論 文 の 内 容 の 要 旨

論文題目 Life Cycle Assessment of Integrated E-waste Management Systems for Developing Countries: Assessment in Jordan
（途上国における統合的電気電子機器廃棄物管理システムのライフサイクル評価：ヨルダンでの評価）

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E-waste (also known as Waste Electrical and Electronic Equipment; WEEE) is one of the fastest-growing waste streams worldwide. Given this rapid growth, major issues related to e-waste are a serious concern: (i) increasing amounts of e-waste pose detrimental effects to the environment and public health through improper recycling and final disposal, (ii) practices of informal recycling in developing countries are common, and the recycling methods are rudimentary, and (iii) a significant portion of e-waste components ends up in unsanitary (uncontrolled) landfill and open dump sites. To address these issues, this dissertation sets the following objective: to evaluate the environmental impacts of the current improper e-waste management practices in developing countries in comparison with state-of-the-art technologies that can replace the existing inappropriate practices. To achieve the objective, this dissertation introduced a systematic approach in the Jordanian context to propose an integrated approach to e-waste management, IEWM (Integrated E-waste Management).

This dissertation comprises six chapters. In Chapter 1, e-waste management issues and related studies in developing countries and Jordan were reviewed, the research problem and research gaps were explained. Based on the problem statement, a systematic approach was designed to address the e-waste management related issues. In Chapter 2, the concept of Integrated Waste Management (IWM) was reviewed as a starting point for discussing proper waste management because it can contribute to figure out solutions to complex e-waste management issues. Therefore, seven topics related to IWM were discussed: (1) the emergence of the concept, (2) the definition of the concept, (3) harmonization of the concept with the waste management hierarchy, (4) planning for an adequate IWM system, (5) implementation of the concept in both developed and developing countries, (6) a comparison between the conventional approach and the integrated one, and (7) the analytical methods employed for planning and assessing IWM systems. Based on the discussions in Chapter 2, a definition and aims of IEWM approach in this dissertation were proposed, and the IEWM approach was introduced. IEWM suggested, the integration between both Municipal Solid Waste (MSW) and e-waste management systems is theoretically possible. That is because both systems share common waste fractions and treatment and disposal technologies.

The proposed IEWM suggested utilization for a suitable e-waste estimation method that is appropriate for developing countries as a first step. Therefore, in Chapter 3, pros and cons of five methods of estimating e-waste used in developing countries were examined, and applicability of these methods was discussed. Then, total and individual amounts of six appliances generated in Jordan, including both firsthand and secondhand of Electrical and Electronic Equipment (EEE), were estimated. Due to limited data availability in developing countries, the

Consumption and Use (C&U) method has been widely employed for e-waste estimates. It was modified for its wider utilization for developing countries.

In Chapter 4, the concept of the IWM was applied to design nine Municipal Solid Waste Management (MSWM) alternatives for Jordan. Life Cycle Assessment (LCA) method was employed to evaluate the environmental impacts of the alternative systems, and they were discussed in comparison with the present system. The economic cost of the alternatives was also estimated. The goal was to identify the most environmentally-friendly and economically-viable alternative. The evaluations of MSWM was a necessity as a second step suggested by IEWM. That was because (i) e-waste stream in most of the developing countries is mixed with the MSW, and (ii) it is advantageous to utilize existing MSWM infrastructure. The results of Chapter 4 indicated that the scenario which utilizes the maximum theoretical recycling rate with waste separation at Material Recycling Facility (MFA), and sanitary landfilling of the remaining waste with energy recovery is the best in terms of the environmental impacts and the cost. These results were employed for developing and evaluating e-waste management scenarios in Chapter 5.

The last step of the suggested IEWM approach is to estimate and evaluate emissions of e-waste practiced in the present situation and in comparison with evaluating advanced management options. Thus, in Chapter 5, seven scenarios for six EEE of e-waste handling were evaluated. These scenarios comprise three advanced technologies: recycling of materials, metals, precious metals, and incineration of plastic and hazardous waste, and sanitary landfill of the remaining waste. The scenarios were assessed for their potential to supplant the existing improper practices. The results of Chapter 5 showed that the best IEWM scenario was the one that features recycling of materials, precious and non-precious metals with an MRF used for waste separation. Such a scenario also features incineration of plastic and Printed Circuit Boards (PCBs), and sanitary landfill of MSW and e-waste residues with the energy recovered from incineration and landfilling. This evaluation was based on a semi-arid to arid climate conditions as seen in Jordan.

Chapter 6 provides the conclusions of this dissertation, its limitations, and the future studies. Overall, the results showed that the environmental impacts of e-waste are significantly high. Among 70 examined cases for e-waste management, the study concluded that the integrated technologies that should be paid attention are: recycling with an appropriate proportion of materials, metals (precious and non-precious) with waste separation at MRF. Such technologies also include landfill or incineration of the hazardous portion of the waste and sanitary landfill of the MSW with energy recovered with a proper recovery efficiency from both landfilling and incineration. These technologies benefit for reduction of the environmental impacts as well as the cost. The results also indicated that incineration of a burnable waste of the MSW stream with a proper efficiency of energy recovery can notably minimize the environmental impacts for an IEWM system. However, implementing an incineration technology would lead to increased cost of the overall system.