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农村生活污水资源化利用对土壤-作物的影响与风险研究进展

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摘要： 随着水资源短缺问题日益严峻，将富含氮磷等营养元素的农村生活污水进行资源化利用，是实现“治污”与“兴农”双赢的重要途径。本研究综述了农村生活污水的水质特性及时空产排特征，系统剖析了污水资源化利用对土壤和作物的复杂影响及潜在的环境风险。研究表明：合理回用不仅能显著降低土壤容重、提升土壤有机质含量与肥力，还能重塑微生物的群落结构与酶活性，实现农作物 10%~30% 的增产及农业生产成本的节约，其效果受污水水质、灌溉时长、土壤深度等因素的综合影响。同时，资源化利用过程中，污水所含病原微生物及微塑料、抗生素等新污染物在土壤-作物系统中的迁移转化亦不可忽视，一旦超出安全阈值，可能通过食物链危及农产品质量安全及人类健康。本研究旨在厘清污水资源化利用的“双刃剑”效应，以期为建立安全、高效、可持续的农村生活污水资源化利用模式提供科学依据和理论支持。图 1 参 87

关键词： 农村生活污水；资源化利用；土壤环境；作物生长；环境风险

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Research progress on the impacts and risks of rural domestic sewage resource utilization on soil-crop systems

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Abstract: As water scarcity becomes an increasingly pressing issue, the resource recovery of rural domestic sewage rich in nutrients such as nitrogen and phosphorus represents a crucial approach to achieving a win-win outcome for both pollution control and agricultural development. This paper reviews the water quality characteristics of rural domestic sewage and its spatiotemporal generation and discharge patterns, and systematically analyzes the complex impacts of sewage resource recovery on soil and plants, as well as its potential environmental risks. Studies have shown that appropriate reuse of rural domestic sewage can reduce soil bulk density and increase soil organic matter content and fertility. It can also reshape microbial community

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structure and enzyme activity, leading to a 10%–30% increase in crop yields and savings in agricultural production costs. These effects are influenced by a combination of factors, including sewage quality, irrigation duration, and soil depth. Meanwhile, the migration and transformation of pathogenic microorganisms, microplastics, antibiotics, and other emerging pollutants carried in sewage within soil-plant system during the resource recovery process must not be overlooked. If these pollutants exceed safety thresholds, they may pose potential threats to agricultural product quality and safety as well as human health through the food chain. This paper aims to clarify the “double-edged sword” effect of sewage resource recovery, and to provide scientific evidence and theoretical support for establishing a safe, efficient, and sustainable model for the resource recovery of rural domestic sewage. [Ch, 1 fig. 87 ref.]

Key words: rural domestic sewage; resource utilization; soil environment; crop growth; environmental risk

2023 年全国城乡建设统计数据显示：中国现有自然村约 234 万个，农村常住人口达 6.2 亿人，农村生活污水年排放量高达 345.3 亿 t。在污水排放总量持续高位运行与水资源供需矛盾日益突出的双重压力下，推动农村生活污水从末端治理对象向可利用资源转变，已成为缓解农业用水短缺、促进乡村绿色发展的关键路径。近 10 a 来，关于“农村生活污水”与“资源化利用/农业回用”领域的相关研究迅速发展，中国知网 (CNKI) 和 Web of Science (WOS) 两大数据库在该领域的年度发文量整体均呈增长态势。研究热点从前期的“水质特征与处理工艺评价”，向“土壤肥力与物理属性提升”“微生态响应机制”，再向“微塑料与抗生素等新污染物风险评估”逐步转变。科学合理的资源化利用能有效提升土壤有机质含量，补充氮磷等养分，改善土壤肥力与保水保肥能力，促进作物生长、提高产量[1]。同时，与工业废水相比，农村生活再生水水质差异小、水体分散、氮磷含量高、生物降解性好，一般不含重金属等有毒物质，作为营养补剂时，灌溉回用安全性更易保障[2−4]。然而，农村生活污水回用于农田易引发土壤盐渍化及引入新型污染物等潜在生态环境风险[5−7]，其安全回用阈值的界定及其与长期生态效应之间的内在关联，仍有待深入探究。本研究系统梳理农村生活污水资源化利用的“双刃剑”效应，剖析对土壤与作物的影响及环境健康风险，为农村生活污水的安全可持续利用提供科学依据。

