件下也会缓慢分解而产生微纳米塑料,它们广泛地分布于水体^[12]、土壤^[13]和大气^[14]中,且能够在各个生态系统中迁移和积累。经年累月,这些环境中的微纳米塑料将不可避免地进入生物圈和食物链,通过生物富集作用最终进入人体中。通过饮食进入人体的微纳米塑料可以滞留在各个系统、器官、组织和细胞中(见图 1),给人类生命健康带来巨大的风险和隐患。

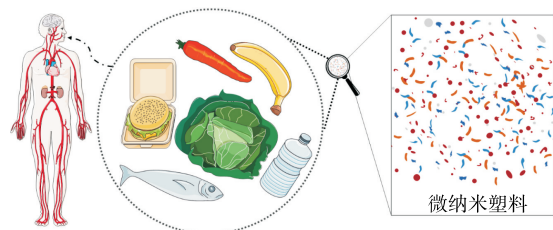


图 1 食物中的微纳米塑料

Figure 1 Micro- and nanoplastics in foods

文章针对食品中微纳米塑料的来源和产生方式、对生命健康的潜在威胁、未来的防控与治理等方面的研究进展进行系统性总结,旨在为未来应对微纳米塑料带来的食品安全和生命健康问题提供有益参考。

1 食品中微纳米塑料的来源和产生方式

按照来源和产生方式,食品中的微纳米塑料可以进一步分为原生和次生微纳米塑料^[15]。前者直接以微纳米塑料的形态存在于食品中。例如,通过环境迁移和生物富集作用在水产品、蔬菜、水果等食材或食品内积累的微纳米塑料^[16-21]。后者主要指食品在加工制作、盛放或保存等过程中,与塑料制品发生复杂的理化作用而产生的微纳米塑料^[22]。

1.1 生物富集作用

由于人类活动的影响,随意丢弃的塑料制品在自然环境中缓慢分解释放出微纳米塑料。作为一种“新污染物”,微纳米塑料强大的环境迁移性与生态渗透力已引发全球关注(见图 2)。它们不仅遍布地球各个角落——从北极^[23]到南极^[24]、从马里亚纳海沟^[25]到珠穆朗玛峰^[26],而且能通过复杂的迁移路径在生态系统中循环。尤其,微纳米塑料能够沿着食物链进行传递,在更高级的生物

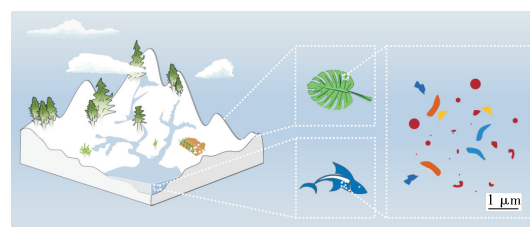


图 2 微纳米塑料遍布于生态环境并富集于动植物体内

Figure 2 Micro- and nanoplastics are ubiquitous in the ecological environment and accumulated in animals and plants

体内积累。这意味着,环境中的微纳米塑料将成为植物性和动物性食品中的原生微纳米塑料,最终将在处于食物链顶端的人类体内富集。

微纳米塑料通过环境迁移进入食物链底层生物,并沿营养级向上传递,呈现出显著的生物富集与放大效应^[27-30],这一过程已在多个生态系统中得到证实。在海洋系统中,微纳米塑料与浮游植物在尺寸和形态上具有高度相似性,且常混杂在悬浮颗粒中或附着于浮游植物表面,导致浮游动物因无法分辨而摄入。数据显示,以藻类为食的大型溞对环境中的微纳米塑料的生物富集系数高达 2 000 个/mL^[31]。微纳米塑料还将进一步富集在以这些浮游植物和浮游动物为主要食物来源的鱼类、虾类、蟹类等体内^[32-33]。Traylor 等^[34]研究发现,粉红虾可食用部位微纳米塑料含量高达 7.35 粒/g。而 Nabila 等^[35]研究发现,石斑鱼通过摄食富集在胃肠道的微纳米塑料达到 $(5\,595.11 \pm 2\,078.71)$ 粒/个体。人们在食用上述鱼、虾、蟹等海鲜或水产品时,原生微纳米塑料将进入体内。

