学 位 論 文 内 容 の 要 旨

博士の専攻分野の名称　博士（工学）　氏名　Katitep Ngamket

学 位 論 文 題 名

Study of Heat Balance and Aeration Strategies in the Solar Greenhouse Biodrying System
(温室内バイオドライングシステムにおける熱収支とエアレーション方法に関する研究)

The high moisture content of municipal solid waste (MSW) significantly reduces the efficiency of mechanical separation and thermal conversion processes in waste management practices. Biodrying, as a pre-treatment method to reduce moisture content (MC) in MSW, offers a sustainable solution by utilizing metabolic heat to evaporate water together with the aid of the aeration system. After the biodrying process, refuse-derived fuel (RDF) can be produced. Biodrying under a greenhouse condition or a solar greenhouse biodrying system is a practical option for reducing moisture in MSW, especially in developing countries with high solar radiation intensity. Although this method has good potential, only a few studies have explored how it performs in various environmental conditions. A clear understanding of how different energy sources contribute to biodrying in a greenhouse system is still lacking. To fill this research gap, a detailed heat balance analysis is needed to quantify the role of each energy source in water removal and to clarify the thermodynamic behavior of the solar greenhouse biodrying process. This study investigated heat transfer behavior through a proposed heat balance model and conducted a comprehensive comparison of solar greenhouse biodrying performance under different aeration patterns and seasonal conditions. The background and objectives of this study were summarized in Chapter 1. In Chapter 2, the literature review was organized.

In Chapter 3, a new heat balance model was proposed to predict temperatures of waste and air (headspace) in greenhouse, offering higher accuracy than conventional heat balance models. The pilot-scale solar greenhouse biodrying system was used as a test case to evaluate the newly proposed heat balance model. Heat balance analysis indicated that metabolic heat (66 percent) was the primary energy input, followed by the enthalpy of inlet air (27 percent) and solar radiation (7 percent). Additionally, a primary proportion of the total heat use was associated with latent heat for water evaporation, which accounted for 59 percent. In the greenhouse headspace, most heat was transferred as sensible and latent heat to the air, representing 88 percent of the heat supplied to this zone. Heat losses occurred through the greenhouse structure (19 percent) and through the exhaust air (81 percent) in the headspace zone. Comparative simulations between greenhouse and non-greenhouse conditions were conducted, and the result found that the use of a greenhouse system provides several benefits for the biodrying process. First, it increased heat input by allowing solar radiation to pass through the cover, which enhances daytime water evaporation. Second, simulation results indicated that the greenhouse system can reach the target moisture content (less than 30 percent) for RDF production within 7 days. Third, the greenhouse roof minimized heat loss from wind-driven convection and thermal radiation from MSW surface to the surroundings, effectively serving as an insulating layer over the waste pile. Finally, the enclosed structure prevents rainwater intrusion, helping maintain the quality of the biodried waste material and reducing the risk of methane generation caused by reduced void space and the development of anaerobic conditions.

In Chapter 4, the effects of positive, negative, and passive aeration modes at varying airflow rates (4–15 L/min) on the laboratory-scale biodrying under the greenhouse system were evaluated to investigate aeration strategies. The results showed that the air direction controls how heat moves inside the biodrying pile. Positive aeration sent heat to the upper layers, negative aeration spread heat more evenly, and passive aeration trapped heat in the middle layer of the waste pile. For mass changes in each aeration mode, positive aeration mainly dried the waste with minimized organic loss, especially in the case of positive aeration at 8 L/min. Meanwhile, negative and passive aeration caused more organic solid decomposition and leachate generation. Leachate generation was ranging from 0 to 20 percent of total water removal, depending on the aeration pattern. Positive aeration, particularly airflow rate at 8L/min, had no leachate generation, suggesting that upward airflow promotes water removal primarily through evaporation. This finding highlighted a practical advantage of using positive aeration with a greenhouse system, offering effective moisture removal while preventing leachate production despite ambient temperature variation. In contrast, negative aeration and passive aeration led to higher leachate production. Negative aeration at 8 L/min and passive aeration generated 0.47 kg (13 percent) and 0.22 kg (20 percent) of total water removal, respectively. Furthermore, environmental conditions played a critical role on this system. Trials conducted during periods of higher solar radiation and ambient temperature exhibited evaporation rates 1.75 to 3.65 times higher than the trial conducted in cooler weather conditions.

A comprehensive assessment of biodrying performance was conducted to understand how operational conditions influence process efficiency in Chapter 5. At first, biodrying performance evaluation through key indicators, such as temperature integration (TI), biodrying index (BI), and air efficiency (AE), was used to provide valuable insights into the system's effectiveness. TI represents the cumulative difference between the waste temperature and the air temperature outside the reactor. BI refers to the ratio of water loss to organic solid loss during the biodrying process, and AE indicates how efficiently the air supply contributes to the amount of moisture removal. Consequently, positive aeration at 8 L/min consistently yielded the highest BI values (from 8 to 12), indicating effective water removal with high solid mass retention. In contrast, passive aeration resulted in the lowest BI (0.23), confirming limited drying capacity without forced convection. Considering TI values, passive, negative, and inverted aeration modes demonstrated higher TI values, suggesting superior heat retention. Positive aeration proved more efficient in utilizing air volume for moisture removal. Trials with airflow rate at 4 and 8 L/min achieved higher AE values compared to negative aeration. While the traditional biodrying index (the mass-based biodrying index) provides a simple ratio of mass reduction between water and organic solid, it fails to reflect the exact concept of biodrying performance. The proposed energy-based biodrying index (BIEB) offers suitable evaluation of biodrying process efficiency by quantifying the direct conversion of biologically generated heat into water evaporation (latent heat). From the results, the energy-based biodrying index showed significant variation across the experimental trials, ranging from a low of 0.03 to a high of 1.57 kJ of latent heat for evaporation per kJ of microbial oxidation. The highest efficiency was achieved in the positive aeration trials at 8 L/min, with indices ranging from 1.0 to 1.2 across winter and summer seasons. In contrast, the negative and passive aeration trials exhibited low BIEB of 0.05 and 0.03, respectively. Despite high microbial heat generation in the negative aeration at 8 L/min, this heat was not effectively used for evaporation. This was likely because the saturated air in the headspace together with the air direction, causing heat to build up (sensible heat) instead of being used to remove moisture (latent heat) within the waste.

In Chapter 6, conclusion was described. This study revealed that the solar greenhouse biodrying system, combined with optimized aeration pattern, effectively enhanced waste drying while minimizing organic loss and leachate generation. The proposed heat balance model quantified heat distribution within the system to understand heat transfer behavior. Positive aeration at 8 L/min consistently maximized moisture removal efficiency, as confirmed by both the traditional and the newly proposed energy-based biodrying index, effectively converting metabolic and solar energy into water evaporation. Lastly, this study provided scientific evidence for the application of the solar greenhouse biodrying system under different operational and environmental conditions, establishing a foundation for future research in this field.