1 农村生活污水的来源与特征

农村生活污水源于居民烹饪、洗涤等日常活动，按来源与污染特性可分为灰水和黑水。灰水主要来自厨房的洗涤、烹饪以及家庭的沐浴和洗衣等活动，约占农村生活污水的 60%[8]。其主要成分包括食物残渣、油脂、表面活性剂、有机物、氮和磷等[9]。此外，灰水中还可能含有抗生素、环境激素等新型微量污染物，构成潜在的环境与健康风险[10]。黑水是冲洗厕所粪便产生的高浓度生活污水，其特点是富含氮磷等营养物质。中国部分省份农村生活污水水质情况显示：黑水质量浓度均显著高于灰水 (表 1)，表

表 1 中国部分省份农村生活污水水质特征情况

Table 1 Characteristics of rural domestic sewage quality in some provinces of China

类型	省份	水质指标/(mg·L^{-1})					参考文献
		化学需氧量	固体悬浮物	铵态氮	总氮	总磷	
黑水	江西	626.5	216.2	112.6	183.6	20.1	[11]
	湖北	1 042.0	1 139.7	97. 4	158.4	35.9	[12]
	江苏	957.0		123.0	411.3	29.2	[13]
	浙江	1 042.5	124.2		187.5		[14]
灰水	江西	487.5	67.5	19.4	33.9	1.7	[11]
	湖北	549.0		6.0	21.2	2.4	[12]
	四川	135.0		7.2	8.7	1.0	[15]
	山东	504.4	64.4	3.1	14.5	1.9	[16]

明黑水是农村生活污水污染物的主要来源[17−18]。同时，农村生活污水水质存在地域差异：北方因气候干燥、降水少，污水易因蒸发浓缩而污染物浓度偏高[19]；南方气候湿润、降雨充沛，雨季雨水会稀释污水，但旱季污染物浓度会快速回升[20−21]。

农村生活污水的产生与排放也存在明显的时空特征分布。首先，污水排放量普遍呈现“夏高冬低”的规律，夏季排放量通常比冬季高 20% 至 50%[22]。这主要是因为夏季高温导致居民洗浴、洗衣等用水活动增加。其次，是经济发达地区 (如华东城郊) 的人均日排放量远高于欠发达地区[23−24]。发达地区用水设施完善，生活方式趋于城市化，促使用水量和污水产生量增加。

2　农村生活污水资源化利用对土壤理化性质的影响

2.1　土壤物理属性

污水灌溉可以通过输入大量溶解性有机物和悬浮颗粒物，促进土壤大团聚体的形成与稳定，从而降低土壤容重，提高土壤孔隙度和持水能力。然而，物理属性的改善并非绝对，WANG 等[25] 分析指出：污水灌溉显著改变了土壤的水力学特性，长期灌溉含钠盐较高的污水或未经充分沉淀的污水，可能导致土壤胶体分散，引起土壤毛细孔隙堵塞，进而导致土壤板结、降低入渗率和导水率，影响根系呼吸。

2.2　土壤有机质与养分含量

农村生活污水资源化利用可直接影响土壤肥力[26]。国内外多数研究证实：无论污水处理程度如何，灌溉均能有效提升土壤有机质含量 (表 2)。污水本身是外源有机碳的直接来源[34]，通过三维荧光光谱等技术解析发现：污水溶解性有机物 (DOM) 中既包含易于降解的类蛋白组分，也包含大量结构复杂、化学性质稳定的类腐殖质与类富里酸组分[35]。易分解有机碳与矿物表面结合形成稳定的微团聚体[36−37]；而难降解组分则作为持久结合剂促进大团聚体形成，延缓了有机质的分解[38]。谢芳[39] 针对棕壤水稻土的研究证实：再生水灌溉能显著促进深层土壤有机碳的累积；马鑫文[27] 在安岳县的长期试验进一步表明：农村生活污水资源化利用显著改变了浅层土壤的地球化学特征和养分分布规律。