粮食作物、蔬菜、水果等植物的根系可以吸收土壤中的微纳米塑料。由于受到凯氏带阻隔,根系吸收的微纳米塑料向地上部分(如茎、叶)运输的效率较低^[36-37]。比如,小麦、生菜等的根系吸收微纳米塑料后,输送到茎叶的微纳米塑料浓度仅为根系浓度的 1%。基于此,Li 等^[38]进一步证实叶片类植物主要通过叶片上的气孔直接吸收大气中的微纳米塑料,经质外体途径转运至维管束并富集于毛状体。植物叶片中微纳米塑料的浓度与叶片生长时间、气体交换能力、生长环境大气污染水平具有显著相关性。在污染区域(如垃圾填埋场)附近,绿叶蔬菜叶片中聚对苯二甲酸乙二醇酯微纳米塑料的质量分数可达 10^4 ng/g。此外,绿叶蔬菜在露天环境生长过程中比在温室中更容易接触并吸收空气中的微纳米塑料。如图 3 所示,天津地区 9 种蔬菜中均检出 PET 微纳米塑料。其中,露天种植蔬菜中的 PET 微纳米塑料质量分数为 $2.48 \times 10^2 \sim 8.70 \times 10^3$ ng/g,而在温室种植蔬菜中的 PET 微纳米塑料质量分数低于检出限($< 2.31 \times 10^3$ ng/g)。Yuan 等^[39]在当地超市随机采购的胡萝卜、生菜、苹果等果蔬中检测发

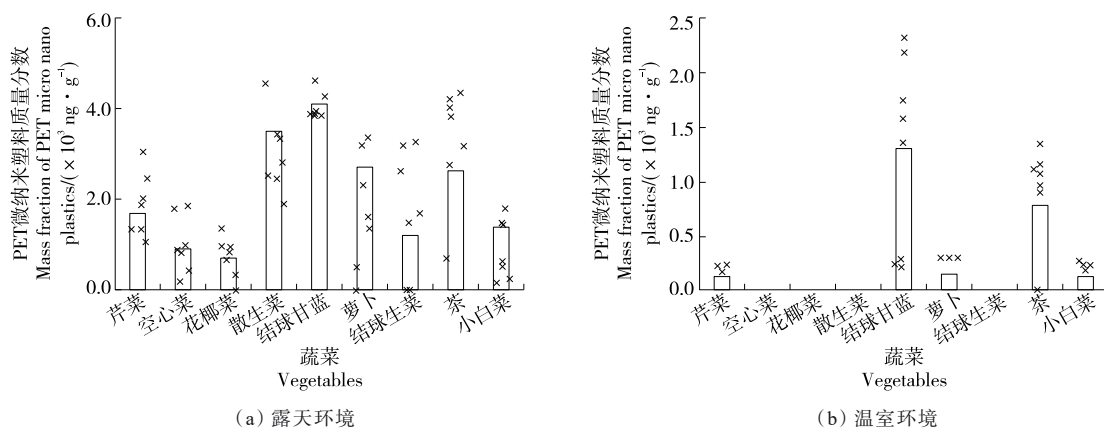
图3 各类蔬菜在露天环境和温室环境中的PET污染对比图^[38]

Figure 3 Comparison of PET contamination in various vegetables grown in open-field and greenhouse environments

现,胡萝卜中粒径 $<10 \mu\text{m}$ 的塑料颗粒数达到 1.02×10^8 粒/kg干重,为所有蔬菜样品中最高。与蔬菜相比,水果中的微纳米塑料污染程度则更为突出。其中,在苹果中微纳米塑料数高达 1.96×10^8 粒/g。人们在食用这些蔬菜、水果和粮食时,其中含有的原生微纳米塑料会随之进入体内。

1.2 物理作用

在食品加工和制作的多个过程中均涉及到使用塑料制品^[40],它们长期与食品发生接触、碰撞、挤压、摩擦、剪切、破碎等物理作用^[41]。在上述这些作用下,塑料制品表面磨损加快,逐渐产生大量的次生微纳米塑料。这些微小颗粒将不经意地附着在食品表面或混入食品中,最终连同食品一起进入人体。

罐装加工是海鲜加工过程中微纳米塑料最主要的来源之一^[42]。金属罐头内壁的聚合物涂层常为聚对苯二甲酸乙二醇酯/聚丙烯/聚乙烯等,在装罐或开罐时发生物理破损或摩擦,从而释放微纳米塑料颗粒。如图4所示,罐

