



畜禽养殖新污染物特征及治理策略

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摘 要: 随着全球人口增长与消费升级, 畜牧业规模化扩张已成为不可逆转的趋势。然而, 畜禽养殖产业的蓬勃发展, 在保障食品供给的同时, 也衍生出严峻的生态环境问题。尤其值得关注的是, 养殖系统已成为新污染物重要的“源”和“汇”: 作为排放源, 养殖过程持续释放抗生素、持久性有机污染物、内分泌干扰物、微塑料、农药等新污染物; 作为汇集端, 这些污染物会通过生物链富集在畜禽体内形成多级放大效应, 最终对生态系统和人类健康构成重大威胁。本文综述了畜禽养殖中新污染物的主要种类和来源、赋存特征、环境行为, 深入剖析了它们对环境和人类健康的潜在影响, 探讨了“源头减量-过程阻断-末端净化”养殖面源新污染物治理思路, 并总结了当前研究的不足, 展望了未来研究的重点方向, 以期为我国新污染物防控体系的构建与政策优化提供科学依据, 促进畜禽养殖业健康可持续发展。

关键词: 新污染物; 健康养殖; 环境毒理; 生态风险; 精准治理

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Characteristics and Management Strategies for Emerging Pollutants in Livestock and Poultry Farming

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Abstract: With global population growth and rising consumption, the large-scale expansion of animal husbandry has become an irreversible trend. However, alongside ensuring food supply, the rapid development of livestock and poultry farming has also brought about severe ecological and environmental problems. Notably, the farming system has become both an important source and sink of emerging pollutants. As an emission source, the farming process continuously releases emerging pollutants such as Antibiotics, persistent organic pollutants, endocrine disruptors, microplastics, pesticides. As a sink, these pollutants accumulate in livestock through the food chain, creating a multi-level amplification effect that poses significant threats to ecosystems and human health. This paper reviewed the main types and sources of emerging pollutants in livestock farming, their occurrence characteristics and environmental behaviors, analyzed their potential impacts on the environment and human health. We further discussed the pollutants management idea of reduction at the source, interception during the process, and purification at the end. We also summarized the

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current research gaps, and outlined future research directions. This paper aims to provide a scientific basis for China's emerging pollutant control system construction and policy optimization, and to promote the sustainable development of the livestock industry.

Keywords: emerging pollutants; healthy farming; environmental toxicology; ecological risk; targeted management

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随着畜牧业的迅猛发展,特别是养殖规模的扩大和养殖方式的变化,畜禽养殖环节日益显现为新污染物迁移和扩散的重要载体,为系统认知新污染物的环境行为及生态效应提供了新的切入点。相比于传统污染物,新污染物的持久性、生物累积性等特点使其具有更加复杂和长期的潜在风险。在“同一个健康”(One Health)理念下,新污染物的风险不仅仅局限于对人类健康的直接影响,而是通过人类、动物和环境三者之间的紧密联系与相互作用,形成多层次的风险传递链条^[1]。任何一个环节遭受污染,都极有可能对整个生态系统造成不可逆转的影响。

畜禽养殖系统既是多种新污染物的关键排放源,也是其在环境介质中的重要汇集节点^[2]。一方面,畜禽养殖活动持续释放抗生素、持久性有机污染物、内分泌干扰物、微塑料、农药等新污染物。以抗生素为例,据统计,中国每年生产的抗生素超过20万t,其中一半以上被用于畜禽养殖^[3]。由于生物利用度有限,大部分抗生素在服用后8~24 h内,以原药或代谢物的形式随动物粪尿排出,排泄率为30%~90%^[4]。未经有效处理的粪肥会携带抗生素等多种新污染物,进入土壤或渗透至地下水系统,最终影响生态安全和人类健康。此外,在畜禽养殖中,雌二醇、睾酮等激素被大量使用,以促进动物的生长和提高肉质^[5];包装材料等塑料制品的使用,产生大量微塑料^[6];毒死蜱、氯氰菊酯等杀虫剂被广泛用于养殖环境的虫害防治^[7]。另一方面,畜禽通过食用受污染的饲料、饮水等,被动摄入各种新污染物,成为新污染物的生物富集载体。随后,这些被污染的动物源食品,如牛奶、肉类和鸡蛋等被人类食用,借助食物链层层传递,最终对人类健康造成不良影响^[8]。

鉴于全球新污染物检出浓度的持续攀升,以及由此所带来的生态系统和人类健康不良影响的日益加剧,亟需更加科学全面地了解畜牧生产中新污染物的特征和影响。因此,本文系统梳理了畜禽养

殖过程中抗生素、持久性有机污染物、内分泌干扰物、微塑料、农药等新污染物来源、赋存特征和环境行为,总结了它们的环境健康影响和消减策略,以期为实现畜牧业绿色、健康、可持续发展提供科学依据。

1 畜牧生产中主要新污染物的来源及赋存特征

1.1 畜牧生产中新污染物的种类

新污染物,是指在环境和自然生态系统中可被检测到,且即使以低剂量存在也能对人体健康和环境安全构成较大风险和隐患,但尚未被纳入现有环境管理体系或现有管理措施不足以有效防控其风险的有毒有害化学物质。这些污染物具有多种特征,包括危害严重、风险隐蔽、环境持久性、来源广泛以及治理复杂性等。根据近期生态环境部出台的《新污染物治理行动方案》以及学术界最新提出的广义概念^[1,9-10],畜牧生产中所涉及的新污染物主要涵盖抗生素、持久性有机污染物、内分泌干扰物、微塑料、农药等^[11-20](表1)。

