論文の要旨
Summary of the Dissertation

論文題目
Dissertation Title:

Environmental Pollutions of Landfilled Municipal Solid Waste and Its Energy Recovery Potential: A Case Study of Phnom Penh Municipality
（埋立固形廃棄物の環境汚染とエネルギー回収の可能性： プノンペン市の事例）

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Municipal solid waste (MSW) generation in Cambodia has significantly increased in recent decades. The absence of intermediate waste treatment facilities and limited source segregation practices have created substantial pressure on MSW landfills throughout the country. Like many other developing nations, the organic fraction accounts for more than 50%, ultimately ending up in landfills, mixing with other waste compositions. Under anaerobic conditions in landfills, biodegradable waste decomposes, producing leachate and methane (CH_4) gas. Leachate is a liquid commonly containing various pollutants, including dissolved organics, inorganic macro components, heavy metals, and xenobiotic organic compounds. If not adequately managed, leachate has the potential to contaminate groundwater and surface water, accumulate in the soil, and substantially enter the food chain, posing risks to human health. Additionally, CH_4 is a potent greenhouse gas (GHG) that contributes to global warming and climate change.

This study aims to assess environmental pollution resulting from MSW landfilling and determine a mitigation strategy by optimizing resource recovery in Phnom Penh municipality. Firstly, the study investigates the influence of landfill leachate on the surrounding environment of the Dangkao landfill site in Phnom Penh and its vicinity. The focus is on determining the concentration of heavy metals in surface water, groundwater, soil, plants, and fish using an Inductive Coupled Plasma Optical Emission Spectrophotometer. Secondly, the study estimates the generation of CH_4 by employing the Landfill Gas Emission Model (LandGEM) and IPCC first-order decay (FOD) model. Based on CH_4 estimation results, the overall GHG emissions from different landfill management options were quantified. Thirdly, various MSW management scenarios are developed to minimize landfilling and maximize recycling and resource recovery. The study evaluates the GHG emissions and reductions associated with these proposed scenarios, following the life cycle assessment framework and IPCC 2006 guidelines. Finally, the study analyzes the economic feasibility of waste-to-energy (WTE) technologies, including incineration, anaerobic digestion (AD), and LFG recovery. This analysis took into account the energy recovery potential, economic viability, and emissions reduction.

The findings indicate that Cd, Cr, Ni, and Pb concentrations in surface water exceeded the permissible limits. Additionally, all heavy metals were found higher in the downstream canal, suggesting a significant accumulation of these pollutants in leachate that is discharged into the canal. Furthermore, Cd, Cr, and Ni were also found to be above the standard limits of the World Health Organization (WHO). The groundwater located in the landfill exhibited a higher level of all heavy metals compared to other sampling sites. This can be attributed to an improper liner, which allows these metals to seep through the landfill and pass through the soil, ultimately

contaminating groundwater. Regarding heavy metals in soil, only Cd and Ni were found to exceed the allowable limits. The soil samples collected from low-lying inundation areas showed a higher accumulation of heavy metals than other sampling sites. This suggests that the heavy metals are likely transported through water and accumulate in the soil during flooding or high-water levels. Similarly, in plant samples, only Cd concentrations exceeded the allowable limits of the WHO, suggesting that the plants have absorbed and accumulated high levels of Cd. Excessive Cd, Pb, and Zn levels were found in fish samples, exceeding the allowable limits. These findings indicate that migration of leachate, coupled with the low-lying topography, contributed to the accumulation of heavy metals in water and soil, which were then transferred to plants and fish. The elevated levels of heavy metals in groundwater, plants, and fish signify a potential health risk for individuals who regularly consume these contaminated sources. The study also observed that the accumulation of heavy metals was mostly higher during the dry season, possibly due to lower water volume, reduced dilution, and higher water temperatures.