装鱼样本中微纳米塑料颗粒的数量中位数和质量中位数分别为2.4颗/g和717 $\mu\text{g/kg}$,远高于其他加工类型的贝类、生鲜鱼等。其中,检出聚对苯二甲酸乙二醇酯、聚苯乙烯和聚丙烯微纳米塑料的样本数分别占样本总数的63%,75%,25%。在所有产品的微纳米塑料分析检测中,罐装加工远高于其他加工类型。

在粮食加工中,粮食常需经历脱壳、研磨、筛选、输送等工序。加工设备的某些塑料部件会与粮食发生直接接触、摩擦和碰撞,使得加工过的食物比未加工食物更容易受到微纳米塑料污染^[43-44]。比如,研磨机的橡胶密封件在与粮食长期接触和摩擦下将导致磨损并产生微纳米塑料;塑料滤网在高频振动中与谷物碰撞导致表面纤维断裂而形成微纳米塑料。这些微纳米塑料颗粒一经脱落便会随粮食进入面粉、大米、麦片等最终食品中。在粮食输送过程中常用到塑料传送带。粮食会与传送带发生摩擦,长期将导致传送带表面磨损并逐渐形成微纳米塑料颗粒,这些颗粒容易附着在粮食粉体/半粉体表面或混入

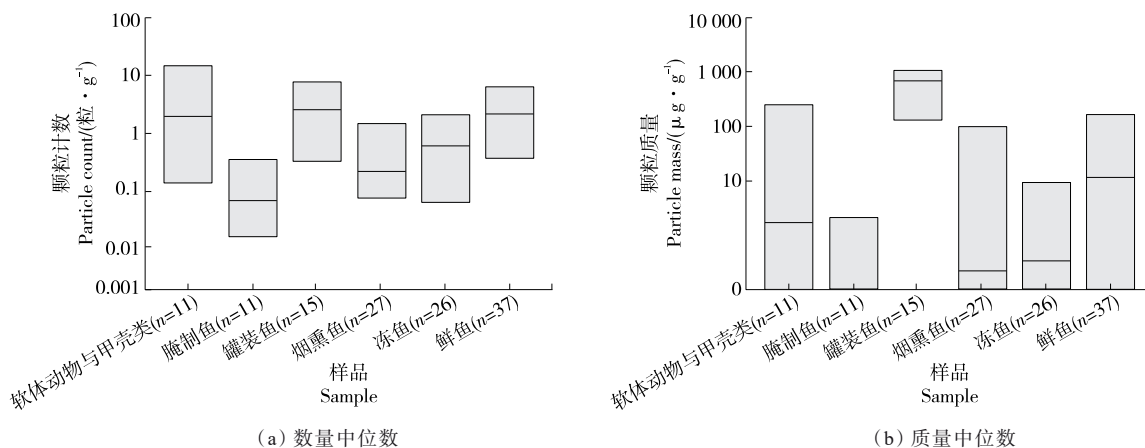
图4 加工方式对海鲜中微纳米塑料颗粒数量中位数与质量中位数的影响^[42]

Figure 4 Influence of processing methods on the median particle and median mass of micro- and nanoplastics in seafoods

其中^[45]。

塑料瓶装饮料生产的所有环节都会释放微纳米塑料,但最大的来源当属封盖过程^[46]。塑料瓶盖在多次开合摩擦产生的机械应力作用下,导致瓶盖结构受损,内表面发生撕裂,产生微纳米塑料颗粒而进入饮料中^[47]。在灌装流水线上,聚对苯二甲酸乙二醇酯瓶与输送轨道、灌装嘴发生摩擦,瓶身表面会因此磨损,脱落的微纳米塑料颗粒会随饮料一同被灌装封装。饮料管道密封件如橡胶垫圈,长期挤压磨损后也会释放微纳米塑料。

在对水产品、蔬菜、水果等食材预处理时,刀具的刀刃与塑料砧板表面发生切削和摩擦,长期会导致塑料砧板表面脱落微纳米塑料颗粒并附着在食材表面。Yadav 等^[48]发现,切削方式和砧板材质对微纳米塑料的释放具有重要影响。如图 5 所示,聚丙烯(PP)砧板释放微纳米塑料颗粒的数量比聚乙烯(PE)砧板高 14%~71%。进一步估算表明,每人每年可能接触到的聚乙烯砧板释放微纳米塑料的数量为 1 450 万~7 190 万个。对于聚丙烯砧板而言,这一数量高达 7 940 万个。将处理好的食材在不粘锅中烹饪时,尤其在高温干烧或使用金属锅铲刮擦翻炒时,聚四氟乙烯涂层难免会形成脱落的微纳米塑料^[49],从而混入烹饪的饭菜中。