1.1.1 抗生素 在畜禽养殖中,抗生素主要来源于兽药治疗、饲料添加剂及养殖环境预防性投药,其具有环境持久性强、生物毒性显著、代谢残留高等特点^[21]。研究表明,动物体内30%~90%的抗生素会以原形或代谢物形式随粪尿排出^[22],使畜禽粪便成为养殖环境中抗生素的主要存储库和周边环境的重要排放源^[23]。例如,Zhi等^[24]研究发现,在不同环境介质中,四环素类、喹诺酮类和大环内酯类抗生素的总浓度均呈现粪污样品>饲料样品>水样品>土壤样品的分布特征,其中四环素类抗生素在粪污中的最高浓度可达144.61 mg·kg⁻¹。Wang等^[25]研究进一步显示,不同动物粪便中抗生素浓度存在差异,猪粪中金霉素平均浓度(30.51 mg·kg⁻¹)显著高于鸡粪(19.39 mg·kg⁻¹)和牛粪(24.47 mg·kg⁻¹)。值得注意的是,这些残留抗生素会通过食物链进入人体。程兆康等^[26]通过统计相关文献发现,食品中

表1 畜牧生产中常见新污染物种类

Table 1 Common types of emerging contaminants in livestock production

污染物类别 Pollutant category	主要类型/成分 Primary types/Components	来源 Sources
抗生素 Antibiotics	四环素类、磺胺类、 β -内酰胺类、喹诺酮类、大环内酯类	畜禽疾病治疗与促生长滥用 ^[11] ; 抗生素滥用导致耐药基因在胃肠道中富集 ^[12] ; 耐药基因通过接合质粒在环境中水平传播 ^[13] ; 粪污未经处理还田, 基因通过土壤-作物传播 ^[14]
持久性有机污染物 Persistent organic pollutants	多氯联苯、二噁英、溴化阻燃剂	受污染的饲料原料; 养殖环境暴露(如焚烧垃圾产生二噁英, 通过牧草沉积进入食物链) ^[15]
内分泌干扰物 Endocrine disrupting chemicals	雌激素(如雌二醇)、雄激素(如睾酮)、生长激素(如重组牛生长激素)、双酚 A、邻苯二甲酸酯	塑料养殖器具释放(如含双酚 A 的饮水器) ^[16] ; 兽药残留(如畜禽粪便中雌激素的残留) ^[17]
微塑料 Microplastics	粒径 <5 mm 的塑料颗粒(如聚乙烯、聚丙烯、聚苯乙烯)	饲料加工过程混入塑料微粒; 养殖水体中塑料垃圾降解产物; 畜禽误食塑料碎片 ^[18]
农药 Pesticide	有机磷类(毒死蜱)、拟除虫菊酯类、氨基甲酸酯类等	牧草/饲料作物农药残留 ^[19] ; 畜禽体外驱虫药滥用 ^[20]

喹诺酮类抗生素的平均残留量高达 $725.1 \mu\text{g}\cdot\text{kg}^{-1}$, 最高可达 $47\,108 \mu\text{g}\cdot\text{kg}^{-1}$, 显著高于磺胺类和四环素类抗生素的残留水平。

需要强调的是, 抗生素的广泛使用不仅造成残留污染, 更会诱导产生和传播抗生素抗性基因(antibiotic resistance genes, ARGs)。ARGs 是细菌基因组中编码耐药性机制的基因, 赋予细菌对抗生素的耐受能力, 能够借助质粒、转座子等可移动遗传元件进行传播, 具有水平转移性强、环境持久性高、宿主多样性广等特征^[27-28]。早在 2006 年, Pruden 等^[29]就呼吁国际社会将 ARGs 作为一种新兴环境污染物。在畜禽养殖环境中, ARGs 主要源于抗生素过量或不合理的使用, 是抗生素污染产生的关键次级环境效应^[30]。研究发现, 在畜牧养殖中, 不同畜禽种类、不同地区的养殖环境中 ARGs 多样性和丰度均存在显著差异。例如, 邹威等^[31]研究发现, 养鸡场粪便中磺胺类抗生素 *sul* 和大环内酯类抗生素 *erm* 基因的相对丰度高于其在养猪场粪便中的相对丰度。如鸡粪中磺胺类抗生素 *sul* II 基因的相对丰度为 $2.16\times 10^{-2}\sim 2.26\times 10^{-1}$, 而其在猪粪中的相对丰度则为 $1.2\times 10^{-4}\sim 5.56\times 10^{-2}$; 天津市养猪场和养鸡场 ARGs 的平均相对丰度分别为 1.89×10^{-2} 和 4.45×10^{-2} , 均低于河北地区养猪场和养鸡场 ARGs 的平均相对丰度(分别为 4.99×10^{-2} 和 1.36×10^{-1})。Cheng 等^[32]通过研究发现, 规模化鸭和鸡养殖场中, 磺胺类抗性基因的相对丰度介于 $1.09\times 10^{-2}\sim 1.32\times 10^{-1}$, 显著高于猪和羊养殖场粪便中的含量。