The estimated CH_4 generation from the Dangkao landfill showed an increasing trend, rising from 1.54 M kg/year in 2010 to 36.50 M kg/year in 2022, according to the LandGEM model. The IPCC FOD model estimated a relatively higher CH_4 generation, ranging from 2.17 M kg/year in 2010 to 42.83 M kg/year in 2022. Considering that 75% of CH_4 generation is collected for electricity production, the energy potential was estimated at 51 GWh/year based on the LandGEM model and 61 GWh/year based on the IPCC FOD model. Four landfill management scenarios were developed to address the environmental pollution arising from CH_4 emissions. Scenario 1 represents the current landfill management practice without leachate treatment and LFG collection systems, resulting in an average of 397 and 496 M kg CO_2-eq/year of GHGs based on the LandGEM and IPCC FOD models, respectively. Scenario 2 involves an improved landfill management practice incorporating a leachate treatment system, emitting an average of 409 M kg CO_2-eq/year based on the LandGEM and 509 M kg CO_2-eq/year according to the IPCC FOD model. The increase in scenario 2 primarily stems from additional emissions arising from the leachate treatment process. Scenario 3 introduces an engineered landfill equipped with a leachate treatment and flaring system, leading to a reduction in GHG emissions of at least 55%. Additionally, scenario 4 presents an upgraded system that utilizes LFG recovery for electricity production, mitigating at least 83% of GHG emissions. Despite being the most favorable option due to its substantial GHG reduction and electricity generation capabilities, scenario 4 still contributes to environmental pollution through uncollected CH_4 and leachate leakage. Hence, implementing a waste landfill reduction strategy is crucial to minimize the environmental impacts of the landfill.

To mitigate environmental pollution resulting from heavy metal contamination and landfill CH_4 emissions, five MSW management scenarios were developed to minimize landfilling. The study considered the direct GHG emissions from waste transportation, open burning, composting, recycling, AD, incineration, and landfilling. Additionally, the avoided emissions from recycling and electricity generation from incineration and AD plants were also quantified. The results indicate that scenario 5 achieved the most significant net GHG emission savings. In this scenario, food waste and recyclables were separated at a rate of 75%, resulting in GHG emissions savings of approximately –1.59 M kg CO_2-eq/day from composting 472 t/day of food waste, recycling 867 t/day of mixed recyclables, AD of 943 t/day of digestible food, and incineration of 1,617 t/day of commingled waste. On the other hand, the worst-case scenario represents the current MSW management method, which generates the highest GHG emissions of 3.89 M kg CO_2-eq/day. This is primarily due to the open burning of uncontrolled waste (200 t/day) and landfilling (3,530 t/day). Based on the analysis, it is highly recommended to implement an integrated MSW management system that includes source separation for recycling and resource recovery purposes.

The economic feasibility of incineration, AD, and LFG recovery technologies was assessed for the period from 2023-2042, considering the levelized cost of electricity (LCOE), payback period (PBP), and net present value (NPV). The results indicate that incineration technology produced the highest energy output, ranging from 793 to 1,626 GWh/year. LFG recovery and AD technologies yielded 115-272 and 163-333 GWh/year, respectively. The economic analysis showed an average LCOE of 0.07 USD/kWh for LFG recovery, 0.053 USD/kWh for incineration, and 0.093 USD/kWh for AD. Incineration and LFG recovery were found to be economically feasible, with positive NPVs and the potential for profitability within 8.36 years for incineration and 7.13 years for LFG recovery. However, AD technology exhibited a negative NPV and required more than 20 years to generate a return on investment. Despite its economic drawbacks, AD technology demonstrated the most promising environmental performance, with potential savings of approximately –139,735 tCO_2-eq/year. Incineration, although profitable, concerns have been raised due to emissions and bottom ash management. To address these concerns, compliance with air emission standards and proper bottom ash management is essential to mitigate potential health risks. The government has recently made efforts to encourage investment in WTE technologies in Cambodia. However, regulations and incentive policies, such as investment subsidies, tax exemptions, carbon credits, etc., should be implemented to make WTE projects more attractive in commercial schemes.

In conclusion, the management of MSW is a pressing global issue. The detrimental effects of heavy metals contamination and the generation of CH_4 can result in local and global pollution, as well as adverse impacts on human health. To address the complexities of MSW management, a comprehensive strategy is needed combining multiple treatment technologies, focusing on enhancing recycling and resource recovery, particularly WTE solutions. Raising public awareness to participate in source separation and providing subsidies for installing the necessary infrastructure and facilities for waste collection and processing are crucial steps in promoting sustainable waste management practices. Government support and partnerships between the public and private sectors can play a vital role in implementing these initiatives and improving the overall waste management system.

備考　論文の要旨はＡ４判用紙を使用し，4,000字以内とする。ただし，英文の場合は1,500語以内とする。

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