Luo 等^[50]研究发现,金属锅铲刮擦不粘锅形成的浅痕可释放约 9 100 个聚四氟乙烯微纳米塑料颗粒,涂层彻底破裂可能导致 230 万个微纳米塑料颗粒的释放。在家里制作果汁或豆浆时,主要依靠电机带动锋利的刀片对塑料罐体内食材进行切割粉碎。在这一过程中,刀片强烈的螺旋运动会产生很大的剪切力,使得刀片以及被切碎的食材与塑料容器内壁之间产生剧烈摩擦^[51]。这种持续长久的摩擦和磨损,会使塑料容器表面脱落微纳米塑料颗粒,随后混入果汁或豆浆中。

1.3 化学作用

食品盛放和储存过程中,也会用到大量的塑料包装和容器。这些塑料制品在光、热、酸碱度等多种化学作用^[52-53]影响下会加速老化、分解并释放大量次生微纳

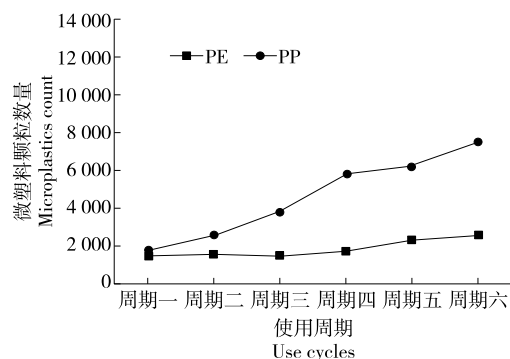


图 5 不同周期下两种砧板的微纳米塑料释放数量变化^[48]

Figure 5 Variation in the number of micro- and nanoplastics released from two types of cutting boards under different use cycles

塑料。一旦附着在食品上或混入食品中,极有可能连同食品一起进入人体。

光化学老化或光氧化过程已被证实会改变塑料的理化性质如外观和质地、结晶度、组成等^[54],主要原因在于塑料对紫外辐射较为敏感^[55]——构成塑料制品的聚合物中的 C—C 和 C—H 键能(分别为 375, 420 kJ/mol)与紫外线光子的能量(波长分别为 320, 290 nm)相当。如图 6 所示,以聚烯烃为例,其光氧化老化是光和氧共同作用的复杂过程。太阳光中的紫外线会引起聚烯烃中 C—C 和 C—H 键断裂生成自由基,自由基与氧气反应生成过氧化物自由基,进一步反应生成更多的自由基和产物,导致塑料材料表面逐渐破碎^[56-57],生成低聚物碎片而释放微纳米塑料颗粒^[58-59],此类次生微纳米塑料颗粒在与食品发生接触后,会伴随食品一同被人体摄入,使其进入人体的概率显著升高^[60]。

温度也是影响食品塑料包装或容器释放微纳米塑料的重要因素之一^[61-64]。温度越高,微纳米塑料的释放量越大,释放速率也越快。将盛有水或食物的婴儿辅食盒(通常为聚丙烯或聚乙烯材质)放入微波炉中加热 3 min,

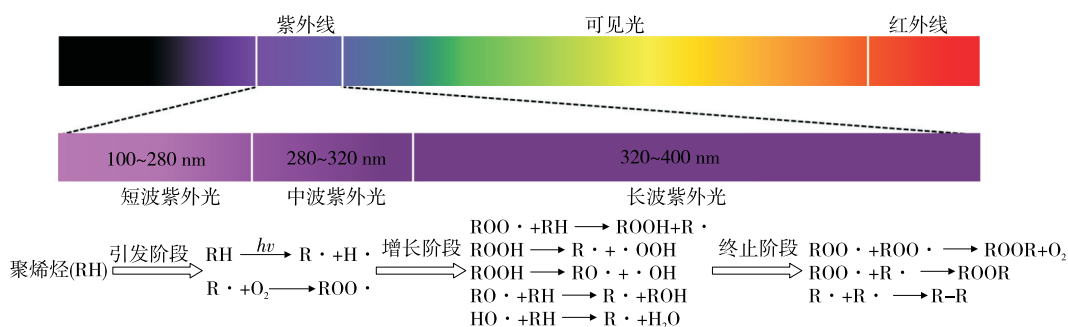


图 6 聚烯烃光氧化降解机理与紫外光谱关联示意图

Figure 6 Schematic illustration of the photo-oxidative degradation mechanism of polyolefins and its correlation with UV spectroscopy