1.1.2 持久性有机污染物(persistent organic pollutants, POPs) POPs 是一类在环境中难以降解、具有生物累积性和长距离传输能力的有机化合物, 因其高度的稳定性、远距离传输能力和生物累积性, 已成为畜牧养殖中受到广泛关注的新污染物之一^[33]。在畜牧生产中, POPs 主要来源于农药残留、工业副产品以及非法或不当使用的兽药, 如多氯联苯、氯化石蜡、溴化阻燃剂及其代谢产物等。POPs 污染源复杂, 这些物质通过饲料、饮水或直接接触等途径进入动物体内, 之后通过排泄物再次释放到环境中, 进而污染土壤、水源和空气^[34]。例如, Li 等^[35]分析了在溴化阻燃剂制造区附近收集的家鸡和环境样本, 发现土壤、自来水、饲料样本以及鸡组织均检测到四溴双酚 A, 平均浓度分别为 $16.4 \text{ ng}\cdot\text{g}^{-1}$ (干重)、 $5.46 \text{ ng}\cdot\text{g}^{-1}$ (干重)、 $0.97 \text{ ng}\cdot\text{g}^{-1}$ (干重)、 $0.20 \text{ ng}\cdot\text{g}^{-1}$ (脂重)。Zhou 等^[36]通过研究发现人为活动对氯化石蜡的污染也有重要贡献, 青藏高原与江西农村散养鸡蛋中短链氯化石蜡和中链氯化石蜡的中位数浓度相近, 分别为 159 和 $1\,390 \text{ ng}\cdot\text{g}^{-1}$ (湿重)、259 和 $938 \text{ ng}\cdot\text{g}^{-1}$ (湿重), 均显著高于养殖鸡蛋的 22.0 和 $81.7 \text{ ng}\cdot\text{g}^{-1}$ (湿重)。此外, POPs 还能通过食物链逐级放大, 最终对人类健康构成长期威胁^[37]。如白润叶^[38]对全国部分主产区 1 445 份鸡肉样品中的 PFASs 进行检测, 结果显示, 检出率较高的全氟和多氟烷基类物质(per-and polyfluoroalkyl substances, PFASs)有 8 种, 其中污染水平最高的全氟丁烷磺酸盐(perfluorobutane sulfonate, PFBS)达 $0.0896 \text{ ng}\cdot\text{g}^{-1}$ 。

1.1.3 内分泌干扰物(endocrine disrupting chemicals, EDCs) EDCs是一类能够干扰生物体内分泌系统正常功能的化学物质,包括天然激素及其类似物、合成化学物质等^[39]。在畜牧生产中,激素类物质是EDCs的核心组成部分和重要来源,如动物生长激素(如雌二醇、睾酮)、兽药中的激素类药物等。EDCs的来源广泛,还包括塑料添加剂中的邻苯二甲酸盐等物质^[40]。EDCs通过饲料添加剂(特别是含有激素的生长促进剂)、养殖环境(水源、土壤和空气迁移)等途径进入动物体内,进而影响动物繁殖、生长发育乃至免疫系统,最终通过食物链富集进入人体,并在生物体内持续累积引发健康风险^[41-42]。

激素类污染物(如雌激素、雄激素)在畜禽粪污中普遍存在且备受关注。其浓度因动物类型、粪污特性、繁殖周期和牲畜的生物学特性不同出现显著差异。例如,胡双庆等^[43]对上海市典型畜禽养殖类型排放的5种天然和人工合成雌激素进行检测,结果显示,猪场粪便和尿液中5种雌激素总量分别为 $94.5 \text{ ng} \cdot \text{g}^{-1}$ 和 $8\,882.2 \text{ ng} \cdot \text{L}^{-1}$,奶牛场粪便和尿液中总量分别为 $84.6 \text{ ng} \cdot \text{g}^{-1}$ 和 $2\,636.7 \text{ ng} \cdot \text{L}^{-1}$,鸡场粪便中总量为 $60.9 \text{ ng} \cdot \text{g}^{-1}$ 。张梦涛等^[44]通过测定规模化奶牛养殖场粪便中雌激素的浓度,发现不同生理时期奶牛粪便中雌激素排放总量有所不同,分别为青年期 $432.90 \mu\text{g} \cdot \text{kg}^{-1}$ 、泌乳期 $1\,114.51 \mu\text{g} \cdot \text{kg}^{-1}$ 、干奶期 $1\,540.13 \mu\text{g} \cdot \text{kg}^{-1}$ 。此外,雌激素还可以通过污水处理厂或养殖场废弃物进入环境,在水体、土壤系统中将发生吸附、迁移、降解和转化等行为^[45]。雌激素在土壤介质中有明显的淋溶迁移行为,如土壤施用猪粪3个月后,距地面1 m深的地下水中雌酮和 17β -雌二醇质量浓度分别可达到 $68.1 \text{ ng} \cdot \text{L}^{-1}$ 与 $2.5 \text{ ng} \cdot \text{L}^{-1}$ ^[46]。激素在食物链中的传递更是不容忽视,例如,梁紫薇等^[47]研究发现,集约化养殖过程中肉鸡粪便中雌二醇(17β -E2)浓度可达 $307.62 \mu\text{g} \cdot \text{kg}^{-1}$ (湿重),每羽鸡日均排放量达 $43.75 \mu\text{g} \cdot \text{d}^{-1}$ 。这些高浓度的雌激素可能通过粪污处理不当或饲料原料污染等途径在养殖系统内循环,最终导致禽类产品中的激素残留,并通过食物链对人类健康构成潜在风险。

