Seasonal Shifts and Smart Stats: Improving Biodrying in Waste Management

Traven, Luka

Source / Izvornik: **Applied Sciences, 2025, 15**

Journal article, Published version
Rad u časopisu, Objavljena verzija rada (izdavačev PDF)

https://doi.org/10.3390/app15031432

applied sciences

MDPI

Article

Seasonal Shifts and Smart Stats: Improving Biodrying in Waste Management

Luka Traven [1,2]

[1] Department of Environmental Medicine, Medical Faculty, University of Rijeka, Braće Branchetta 20/I, 51000 Rijeka, Croatia; luka.traven@medri.uniri.hr; Tel.: +385-91-619-1109
[2] Department for Scientific and Educational Activities, Teaching Institute of Public Health of the Primorsko-goranska County, Krešimirova 52a, 51000 Rijeka, Croatia

Abstract: The biodrying process is a well-established method in solid waste management for reducing the moisture content of municipal solid waste (MSW), facilitating its mechanical treatment, enhancing energy recovery efficiency, and simplifying disposal. However, challenges such as variability in drying efficiency, seasonal fluctuations, and operational inconsistencies limit its optimization and broader applicability. This study undertakes a detailed evaluation of biodrying operations using Statistical Process Control (SPC) techniques to improve process stability and identify key factors influencing efficiency. Data collected over a one-year period from a waste management facility employing Herhoff Rotteboxes® reveal an average drying efficiency of 28%, with notable seasonal trends showing reduced efficiency during summer and fall. A regression model analyzing waste load, operational parameters, and seasonal effects accounted for 25% of the variability in drying efficiency, suggesting additional factors like waste composition and microbial activity significantly impact the process. This study highlights the value of SPC tools in monitoring process stability and demonstrates how targeted optimization strategies—such as seasonal adjustments and refined loading practices—can enhance biodrying outcomes. By addressing gaps in current practices, these findings contribute to the advancement of waste management technologies and support the development of more efficient and sustainable systems for handling municipal solid waste.

Keywords: biodrying performance; process stability analysis; municipal solid waste treatment; Herhoff Rotteboxes® technology; seasonal effects on biodrying; waste moisture reduction

check for updates

Academic Editors: Francisco Jesús Fernández Morales, Jose Luis García-Morales and Miguel Suffo

Received: 26 December 2024
Revised: 23 January 2025
Accepted: 27 January 2025
Published: 30 January 2025

Citation: Traven, L. Seasonal Shifts and Smart Stats: Improving Biodrying in Waste Management. *Appl. Sci.* **2025**, *15*, 1432. https://doi.org/10.3390/app15031432

1. Introduction

The biodrying process is a well-established method for reducing the moisture content of municipal solid waste (MSW). It is considered a relatively new method compared to traditional drying or stabilization techniques used in solid waste management, such as composting or direct thermal drying. While the concept of using biological activity to generate heat for moisture reduction has been explored, its application as a standalone technique for large-scale municipal solid waste (MSW) management has only gained traction over the past two decades. This is largely due to advancements in process control technologies and the increasing demand for efficient pre-treatment methods that align with resource recovery goals and energy efficiency. In particular, biodrying integration with refuse-derived fuel (RDF) production systems has been a recent focus of research and development [1,2]. For more details, readers can refer to related studies, including those that explore its engineering and environmental applications [2–6].

The drying methods for municipal solid waste (MSW) have evolved significantly over the years, with various techniques employed to reduce moisture content and improve waste management efficiency. Traditional methods like solar drying and hot air drying have been widely used due to their simplicity and low operational costs. However, these methods often suffer from long drying times, poor quality control, and inefficient energy use [7]. More advanced techniques have emerged to address these limitations.