每平方厘米塑料容器会释放超过21.1亿个纳米塑料颗粒和422万个微塑料颗粒^[65]。这些微纳米塑料将不可避免地沾染食物和水,最终进入婴幼儿体内。同样,一杯热茶也可能在不知不觉中让人们摄入大量微纳米塑料。当用开水冲泡由聚酯或聚丙烯等材质封装的市售茶包时,仅一次冲泡就会释放出高达11.6亿个微塑料颗粒和1.3亿个纳米塑料颗粒。此外,聚对苯二甲酸乙二醇酯瓶在吹塑成型阶段,高温可能使部分聚合物链断裂,产生的微纳米塑料也会残留在瓶内,从而与所盛装的饮料发生接触。

周围环境的酸碱度(pH)也会对食品塑料包装或容器释放微纳米塑料产生重要影响^[66-68]。通常,酸碱性越强,释放速率和释放量就越大。在 $\text{pH} < 4$ (强酸性)或 $\text{pH} > 10$ (强碱性)条件下,聚乙烯包装的微纳米塑料年释放量为中性条件的1.5~2.0倍,且尺寸 $< 10 \mu\text{m}$ 的微纳米塑料颗粒占比为70%以上,更易进入食品并被人体摄入^[69]。盛装碳酸饮料的塑料瓶内壁会因聚对苯二甲酸乙二醇酯在酸性条件下的缓慢水解反应而产生微纳米塑料,脱落后随即进入饮料中。不仅如此,当用塑料包装或容器盛装果汁、醋、咸菜等其他酸性或碱性食品也会出现类似的情况。此外,罐装饮料流水线上的饮料管道密封件如橡胶垫圈,长期接触酸碱碱性饮料发生腐蚀后也会释放微纳米塑料。

微纳米塑料的产生源于原生积累与次生生成两大核心路径,原生层面是环境中游离的微纳米塑料通过生物富集沿食物链逐级传递,或被植物根系叶片吸收而进入果蔬等食材。次生层面则是食品在加工制作过程中产生的物理作用,与盛放储存时光、热、酸碱度引发的化学作用共同催生。在这些复杂的联动作用下,食品中广泛存在微纳米塑料正是自然迁移、生物传递、物理磨损、化学降解等综合作用的结果。

2 食品中微纳米塑料对生命健康的潜在威胁

微纳米塑料这些容易被忽视的“入侵者”通过饮食进入人体^[70-73]后,并非简单地被排出体外^[74],而是经消化道吸收,进而扩散至循环、泌尿、生殖、神经等多个系统^[75-84](见图7),引发一系列潜在的生命健康风险^[85]。

2.1 细胞与血管

研究^[86]发现,食品中的微纳米塑料进入人体并被消化道细胞摄取后,会引发氧化应激、线粒体功能障碍及内质网应激,导致细胞毒性、炎症和凋亡,还会破坏肠道屏障,改变菌群结构。Zha等^[87]证实食源性聚乳酸微纳米塑料通过“肠道菌群—肠—肝”轴,导致肠道菌群失调、代谢紊乱及肝脏转录组异常;微纳米塑料还会破坏肠道屏障,影响菌群平衡,进而引发肠胃及全身毒性。