1.1.4 微塑料 微塑料指直径小于5 mm的塑料颗粒、纤维或碎片。在畜牧生产中,微塑料主要来源于饲料包装材料、养殖设施磨损以及塑料垃圾的不当处理^[48]。这些微小颗粒易于被动物摄入,不

仅影响其消化系统健康,还可通过食物链传递至人类^[49]。研究发现,家禽养殖场普遍存在微塑料污染。例如,Wu等^[50]通过对华南地区19个不同种属的畜禽养殖场进行微塑料数量检测,发现在粪便样本中,猪、蛋鸡和奶牛粪便中微塑料的整体丰度分别达到 $(9.02 \times 10^2 \pm 1.29 \times 10^3) \cdot \text{kg}^{-1}$ (湿重)、 $(6.67 \times 10^2 \pm 9.90 \times 10^2) \cdot \text{kg}^{-1}$ (湿重)和 $(7.40 \times 10^1 \pm 1.29 \times 10^2) \cdot \text{kg}^{-1}$ (湿重),在饲料样本中分别达到 $(1.39 \times 10^2 \pm 1.15 \times 10^2) \cdot \text{kg}^{-1}$ (湿重)、 $(9.60 \times 10 \pm 1.09 \times 10^2) \cdot \text{kg}^{-1}$ (湿重)和 $(3.60 \times 10^1 \pm 6.30 \times 10^1) \cdot \text{kg}^{-1}$ (湿重)。Li等^[51]研究发现,微塑料在土壤、池塘水体和家禽肠道中含量丰富,分别为 $(6.75 \pm 2.78) \cdot \text{g}^{-1}$ (干重)、 $(0.94 \pm 0.28) \cdot \text{g}^{-1}$ (湿重)和 $(45.35 \pm 19.52) \text{ 个} \cdot \text{g}^{-1}$ (湿重),主要呈现为 $20 \sim 50 \mu\text{m}$ 的碎片颗粒。此外,在农业土壤中施用有机肥料和在农田中使用塑料覆盖物会引入微塑料。王长远等^[52]针对江苏省辣椒试验田的研究发现,长期施用有机肥的土壤中微塑料丰度最高达 $543.33 \text{ 个} \cdot \text{kg}^{-1}$ 。Wang等^[53]收集了六个农场及周边地区的新鲜粪便和土壤样本,检测到畜禽粪便中微塑料平均丰度为 $(50\,583 \pm 24\,318) \cdot \text{kg}^{-1}$,土壤中的微塑料平均丰度为 $(3\,056 \pm 1\,746) \cdot \text{kg}^{-1}$ 。

1.1.5 农药 农药在畜牧生产中的使用主要与畜禽疾病防治、养殖环境消毒、饲料原料生产有关^[54]。常见的农药包括有机磷类和拟除虫菊酯类^[55]。这些农药通过空气、水体和土壤迁移到养殖场,或通过受污染的饲料原料进入动物体内。农药残留广泛存在于土壤、水体和动物产品中,对动物和人类健康造成不良影响^[56]。例如,有机磷农药(如毒死蜱、敌敌畏)在养殖环境中广泛存在,其残留不仅直接污染水体,还可以通过饲料或环境迁移进入动物体内。Peterson等^[57]研究发现,从肉牛饲养场收集的颗粒物样品中定量的16种不同农药中,氯菊酯的检出频率最高,占颗粒物样品的67%,平均浓度可达到 $(1\,211.7 \pm 781.0) \text{ ng} \cdot \text{m}^{-3}$,吡虫啉为 $(62.8 \pm 38.2) \text{ ng} \cdot \text{m}^{-3}$,并且可以通过大气沉降污染周边水体。

综上,畜牧生产中的新污染物具有显著的差异化特征:抗生素因高排泄率(30%~90%)和耐药基因传播构成主要风险;POPs和EDCs具有持久性、强生物累积性、长距离迁移能力及内分泌干扰效应;微塑料兼具物理损伤和化学载体(如吸附重金属、POPs)的双重危害;农药则通过急性毒性和食物

链富集威胁生态多样性。这些污染物通过“养殖排放-环境迁移-生物富集”的链条,形成跨介质的复合污染网络,对生态系统和人类健康构成多维度威胁。

1.2 畜牧生产中新污染物的暴露途径

如图1所示,畜牧生产中的新污染物主要通过食物链及畜禽粪便影响环境和人类健康。具体而言,源自饲料添加剂、兽药残留或环境中的新污染物被动物摄入,进而通过生物富集作用在动物体内积累,最终通过肉类、奶制品等畜产品进入人类食物链,对人类健康构成潜在威胁^[58]。例如,某些激素类生长促进剂或抗生素的滥用,不仅影响动物产品的安全性,还会引发人体内的激素紊乱或抗药性

增强等问题^[59]。另一方面,粪便污染是畜牧生产中另一个不容忽视的暴露途径。大量畜禽粪便若未经妥善处理直接排放到环境中,不仅会造成水体富营养化、土壤污染,还会通过空气传播病原体,影响周边居民的生活质量与健康^[60]。粪便中的新污染物,如微塑料颗粒、内分泌干扰物及抗生素抗性基因等,能够通过渗滤作用进入地下水系统,或通过径流进入地表水体,进而影响到更广泛的生态系统^[61]。此外,这些污染物不仅可以通过直接接触对环境和人类健康造成影响,还可以通过植物根系和叶面吸收等途径进入农作物,形成二次污染,进一步拓宽了人类暴露的途径^[62]。