Thermal drying, including convective and conductive methods, has been extensively studied for its ability to rapidly reduce moisture content in MSW. While effective, this approach can lead to high energy consumption and a potential loss of volatile organic compounds [8]. Biodrying has gained attention as a more sustainable alternative, leveraging microbial activity to generate heat and facilitate moisture removal. This method has shown promise in reducing waste volume and increasing calorific value, making it suitable for producing refuse-derived fuel [9]. The process is primarily employed in solid waste management to reduce the moisture content of waste, transforming it into a more manageable material [3]. The process leverages heat produced during the aerobic decomposition of organic matter to drive convective evaporation and facilitate drying. The primary objective of biodrying is to lower the moisture content of waste, reducing its mass and volume, thereby improving its suitability for mechanical processing, energy recovery, or disposal [10]. Biodrying provides several advantages, including substantial volume reduction, with studies indicating decreases in waste volume of up to 56.5% [11,12]. Additionally, the process can increase the substrate's bulk density by up to 52%, resulting in a more compact material that is easier to handle [13]. The moisture content of the waste is significantly reduced, with average reductions of approximately 20% being commonly reported [14]. Although biodrying is being increasingly adopted, maintaining the stability and consistency of the process is essential to maximize its efficiency. Variability in process outcomes, such as inconsistent weight reductions, can result in inefficiencies, increased operational costs, and fluctuations in the quality of the final product. Biodrying efficiency can be affected by factors such as aeration rate, waste composition, and environmental conditions [4]. Variations in these parameters can directly affect the rate of moisture removal, the consistency of the process, and the overall quality of the final output [15]. Consequently, continuously monitoring and precisely controlling parameters such as initial moisture content, airflow rate, and temperature are essential to maintaining optimal performance in the biodrying process. This ensures that the system operates within specified limits, minimizes variability, and achieves consistent efficiency, ultimately leading to improved waste management outcomes.

An effective approach to maintaining process stability and efficiency is the use of Statistical Process Control (SPC) tools. SPC employs statistical methods to monitor and control processes, minimizing variation and ensuring consistent performance. Techniques such as control charts are particularly useful for detecting shifts or trends in the process before they lead to significant deviations. In the context of biodrying, SPC provides a framework for tracking critical parameters, such as moisture reduction, to evaluate the process's stability over time. Understanding and controlling process variability allows waste management facilities to optimize biodrying operations, resulting in more efficient resource utilization and a reduced environmental footprint. This is especially critical given biodrying's potential to address the challenges posed by the high moisture content in municipal solid waste, which can impede both waste-to-energy conversion and mechanical treatment processes [16,17].

It has to be stated that emerging technologies like electrohydrodynamic (EHD) drying offer potential advantages in terms of energy efficiency and product quality preservation, though they remain largely in the research phase [18]. Each drying method presents a unique set of advantages and challenges, highlighting the need for continued innovation in waste drying technologies to meet the growing demands of sustainable waste management.

2. Study Design and Objectives

The primary objective of this study is to assess the stability of the biodrying process using Herhoff Rotteboxes®, a specialized system designed for moisture reduction in municipal solid waste (MSW). This is achieved through the application of Statistical Process Control (SPC) techniques to monitor and analyze process performance. This study aims to determine the long-term stability of the biodrying process by monitoring key performance indicators, such as weight reduction, throughout the biodrying cycle. Conducted at the municipal waste management facility "Marišćina" in Croatia, this research focuses on the biodrying of MSW using a series of Herhoff Rotteboxes® prior to mechanical treatment of waste. The Herhoff Rottebox® system is specifically designed to facilitate the aerobic degradation of the organic fraction of MSW, reducing both moisture content in the waste and its overall mass. The process actively circulates air through the waste to accelerate microbial activity, generating heat that drives moisture removal by convective evaporation. Each batch of organic waste undergoes a seven-day biodrying cycle before proceeding to mechanical treatment. The system's performance is evaluated primarily by measuring the reduction in total waste mass before and after the biodrying cycle, providing critical insights into its efficiency and operational consistency. The results of this study provide valuable insights into the performance of the biodrying process using Herhoff Rotteboxes®. They are practical tools for waste management operators that enhance process stability and control. These findings contribute to the broader objectives of sustainable waste management and resource recovery by improving the efficiency of waste treatment facilities and minimizing the environmental footprint associated with waste management operations.

3. Materials and Methods

Data were collected from 12 individual Herhoff Rotteboxes® over a one-year period to evaluate the stability of the biodrying process. For each biodrying cycle, key parameters were systematically recorded, including the initial mass (tonnage) of waste loaded into the Rottebox® prior to drying and the final mass (tonnage) of waste after the drying period. From these measurements, the weight reduction was calculated as the difference between the initial and final mass for each cycle, along with the percentage reduction in weight as a key performance indicator.

