Antibiotic Resistance in Sustainable Solid Waste Management Systems: Quantitative Evidence, Molecular Insights and Process-Level Control Strategies

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Antibiotic resistance (AR) is increasingly recognized as an environmental and engineering challenge, with solid waste management systems emerging as relevant reservoirs and transmission pathways. This review synthesizes recent quantitative and molecular evidence on the occurrence, drivers, and mitigation of antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs) in municipal, healthcare, and organic solid waste streams.

Studies based on quantitative PCR (qPCR) and metagenomic analyses consistently report high ARG abundances in untreated solid waste matrices, typically ranging from 10^5 to 10^8 gene copies g^{-1} (dry weight), with landfill leachates reaching up to 10^6–10^7 copies mL^{-1}. Frequently detected markers include sul1, *sul*2, *tet*(M), *tet*(W), bla_{TEM}, bla_{CTX-M}, and *intI*1, the latter being widely used as an indicator of anthropogenic pollution and horizontal gene transfer potential. Metagenomic profiling reveals a diverse resistome dominated by multidrug resistance mechanisms and clinically relevant resistance classes, often co-occurring with mobile genetic elements such as plasmids, integrons, and transposases.

From an engineering perspective, landfills, composting facilities, and mechanical–biological treatment plants are identified as AR hotspots, particularly under conditions of heterogeneous waste composition, suboptimal aeration, and insufficient temperature control. Co-selection pressures driven by heavy metals (e.g. Cu, Zn, Pb) and residual antibiotics were repeatedly shown to correlate with increased ARG persistence and dissemination.

Comparative assessment of treatment technologies indicates that thermal processes, including incineration and high-temperature pyrolysis, achieve near-complete elimination of ARB and ARGs. Anaerobic digestion shows variable performance, with ARG reductions of 1–3 log units depending on operational parameters such as temperature regime (mesophilic vs. thermophilic), hydraulic retention time, and feedstock composition. Thermophilic digestion (>55 °C) consistently outperforms mesophilic systems. In contrast, conventional composting frequently results in incomplete ARG removal or transient enrichment, particularly during the mesophilic phase, unless sustained thermophilic conditions and extended maturation times are applied.

Overall, the reviewed evidence demonstrates that solid waste management systems represent both a source and a critical control point for environmental AR. Integrating molecular monitoring tools, process optimization, and risk-based engineering design into sustainable solid waste management strategies is essential to limit AR dissemination and support public health protection within circular economy frameworks.

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