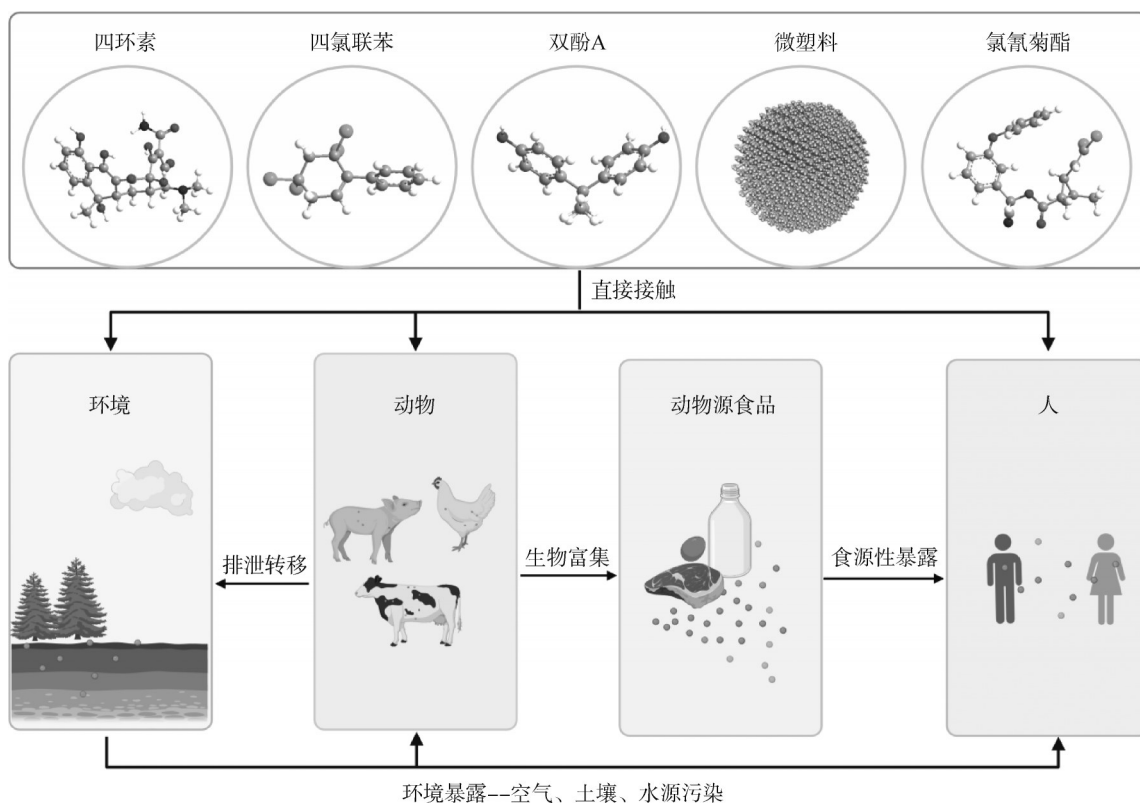


图1 “One Health”背景下畜禽养殖中的常见新污染物暴露途径

Fig. 1 Common exposure pathways to emerging contaminants in livestock and poultry farming in the context of One Health

2 畜牧生产中新污染物对环境和人类健康的潜在影响

2.1 畜牧生产中新污染物对人类健康的影响

在过去的半个多世纪,抗生素的广泛使用在预防和治疗动物疾病以及促进动物生长方面扮演了重要角色^[63]。然而,不合理、超量使用或未遵循休药期规定,会导致大量抗生素残留在动物源食品

中^[64]。当人类摄入这些食品后,抗生素会打破肠道内原本平衡的微生物群落结构,干扰营养物质的吸收和代谢,削弱人体免疫力^[65]。更为严峻的是,抗生素会促使肠道内细菌产生耐药性,这些耐药菌一旦传播,可能引发难以治疗的感染性疾病,给公共卫生安全带来极大挑战^[66]。此外,抗生素所产生的其它毒副作用也不容忽视,如肝毒性、过敏反应、神经毒性、肾毒性^[67-70]等。例如,Keerty等^[71]研究发现

头孢菌素会引起神经毒性,临床表现主要包括意识水平受损、谵妄、肌阵挛和癫痫发作。

POPs(如多氯联苯和二噁英)因其化学稳定性高、难以降解的特性,在环境中长期存在并通过生物富集作用在食物链中逐级放大^[72]。人类通过食用受污染的动物产品(如鱼类、肉类和乳制品)摄入这些污染物,可能导致严重的健康问题,例如癌症、糖尿病、出生缺陷、内分泌紊乱、心血管疾病以及免疫和生殖系统功能失调^[73-77]。PFAS是一类典型的持久性有机污染物,广泛存在于日常消费品和工业生产中^[78]。研究表明,PFAS在人体内广泛暴露和积累,如Li等^[79]通过研究发现PFAS暴露不仅与急性冠脉综合征风险增加相关,与冠状动脉狭窄也呈正相关,并且显著增加不良预后的发生率。

EDCs通过塑料制品、农药残留和畜牧废水进入环境,最终通过食物链进入人体^[80]。EDCs能够与人体激素受体结合,干扰正常的激素信号传导,导致生殖系统异常、发育障碍和代谢疾病^[81-83]。例如,双酚A是一种广泛用于塑料生产的EDCs,其暴露与儿童性早熟、男性精子质量下降以及女性不孕症密切相关^[84-86]。Huang等^[87]研究表明,孕期暴露双酚A可能导致婴儿出现认知功能发育迟缓。此外,EDCs还可能干扰胰岛素分泌和脂肪代谢,增加肥胖和糖尿病的风险^[88]。例如,Lin和Yin^[89]研究发现,某些EDCs(如双酚A、邻苯二甲酸盐)通过控制参与脂质储存和葡萄糖代谢的基因表达,导致体重异常增长和代谢综合征的发生。