通常,较大尺寸的微纳米塑料颗粒($> 5 \mu\text{m}$)会被肠道物理屏障阻挡,难以进入循环系统,主要滞留于肠道引

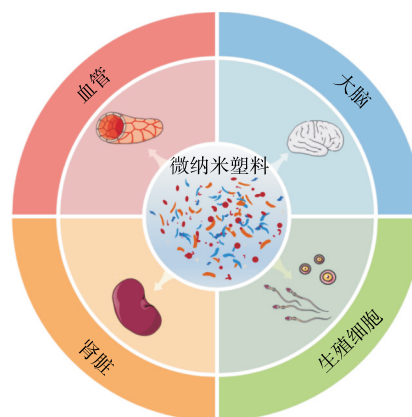


图7 微纳米塑料存在于常见的人体器官及细胞

Figure 7 Presence of micro- and nanoplastics in common human organs and cells

发局部炎症;而纳米塑料可以直接穿透肠道细胞膜,通过毛细血管壁进入血液系统,对血管造成不可忽视的重大影响。Marfella等^[88]的临床研究表明,在33个月随访的257名颈动脉粥样硬化患者中,约58.4%的患者的硬化斑块中检测到聚乙烯微纳米塑料;12.1%的患者的硬化斑块中发现了聚氯乙烯(PVC)微纳米塑料颗粒。检出微纳米塑料的患者罹患心肌梗死和心脑血管疾病的风险是未检出患者的4.53倍。另一项研究^[89]发现,微纳米塑料还会对血管生成相关的信号传导通路产生抑制作用,同时干扰细胞的伤口愈合进程与迁移能力,从多个维度影响循环系统的正常生理功能。比如,人脐静脉内皮细胞暴露于聚苯乙烯微纳米塑料颗粒后,这些颗粒会在细胞内呈剂量依赖性积累,同时显著降低细胞活力与管腔形成能力,而这两种能力对血管生成至关重要。

2.2 肾脏

食源性微纳米塑料随血液循环抵达肾脏会对泌尿系统造成一定的损伤。Chen等^[90]研究发现,经染色后的聚苯乙烯微纳米塑料颗粒在肾脏中的积累与暴露时间呈正相关。而且富集在肾小管上皮细胞的微纳米塑料可以被肾类器官内化。Wang等^[91]研究表明,将人肾皮质近曲小管上皮细胞(HK-2细胞)暴露于聚苯乙烯微纳米塑料PS-MPs中,会导致PS-MPs被细胞摄取,并增加内质网应激、炎症以及线粒体活性氧水平。

与永生肾小管上皮细胞系相比,肾类器官对微纳米塑料表现出高度敏感性,即使是低浓度也会引发层状细胞凋亡和类器官细胞脱离。早期肾脏发育对于确保正常的结构和功能至关重要。在目前的研究中,研究人员使用人肾类器官检查了微纳米塑料对肾发生的影响。在应用与环境相关的微纳米塑料浓度后,肾脏类器官表现出缩小和异常的管状结构,微纳米塑料导致线粒体活性氧水平升高和DNA损伤。转录组学和中心碳代谢分析

数据^[92]显示,微纳米塑料暴露后代谢途径发生显著改变,糖酵解减少,三羧酸循环活性增加。糖酵解抑制被确定为导致肾脏类器官体积减小和肾小管结构异常的一个因素,这些结果强调了微纳米塑料通过代谢重编程对肾脏发育的负面影响。

2.3 生殖系统

食源性微纳米塑料也可以在生殖系统积累并产生多方面损害。Kong 等^[93]在 51 对接受体外受精夫妇的卵泡液和精液中发现了聚乙烯和聚氯乙烯微纳米塑料颗粒。这两种微纳米塑料在受检卵泡液中的平均质量分数分别为 1.21, 1.85 $\mu\text{g/g}$,而在精液中则为 3.02, 2.67 $\mu\text{g/g}$ 。该研究还证实,卵泡液中高质量分数的聚乙烯和聚氯乙烯与受精率降低显著相关,精液中聚氯乙烯质量分数升高会导致精子活力下降。此外,其他微纳米塑料对男性精子质量的作用也得到了进一步探究。中国多家医学机构涉及 113 名男性的研究^[94]发现,其精液和尿液中均存在微纳米塑料。其中,聚四氟乙烯的出现与精子浓度、活力降低相关,且暴露在微纳米塑料环境中种类越多,精子质量下降越明显。在女性生殖系统方面,微纳米塑料的危害同样不容忽视。Afreen 等^[95]指出,聚苯乙烯微纳米塑料会通过激活 NLRP3/caspase 通路导致卵巢颗粒细胞凋亡,破坏 Wnt 信号通路引发纤维化,还会干扰下丘脑—垂体—性腺轴,影响激素水平,降低胚胎数量和妊娠次数,甚至可能通过胎盘对后代产生影响。

2.4 大脑

食源性微纳米塑料也可以穿透血脑屏障,痴呆症患者大脑中的微纳米塑料浓度普遍高于正常人^[96],表明痴呆症可能与大脑中的微纳米塑料毒性颗粒积累有直接关系。在 2024 年病理样本中,正常已故者大脑平均含有 6~7 g 微纳米塑料,相当于一个塑料勺子的质量;而痴呆症患者的大脑中则高达 34~36 g。与其他人体器官相比,大脑更容易富集微纳米塑料。正常的大脑样本中的微纳米塑料浓度是其肝脏或肾脏中浓度的 7~30 倍,痴呆病患者大脑样本中则富集了更多的微纳米塑料颗粒。此外,临床观察数据^[97]也表明,在大脑中积累,部分微纳米塑料颗粒被免疫细胞吞噬后会滞留在脑血管,容易诱导脑血栓形成,脑微血管阻塞率提升 30%。