表 2　农村生活污水对土壤有机质的影响

Table 2　Impact of rural domestic sewage on soil organic matter

地点	农村生活污水类型	灌溉的植物/作物	灌溉时长	试验场地	土壤深度/cm	土壤有机质变化	参考文献
四川省安岳县南薰镇红山村	化粪池处理	蔬菜	123 d	农田	0~20	增长150.00%	[27]
		玉米、红薯、油菜			0~20	少水量灌溉增加10.00%，多水量灌溉增加29.00%	
山东省莱西市河头店镇东大寨村	经厌氧、好氧、沉淀预处理	小麦、玉米	自2006年起	农田	0~20	距污水进水口0~20、20~40和40~60 m处分别比对照提高6.30%、8.50%和9.30%	[28]
浙江省金华市永康农村生活污水处理及回用基地	经多级处理及生态塘净化	水稻	2 a	试验小区	0~20	增加6.00%	[29]
湖北省十堰市茅箭区南部山区	经二级处理的农村生活再生水	菠菜	5个月	农田	0~30	大约增加18.00%	[30]
摩洛哥Tidili村	经混合人工湿地系统处理	紫花苜蓿	9个月	农田	0~20	增长约159.15%	[31]
	未经处理的原污水					增长177.46%	
浙江省金华市永康市舟山镇集镇区舟三村	经一级处理	水稻	101 d	农田	0~20	平均增长52.80%	[32]
江苏省苏州市农业科学院	经农村生活污水处理站处理	白菜	40 d	盆栽	0~15	农村生活再生水和化肥配比为66.00%时增长8.26%	[33]

说明：玉米 *Zea mays*；红薯 *Ipomoea batatas*；油菜 *Brassica napus*；小麦 *Triticum aestivum*；水稻 *Oryza sativa*；菠菜 *Spinacia oleracea*；紫花苜蓿 *Medicago sativa*；白菜 *Brassica campestris chinensis*。

农村生活污水作为一种富含氮磷等养分元素的水源，对土壤养分库具有显著影响。污水中的氮磷主要以铵态氮、硝态氮和可溶性磷酸盐等高生物有效性的形态存在，灌溉后可显著提升土壤表层全氮、速