微塑料可通过水源、饲料等途径被动物直接或间接摄入并在体内积累,并通过食物链进行积累和营养转移,对动物和人类健康构成威胁^[90]。研究表明,长期暴露于微塑料可增加多种慢性疾病的发生风险,并可引发消化、呼吸和免疫等器官系统异常^[91-93]。例如,Marfella等^[94]研究发现,颈动脉斑块中检测到微塑料的患者,在34个月的随访期内,发生心肌梗死、中风或因任何原因死亡的综合风险比未检测到微塑料的患者更高。此外,微塑料具有较大的比表面积,能够吸附环境中的持久性有机污染物、重金属等有害物质。当动物摄入微塑料后,这些有害物质会随着微塑料一同进入动物组织,并在体内积累,产生更大的毒性效应^[95-96]。人类食用含有微塑料的动物源食品后,微塑料及其携带的有害物质可能进入人体细胞,进而干扰细胞的正常代谢过程,并对人体健康构成潜在威胁^[97]。

农药残留通过受污染的食品进入人体,长期食用低剂量农药残留的食品,可能导致农药在体内蓄积,引发慢性健康问题^[98]。部分农药及其代谢产物具有致癌、致畸作用^[99-100]。例如,有机氯农药(如六氯苯)可通过干扰DNA修复机制或诱导基因突变,增加癌症风险^[101-102]。此外,农药残留还会引起人体肠道菌群失衡、代谢失调、肥胖等健康问题^[103-104]。例如,Liang等^[105]研究发现,毒死蜱能够破坏肠道屏障的完整性,促使脂多糖进入肠道,进而引起炎症和肠道菌群的改变。此外,接触毒死蜱改变微生物群的小鼠出现脂肪增多和胰岛素敏感性降低的现象。

2.2 畜牧生产中新污染物对环境的影响

畜牧生产中抗生素的滥用和不当处理,导致大量药物未能被生物体完全吸收或降解,而是直接排入水体、土壤等自然环境中^[106-107]。这些抗生素残留物在环境中难以自然消除,会逐渐积累并扩散,形成持久的污染源。水体中的抗生素残留可通过农业灌溉、饮用水供应等途径进入农田和饮用水水源,这不仅破坏土壤和水体中的微生物群落平衡,还通过选择压力促进抗性基因的产生和传播,进一步加剧环境污染^[108]。例如,韩婉雪等^[109]研究发现,长期堆放猪粪和鸡粪会增加土壤中四环素类和磺胺类抗性基因的丰度。此外,抗生素(如喹诺酮类、磺胺类)在河流、地表水等水体中残留,会对水生生物产生遗传毒性,并在鱼类组织中发生生物积累^[110]。例如,Duan等^[111]研究发现,四环素暴露可通过肠-肝轴对石斑鱼生理稳态产生影响,引起肝脏病理改变、脂质积累,增加肝功能损伤指数和氧化应激等不良反应。

POPs在环境中长期积累,并通过食物链逐级富集,对生物多样性和生态平衡造成严重威胁。例如,二噁英在鱼类体内的富集不仅导致繁殖能力下降,还通过食物链影响更高营养级的生物,如鸟类和哺乳动物,最终威胁整个生态系统的稳定性^[112]。此外,持久性有机污染物还通过土壤和地下水被植物吸收并积累,其潜在的植物毒性会对生态系统的稳定产生不利影响^[113-114]。

EDCs通过畜牧废水和塑料制品进入环境,对动物的内分泌系统造成干扰^[115]。例如,在水生生态系统中,雌激素类物质(如雌二醇)在水体中形成低浓度长期暴露环境,某些鱼类因暴露于雌激素类物质而出现性别畸变,雄性鱼类表现出雌性化特征,

导致种群性别比例失衡,进而影响其繁殖能力和种群稳定性^[116]。此外,内分泌干扰物还能影响两栖动物和鸟类的发育,导致孵化率下降和幼体存活率降低,进一步威胁生物多样性^[117]。

微塑料是近年来备受关注的环境污染物,其通过饲料、塑料制品降解和废水排放等途径进入环境,污染土壤、水体乃至大气,对生态系统产生不良影响^[118]。例如,微塑料可扰乱土壤微生物的群落结构与代谢,同时对土壤动物和植物的生长发育造成损害^[119]。微塑料被动物误食,会导致消化系统阻塞和营养不良。例如,海洋生物摄入微塑料后,会出现发育迟缓、行为异常,甚至因能量代谢紊乱导致死亡^[120]。此外,微塑料还能吸附其他有毒物质(如重金属和持久性有机污染物),加剧其毒性效应^[121]。例如,Feng等^[122]研究发现微塑料会增加Pb在小鼠体内的生物积累,并且还会通过诱导细胞凋亡,导致小鼠卵巢损伤。

在畜禽养殖过程中,农药可通过直接施用(如畜禽体表处理、圈舍环境消杀)和间接迁移(如饲料残留、养殖废水排放)等途径进入环境,最终对生态系统造成多重危害。例如,有机磷类(如毒死蜱)农药在土壤中长期滞留,破坏微生物群落平衡并抑制