总之,微纳米塑料在人体中呈现出全方位、高检出的普遍污染状态。目前,已在人体血液、肾脏、肝脏和胎盘等中检出。富集在体内的微纳米塑料可能产生联合毒理效应,对多器官造成系统性损伤,从而影响人体的正常新陈代谢^[98],严重威胁人类生命健康。

3 食品中微纳米塑料污染的防控与治理

3.1 政策层面

据报道^[99-100],1950—2017 年全球范围内塑料制品累计总产量达 92 亿 t,预估到 2050 年将增加到 330 亿 t。联

合国环境规划署 2022 年度报告^[101]中进一步指出,塑料污染已渗透至农业生态系统,对土壤健康、粮食安全构成直接威胁。对此,各国已启动从政策层面到技术层面的链条式管控措施。

食品中微纳米塑料污染的防控与治理已成为全球共同挑战^[101-107],国内外均构建了多元治理体系并推进协同合作。在国际上通过以《巴塞尔公约》修正案、《斯德哥尔摩公约》、《全球塑料污染防治公约》等构建全球协同治理框架,明确塑料废弃物管控与食品链微纳米塑料防控目标。联合国环境署通过相关《展望简报》推动食品体系塑料污染治理。欧盟以 REACH 法规禁止食品相关产品故意添加微纳米塑料,并于 2025 年实施食品接触材料双酚类化合物禁令,美国、加拿大通过专项法案管控塑料微珠并建立监测网络。

中国现已形成全链条治理的政策与标准闭环:在设计上,以生态环境部等多部门联合印发《关于进一步加强塑料污染治理的意见》《“十四五”塑料污染治理行动方案》为指引,明确将微纳米塑料防控纳入重点任务。《固体废物污染环境防治法》提供法律保障,宁夏等省份还将微纳米塑料纳入重点管控新污染物清单,持续完善标准体系。GB 4806.7—2023 等国标强化食品接触塑料微塑料迁移限量管控,GB 31604 系列标准建立配套检测方法,同时通过源头禁限一次性塑料制品、推广可降解替代材料,建立全生命周期追溯系统、研发拉曼光谱现场检测设备等措施推进防控,共同保障食品体系安全可持续。

3.2 技术层面

由于微纳米塑料具有一定的化学稳定性和难降解性,大量微纳米塑料排放和积累将会永久性滞留在环境中,对生态系统构成巨大的危害。环境中的微纳米塑料将逐步成为植物性和动物性食品中的原生微纳米塑料,最终将在处于食物链顶端的人类体内富集。因此,减少微纳米塑料污染迫在眉睫。此外,开发低释放、可降解、可替代的食品接触材料是降低和消除食源性微纳米塑料风险的关键途径之一,特别是在食品包装、储存和加工领域,以全生物降解生物基材料替代传统石油基塑料,有望从源头上减少食品中次生微纳米塑料的生成。

微纳米塑料的定性和定量检测具有复杂性,主要取决于微纳米塑料本身各异的微观形貌、尺寸、组成、聚合物类型、老化状态等物理化学性质。因此,选择合适的检测方法对于食源性微纳米塑料的定量追踪检测至关重要。光谱法和质谱法为目前微纳米塑料的主要检测手段。光谱法是分析微纳米塑料的关键技术,可同步获取其形状、颜色、尺寸、数量及聚合物种类等信息,实现微纳米塑料颗粒水平的定性定量。其中,傅里叶变换红外光谱技术在表层水域、沉积物和海洋环境中对多种聚合物类型的表征效果已有充分文献记载^[108-109];拉曼光谱在滤

膜上可以直接对微米级微纳米塑料进行表征^[110],其是主流无损检测技术,可基于分子振动特征提供精准的化学指纹图谱。质谱法则可对微纳米塑料的质量浓度进行精确测定。热解气相色谱质谱是微纳米塑料分析的一种顶尖技术,结合无氧热分解(热解)与气相色谱和质谱技术,通过聚合物的挥发性片段进行鉴定。该方法擅长分析复