效磷和速效钾的含量，直接为作物生长提供养分，长期施用甚至可以部分替代化肥[30]。

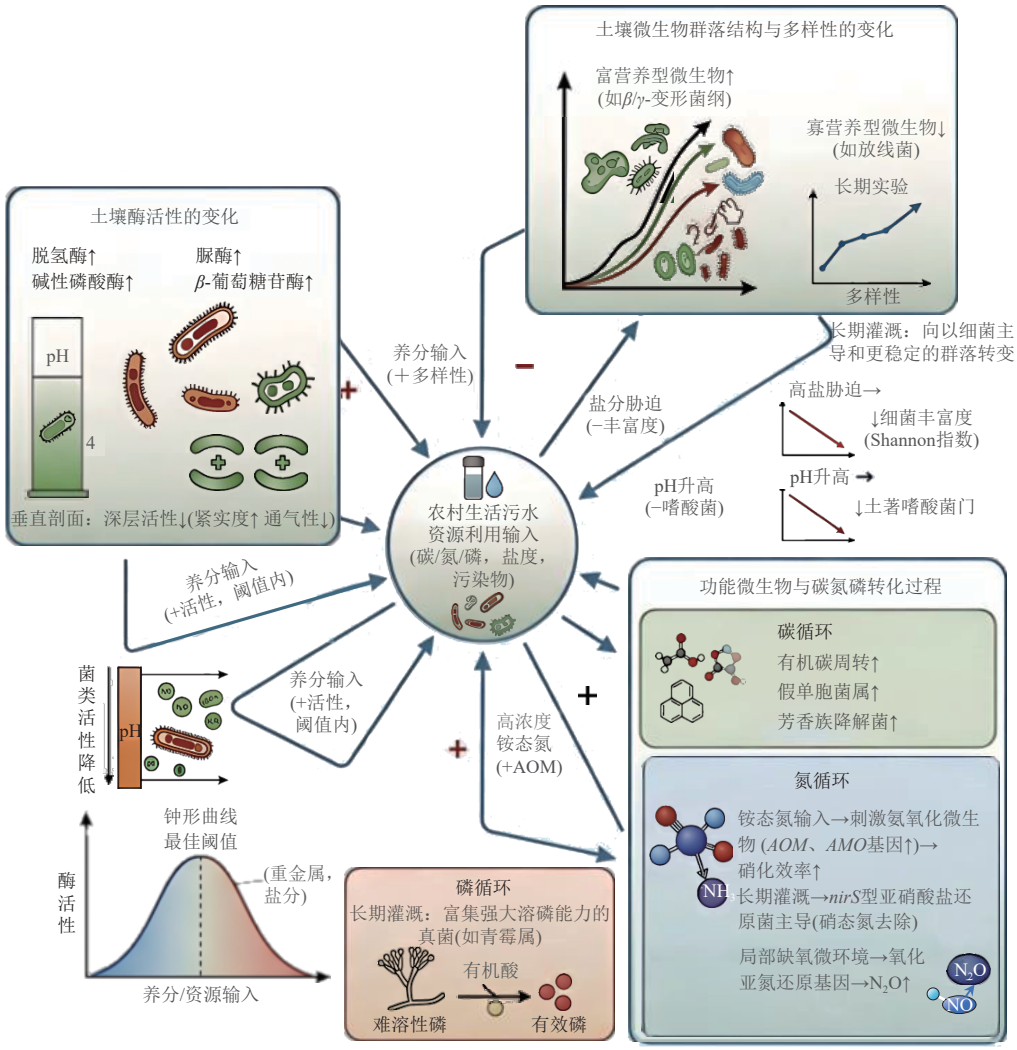
2.3 土壤酸碱度

在已有的研究中，污水灌溉对土壤 pH 的影响呈现升高、降低或无显著变化 3 种结果[40]。这种多样化的结果主要源于污水施用对土壤的酸化与碱化拮抗作用机制。一方面，污水可使土壤酸化：①污水中富含的氯化物与碳酸盐发生中和反应导致 pH 下降[41]；②高浓度的铵态氮在氨氧化细菌 (AOB) 和氨氧化古菌 (AOA) 驱动的硝化过程中释放大量氢离子[42−43]；③有机质矿化释放的有机酸引起酸碱度降低[44]。另一方面，污水也具有碱化能力，富含的碳酸氢根能有效中和产生的酸[29, 45]。土壤 pH 的最终变化是这 2 种作用相互博弈及土壤自身缓冲性能共同决定的结果。

3 农村生活污水资源化利用对土壤微生物的影响

3.1 土壤微生物种群结构与多样性的变化

为了更清晰地展示资源化利用对土壤微生态的复杂驱动机制，本研究归纳了该机制的内在关联性，并构建了相应的结构示意图 (图 1)。



β/γ-变形菌纲Betaproteobacteria/Gammaproteobacteria；放线菌Actinobacteria；土著嗜酸菌门Acidobacteria；假单胞菌属*Pseudomonas*；青霉属*Penicillium*；AOM. 氨氧化微生物；AMO. 氨单加氧酶。

图 1 农村生活污水资源化利用对土壤微生态的驱动机制

Figure 1 Mechanisms driving the effects of rural domestic sewage recycling on soil microecology