土壤肥力,导致农作物吸收后二次污染^[123-124]。未经处理的养殖污水携带农药流入水体,可引发生物急性中毒或慢性生态毒性,如鱼类死亡和藻类过度繁殖,加剧水体富营养化^[125]。此外,农药在环境中通过食物链逐级富集,不仅威胁鸟类、昆虫等生物类群的生存,还显著降低区域生物多样性。例如,研究显示,新烟碱类化合物使用量的增加导致鸟类生物多样性显著减少,特别是对于草原鸟类和食虫鸟类,平均年减少4%和3%^[126]。

综上,畜牧生产中产生和使用的抗生素、POPs、EDCs、微塑料及农药残留等新污染物,因其环境持久性、生物累积性和跨介质迁移能力,对生态环境和人类健康造成了严重影响(表2)。在健康层面,人类通过食用受污染的动物产品摄入这些污染物,可导致肠道菌群失调、耐药性增加、内分泌紊乱、生殖发育障碍、代谢性疾病、免疫抑制乃至癌症等多种健康风险。在环境层面,它们破坏土壤和水体微生物平衡,诱导抗性基因传播,损害生物多样性,干扰生态系统功能,并通过食物链不断富集放大。这些影响相互关联,揭示了畜牧生产中新污染物问题的复杂性和严峻性,亟需采取综合措施加强畜牧生产中新污染物的治理,以保障生态安全和公共卫生。

表2 畜牧生产中新污染物对人类健康和环境的影响

Table 2 Impacts of emerging contaminants from livestock production on human health and the environment

污染物类别 Pollutant category	对人类健康的不良影响 Adverse effects on human health	对环境的不良影响 Adverse effects on the environment
抗生素 Antibiotics	破坏肠道菌群平衡 ^[65] ;诱导耐药菌增殖 ^[66] ;各种毒副作用 ^[67-70]	破坏微生物群落平衡 ^[108] ;通过水平基因转移促进耐药菌扩散 ^[109] ;遗传毒性 ^[110]
持久性有机污染物 Persistent organic pollutants	癌症、糖尿病、出生缺陷、内分泌紊乱、心血管病以及免疫和生殖系统功能失调 ^[73-77]	生物富集 ^[112] ;生态毒性 ^[113]
内分泌干扰物 Endocrine disrupting chemicals	生殖系统异常 ^[81] ;发育障碍 ^[82] ;代谢紊乱 ^[83]	干扰动物内分泌系统 ^[115] ;野生动物性别畸变 ^[116]
微塑料 Microplastics	多种慢性疾病和器官系统异常 ^[90-93]	物理污染 ^[118] ;复合污染 ^[119]
农药 Pesticide	致畸 ^[99] ;致癌 ^[100]	破坏微生物群落平衡 ^[123] ;生态平衡破坏 ^[125]

3 畜牧生产中新污染物的治理

畜牧生产中的新污染物,通过废水排放、空气传播以及土壤渗透等途径,进入自然环境中,对生态系统和人类健康构成了严重威胁。为降低这些污染物的影响,治理策略可围绕“源头减量-过程阻断-末端净化”这一思路展开。

3.1 源头减量

源头减量是畜牧污染治理的首要环节,可以通过政策管控、优化饲料配方、推广替抗产品(如抗菌肽、中药提取物与中药发酵、有机酸、微生态制剂等)^[127]、研发环境友好型饲料添加剂(如丝兰提取物、花青素等)^[128-129]、改善饲养环境等途径,从源头降低抗生素及耐药基因等新污染物产生的风险。例如,Li等^[130]通过对比长期施用与停用新鲜鸡粪对

土壤-生菜系统中 ARGs 分布的影响,发现停用粪肥可使大块土壤、根际土壤和叶片中 ARGs 丰度分别降低 34.0%、53.7% 和 23.9%,研究提出通过优化施肥时序(如采收前 3~6 个月停用粪肥)阻断 ARGs 传播路径。Zhang 等^[131]研究发现 γ -氨基丁酸作为天然饲料添加剂,可显著提升犊牛日增重和体高,降低瘤胃挥发性脂肪酸水平,减少了抗生素依赖。

此外,还可以采用可降解材料替代传统塑料器具等方式推进养殖设施“减塑”改造,减少微塑料及其添加剂(如 PFAS、PCBs)的排放。例如,Chen 等^[132]发现聚(己二酸丁二醇酯-对苯二甲酸丁二醇酯)地膜覆盖的堆肥系统不仅减少了传统塑料地膜使用量,还能通过微生物降解加速有机质转化,提升粪污资源化效率。Guo 等^[133]采用接枝聚合技术,以牛粪为主要原料合成了牛粪基可降解液体地膜,该技术既解决牛粪处置难题,又为传统塑料地膜提供环保替代方案。