杂混合物,并量化多种基质中的塑料,包括沉积物和生物组织^[111]。有研究人员^[112]将其应用于包括评估食用鱼类和海洋样本中的微纳米塑料丰度和添加剂。近些年来随着科技的进步,检测方法的种类和质量较以往都有巨大进步,主要集中在提升灵敏度、速度和准确性方面,表1归纳了多种新检测技术并重点介绍其原理和检测应用。

表 1 微纳米塑料的检测方法
Table 1 Detection methods for micro- and nanoplastics

方法	尺寸检测极限/μm	原理	优点	缺点
傅里叶变换 红外光谱法	10	利用特定的红外光谱	操作简单、成本低	易漏检小尺寸颗粒
拉曼光谱法	1	通过激光激活分子振动,产生特异性光谱	操作简便,可以准确定性,灵敏度高	设备昂贵,对样品处理要求高
核磁共振光 谱法	40	分析原子核的磁性特征,提供详细的分子结构信息	化学信息解析度极高,可区分结构复杂的聚合物	要求样品溶解或为纯品,不适用于固体颗粒样品
光热红外光 谱法	0.5	通过检测光热效应,间接测定样品的红外吸收特性	空间分辨率高,可分析超小颗粒	成本高昂、仪器结构复杂,对部分材料的检测灵敏度较低
荧光测定法	1	荧光标记后用显微镜直接观察	可直接观察生物体内微纳米塑料的原位分布	需提前对样品染色,易受环境影响
热重分析	1	测定样品在加热过程中的质量变化,提供热稳定性与成分相关信息	装置简单,可分析少量样品,适用于评估塑料的热稳定性	仅适用于热分解过程,无法提供具体的化学定性结果
差分扫描量 热法	1	测定样品在加热或冷却过程中的热流变化,揭示热转变(熔融、结晶)规律	可提供特定热性质,适用于表征聚合物加热过程中的行为	粒径检测范围有限,无法直接鉴别具体聚合物
热解—气 相色谱— 质谱联用	1	在惰性气氛下使聚合物热分解,对生成的气态产物进行气相色谱—质谱联用分析	灵敏度高、特异性强,可对微纳米塑料进行详细的化学定性	成本高昂,样品前处理复杂,无校准条件下不适合定量分析

以上这些方法允许对食源性微纳米塑料进行化学鉴定和定量,提供颗粒数、粒径分布和形状的信息。因此,对具有不同特性的食源性微纳米塑料进行全面分析无法用单一方法完成,必须结合多种分析方法。

4 结论与展望

根据来源和产生方式,可将食品中的微纳米塑料划分为原生微纳米塑料和次生微纳米塑料两类。前者指通过环境迁移和生物富集作用在各类食材或食品内部积累的微纳米塑料;后者主要指塑料制品发生复杂的物理和化学作用释放的微纳米塑料,间接掉落或沾染在食品表面。通过日常饮食,这些食源性微纳米塑料最终将在人体内不断积累,对人体细胞、组织、器官和系统造成不同程度的损害,严重威胁人类生命健康。

作为负责任的主体,人类在应对食品的微纳米塑料污染和相关的人类生命健康问题上肩负着重要的使命,亟需从多方面发力推进系统性治理。首先,应积极开展系统性毒理学和病理学研究,进一步明确微纳米塑料在食物链中的迁移规律和对人类生命健康的潜在影响,为微纳米塑料污染的治理决策提供科学支撑。在技术创

新层面,材料革新是核心方向。在塑料食品包装领域,开发全生物降解的生物基塑料替代传统石油基塑料,对于降低微纳米塑料释放至关重要。尽管当前应用全生物降解生物基塑料仍面临成本偏高的现实挑战,这种趋势不仅符合绿色化学和双碳目标的要求,而且有利于从源头上大幅削减微纳米塑料的产生。在社会治理和监管方面,应加强宣传教育和相关法律法规的制定,需尽快完善食品接触塑料制品的监管制度。针对不同类型食品包装、加工设备、餐饮用具等制定差异化的微纳米塑料迁移限量标准,明确生产企业的源头防控责任,要求企业在产品标签中注明材质特性、使用禁忌(如是否可微波加热)及潜在微纳米塑料释放风险提示,推动形成企业自律、政府监管、公众参与的社会治理共同体,从制度与意识双重层面筑牢食品中微纳米塑料污染的防控防线。

总之,通过技术创新降低生物基材料成本、以系统性研究支撑风险管控、联动产业升级与制度约束,形成全方位治理合力,才能有效降低食品中微纳米塑料的环境输入,最终守护好食品安全与生态环境的双重健康。

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