农村生活污水通过输入营养物质，可显著提高土壤中 β-变形菌纲 Betaproteobacteria、γ-变形菌纲 Gammaproteobacteria 等富营养型微生物的相对丰度，降低放线菌 Actinobacteria 等寡营养型菌群比例[46−47]。长期研究发现：细菌、真菌和放线菌的群落多样性均随灌溉年限延长呈递增趋势[48]。然而，高盐环境会

显著抑制细菌的物种丰富度，表现为细菌 Shannon-Wiener 指数随盐度升高而递减[49]；灌溉导致的 pH 升高则会显著抑制土著嗜酸菌门 Acidobacteria 的丰度[50]。尽管存在短期波动，长期灌溉最终会促使土壤微生物群落向更稳定且以细菌为主导的类型转变[51]。

3.2　碳氮磷循环功能微生物

污水资源化利用可影响参与碳氮磷循环功能微生物的群落结构。在碳循环方面，污水中的脂肪族烷烃使得假单胞菌属 *Pseudomonas* 丰度显著增加，加速了有机碳周转；残留的芳香族组分会诱导芳香族降解菌上调降解基因的表达[47, 52]。在氮转化过程中，污水中高浓度的铵态氮作为底物直接刺激氨氧化微生物 (AOM) 的生长，提高氨单加氧酶 (AMO) 功能基因丰度，提升了硝化效率[53]。同时，长期灌溉下 *nirS* 型亚硝酸盐还原菌成为截留去除硝态氮的主导群落[54]，而局部缺氧微环境会引起氧化亚氮还原基因 (*nosZ*) 表达异常，可能导致温室气体一氧化二氮 (N_2O) 排放增加[55]。在磷转化方面，长期灌溉显著富集了具有强大溶磷能力的真菌 (如青霉属 *Penicillium*)，通过分泌有机酸将无效磷转化为植物可利用的有效磷[56−57]。

3.3　土壤酶活性的变化

酶活性是反映微生态代谢活力的关键指标。污水资源化利用可显著提升表层土壤中脱氢酶、脲酶、碱性磷酸酶及 *β*-葡萄糖苷酶的活性[58−60]。然而，该效应的影响呈现典型的“钟形曲线”特征，即在特定阈值内酶活性随养分输入而递增，一旦超过该阈值，则可能因重金属累积或盐分胁迫等负面效应而产生抑制作用[61]。在垂直剖面上，深层土壤的酶活性也可能因物理紧实度增加和通气性变差，而呈现下降的趋势[62]。

4　农村生活污水资源化利用对作物产量和品质的影响

农村生活污水富含植物生长所必需的营养元素，能够被植物根系更迅速地吸收利用，在贫瘠土壤中能呈现出类似化学施肥的增产效应[63−66]。据已有研究报道：通过污水灌溉可使玉米 *Zea mays*、小麦 *Triticum aestivum* 等粮食作物增产 10%~25%，蔬菜类作物 (如白菜 *Brassica campestris chinensis*、菠菜 *Spinacia oleracea*) 增产幅度可达 15%~30%[27, 33]。在品质方面，再生水不仅降低了空心菜 *Ipomoea aquatica* 的硝酸盐含量，还能显著提升辣椒 *Capsicum annuum* 的维生素 C 含量[67−68]。

相较于传统化肥，配合污水灌溉的养分表观利用率平均可提升 5%~12%[45]。从经济效益分析，污水资源化就近利用大幅减少了地下淡水的开采成本和化肥施用量，据测算，每公顷农田平均可节约农业综合生产成本 15%~20%，展现出极高的经济与生态双重效益[46]。但需注意的是，长期过量灌溉可能伴随土壤盐分积累，通过渗透胁迫抑制根系吸水[69]。因此，必须集成精准调控技术以防范潜在风险。