3.2 过程阻断

过程阻断聚焦于养殖过程中污染物的高效处理,通过物理、化学与生物技术协同,阻断污染物在养殖环境中的迁移与转化。进行粪污处理时,可以通过高温堆肥、厌氧发酵等工艺提升畜禽粪便无害化处理效率,利用生物降解、化学稳定化等技术降低抗生素残留及抗性基因活性^[134]。高温堆肥是降低抗生素残留和 ARGs 丰度的核心工艺。最新研究表明,链霉菌-芽胞杆菌合成菌剂的引入可显著提升堆肥效率,并有效抑制有害病菌繁殖^[134]。例如,Zhou 等^[135]利用链霉菌-芽胞杆菌合成菌剂进行牛粪、玉米秸秆堆肥发酵,不仅能够加速牛粪堆肥过程中的纤维素分解和有机质腐熟,还能将禾谷镰孢菌等植物病原菌丰度降低 80%,同时削减 90% 以上的 ARGs(如 *tetM*、*suI*),并抑制抗性基因的水平转移。此外,阚泽鑫等^[136]研究发现,利用高温预处理联合生物炭堆肥可加速抗生素降解并钝化重金属,同时抑制 ARGs 的传播。该技术可使四环素类抗生素在堆肥 14 d 后实现 100% 去除,喹诺酮类和磺胺类抗生素在 28 d 后去除率分别达到 100% 和 99%,较传统堆肥工艺,处理周期缩短了 14~28 d。此外,重金属(如 Cu、Zn、Pb)的钝化率可达 35.8%~58.9%,与对照组相比,有效态重金属含量降幅可达 12.8%~34.8%。

此外,还可以利用功能材料等方法强化传统污染物(如重金属)与新污染物的协同去除^[137]。例如,

Qiu 等^[138]开发的非对称磁性介孔二氧化硅纳米瓶在养殖废水处理中表现出高效吸附能力。该材料通过介孔结构吸附多氯联苯和重金属离子(如镉、铅),去除率超过 90%,并可通过磁场定向回收实现循环利用。

3.3 末端净化

末端净化针对已进入环境的污染物,可以采用功能材料与生态技术进行污染物的处理。例如,Jia 等^[139]研究发现,生物炭能够通过吸附-生物协同机制特异性去除水体中的抗生素,对喹诺酮类、四环素类、大环内酯类和磺胺类抗生素表现出显著的吸附能力,最大吸附容量范围为 0.3~612.2 mg·g⁻¹。Wang 等^[140]开发了一种稻壳生物炭与黏质沙雷菌的协同降解体系,显著提升了农业土壤和水中四环素的降解效率。

此外,还可以利用膜分离技术截留微塑料、持久性有机污染物等畜禽养殖过程中所产生的新污染物^[141]。常用的膜分离技术有微滤(microfiltration, MF)、超滤(ultrafiltration, UF)和膜生物反应器(membrane bioreactor, MBR)。MF 和 UF 被广泛应用于去除胶体物质、大分子有机物和藻类等,膜孔径一般在 0.1 μm 左右,可有效去除水中的微塑料^[142]。例如,Pramanik 等^[143]研究发现, MF 和 UF 对尺寸在 75 μm 以上的 MPs 去除效率分别为 91% 和 96%。此外,其它新兴技术的出现也为新污染物的末端治理提供了解决方案,如基因编辑微生物定向分解难降解污染物(如二噁英类化合物)^[144];高级氧化技术可利用强氧化性物质破坏污染物结构,对多种抗生素,包括氟喹诺酮类、磺胺类等都有良好的降解效果,其降解原理是通过自由基攻击抗生素分子中的化学键,使其分解为小分子物质^[145]。

3.4 治理技术综合评估

当前基于“源头减量-过程阻断-末端净化”框架的治理策略已取得显著成效,但仍面临关键挑战。在源头减量方面,替抗产品和可降解材料的应用有效降低了污染产生,但仍存在作用机理、使用规范、功能的稳定性、潜在的风险等方面的研究空白^[146]。过程阻断技术如高温堆肥能高效降解污染物,但面临处理成本高和二次污染风险^[147]。末端净化技术虽能有效清除污染物,但受限于高昂成本和复杂环境的适应性^[148]。

未来需重点突破以下方向:1)开发低成本、高效率的新型治理技术;2)优化现有工艺以降低成

本;3)加强污染物传播机制和风险评估研究;4)完善政策监管和标准化体系。通过多管齐下的综合治理,才能实现畜牧生产的可持续发展。

4 展 望

畜禽养殖作为新污染传播的关键环节和“同一健康”框架中的重要组成部分,既需要保障动物健康和福利,也需重视生态环境和公共卫生的可持续发展。当前,畜牧业中的新污染物已形成“环境-动物-人”的复合污染网络,其跨介质迁移与生物累积效应威胁全球健康安全。尽管通过源头减量、过程阻断和末端治理等策略已取得一定成效,但污染物的隐蔽性、环境持久性等特性仍对现有技术提出严峻挑战。

首先,应加强畜禽养殖过程中的环境管理和污染控制,制定和实施更为严格的养殖标准和规范,减少新污染物的产生和排放。如建立智慧管理体系,运用区块链技术构建全程溯源系统,依托大数据和AI实现精准环境治理^[149]。其次,加大对新污染物检测和监测技术的研发投入,建立完善的检测体系和监测网络,及时掌握污染物在畜禽养殖环境中的分布和变化情况,为科学制定防治措施提供数据支持。例如,在畜禽管理中应用传感器,传感器技术可实现对畜禽养殖环境的实时监测,为智能监测预警网络的构建提供技术支持^[150]。此外,加强公众健康教育和宣传,提高消费者对新污染物及其潜在健康风险的认识,引导消费者选择安全、健康的动物源食品,促进绿色消费理念的普及。同时,加强跨学科、跨领域的合作与交流,整合各方资源和优势,共同开展新污染物对环境和人类健康影响的研究,推动相关技术的创新和应用,为实现畜牧业的可持续发展和保障人类健康提供有力的科技支撑。

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