5　农村生活污水资源化利用的潜在风险与安全阈值

在农村生活污水农田回用过程中，病原微生物带来的传播风险不容忽视。污水中通常含有沙门氏菌 *Salmonella*、诺如病毒 *Norovirus* 等病原微生物，可通过气溶胶或直接接触途径对人体构成高危暴露，引发肠道疾病[70−71]。为保障农业安全，依据 GB 5084—2021《农田灌溉水质标准》以及世界卫生组织 (WHO) 指南，均对安全阈值做出了严格限定，如每 100 mL 回用水的粪大肠菌群安全阈值通常要求≤10^3 CFU 或更低。因此，资源化利用前采用紫外线辐照、膜过滤等消毒技术至关重要[72]。

农村生活污水中携带的微塑料对土壤系统的物理结构和生态功能也构成潜在威胁。研究表明：污水中的微塑料极易随优先流途径向深层土壤迁移，从而对地下水构成污染风险[73−74]。微塑料不仅破坏土壤团聚体导致保水能力下降[75]，还会抑制脲酶等胞外酶活性[76]，甚至穿透植物细胞在体内累积[77−79]。目前学术界对微塑料的土壤安全阈值尚无统一标准，但已有研究表明：当土壤微塑料质量分数超过 1% 时，作物的生物量和抗氧化系统将受到显著抑制，亟需研发如生物炭强化人工湿地等阻控技术[80]。

抗生素的累积是另一重大环境风险。由于农村抗生素使用不规范，四环素类等稳定型抗生素易在表层土壤强络合累积 (半衰期长达 9~180 d)[81−84]。高质量浓度抗生素不仅破坏碳氮磷循环微生物的功能[85−86]，更会导致抗生素抗性基因 (*ARGs*) 在环境中的水平转移富集。环境管理上，目前正致力于将污水中目标抗生素的质量浓度降至预测无效应质量浓度 (PNEC，多数抗生素的水生生态 PNEC 集中在 10~1 000 ng·L^{-1})

以下，利用厌氧消化等生物技术强化去除是降低此类风险的有效途径[87]。

6 总结与展望

本研究系统梳理了农村生活污水资源化利用的正面效应和潜在风险。科学合理的污水资源化利用不仅补充了宝贵的水资源，还能有效改善土壤物理结构、提升土壤肥力与酶活性，从而实现作物10%~30% 的增产及经济成本的节约。但污水中携带的病原微生物及微塑料、抗生素等新污染物在超出安全阈值时，会严重损害微生态功能并威胁人类健康。未来研究可以从以下几个方面展开：①构建全方位长期定位观测与综合评估体系。鉴于目前缺乏长期、系统的监测数据，亟须在不同气候区域、土壤类型及技术模式下建立具有代表性的长期定位观测网络。通过对“土壤-地下水-农产品”系统进行连续跟踪，构建涵盖土壤健康、生态稳定性及农业经济效益的综合评估指标体系。基于长期实测数据，开发资源化利用的风险预警模型与决策支持系统，为实现分区域、差异化的灌溉定额管理与工艺参数优化提供坚实的数据支撑。②解析污水回用情境下的长期土壤微生态响应机制。深入探究长期污水灌溉对土壤微生物群落多样性、群落组成及关键功能菌群演替的驱动机制，特别是其对碳氮循环、有机物降解等关键生态过程的影响。重点关注抗生素抗性基因在土壤环境中的富集特征与传播风险，从微生态视角阐明资源化利用对土壤生态功能与生物安全的影响机制。③阐明污染物在“土壤-作物”系统中的多介质迁移转化归趋。针对重金属及微塑料、抗生素等新污染物，重点解析其在复杂环境介质中的吸附-解吸、生物转化等界面过程。探究污染物从土壤向作物可食用部位迁移的通量与富集规律，界定累积阈值。同时，建立污染物长期迁移转化的数学模拟模型，实现从污染源头到受体终端的全过程风险预测，为制定精准的阻控策略提供理论依据。

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