The weight reduction (W_r) is calculated as follows:

$$Wr = M_{initial} - M_{final} \quad (1)$$

where:

- W_r = weight reduction (tons)
- $M_{initial}$ = initial mass of waste loaded into the Rottebox® (tons)
- M_{final} = final mass of waste after drying (tons)

The percentage weight reduction (%Wr) is calculated as follows:

$$\%W_r = (W_r/M_{initial}) \times 100 \quad (2)$$

Measurements were taken across multiple biodrying cycles for each Rottebox®, resulting in a comprehensive dataset to assess the stability and efficiency of the process. This dataset serves as the basis for statistical analysis and process control evaluation, providing valuable insights into the consistency of biodrying performance under real-world operational conditions.

The composition of MSW in Croatia is primarily characterized by high quantities of mixed food waste (30.9%), mixed paper waste (23.2%), and plastics (22.9%), based on national averages derived from sampling campaigns conducted during 2014–2015. Other waste fractions include mixed green waste (5.7%), textiles (3.7%), metals (2.1%), glass (3.7%), and miscellaneous categories (6.3%). These values reflect country-wide averages, as no site-specific data are available. While no published data are available for the moisture content of Croatian MSW, it is estimated to be approximately 50% based on expert judgment and data from comparable regions [19]. This estimate is consistent with the high fraction of mixed food and green waste, which are typically associated with elevated moisture levels. In addition to moisture content, the estimated higher heating value (HHV) of Croatia's MSW is around 14 MJ/kg, with the lower heating value (LHV) estimated to be approximately 12 MJ/kg when accounting for the high moisture content [20].

The municipal solid waste (MSW) used in this study was pre-shredded prior to the biodrying process to enhance the efficiency and uniformity of drying. Pre-shredding reduces the size of the waste particles, increasing the surface area available for heat and air exchange during the biodrying process. This step is critical for facilitating the removal of moisture through convective and evaporative mechanisms. Additionally, shredding ensures a more homogenous distribution of the waste material, which minimizes the formation of air pockets and improves the consistency of airflow throughout the biodrying chambers. These improvements contribute to a more stable and efficient biodrying process, ensuring better control over key parameters such as temperature and moisture reduction rates. Pre-shredding is an established best practice in waste management facilities to optimize downstream processes, including mechanical treatment.

Herhoff Rotteboxes® are designed to handle 155–161 tons of waste per cycle as part of the biodrying process, and there are 12 such boxes in the facility. The dimensions of the boxes are as follows: 17.5 m in length, 5 m in width, and 5.5 m in height.

A flow diagram of this study is shown in Figure 1.

The biodrying process parameters were systematically monitored throughout this study to ensure consistent operational performance. The key parameters included the temperature within the Rotteboxes, airflow rates, and weight reduction over the drying period. The air velocity was controlled to optimize the convective removal of moisture, while temperature was monitored as a critical indicator of microbial activity and the heat generated during aerobic decomposition. The pH of the waste was not directly measured but is known to remain relatively stable during biodrying due to the buffering effect of organic matter degradation. These parameters were recorded consistently across all biodrying cycles to ensure uniformity and reliability in the process outcomes. Although this study did not explicitly investigate the influence of external factors, such as seasonal variations or fluctuations in waste composition, the results provide valuable insights into the stability and efficiency of the biodrying process under typical operational conditions.

3.1. Control Chart Development

A 3-sigma control chart was developed to monitor weight reduction values across multiple biodrying cycles for each Rottebox®. The 3-sigma control limits are statistical thresholds used to identify whether a process is operating within normal parameters. These limits are based on the average weight reduction values and the variability of the data, as measured by standard deviation. The upper control limit (UCL) represents the highest value that would be expected under normal operating conditions, while the lower control limit (LCL) represents the lowest expected value. These limits are set far enough from the average to account for natural variations in the process. In this case, the 3-sigma limits encompass approximately 99.73% of the data points, assuming a stable and consistent process. Data points that fall outside of these limits are considered outliers and may indicate unusual circumstances, such as changes in waste composition or operational inconsistencies, that require further investigation. The use of 3-sigma control limits allows for a reliable assessment of process stability by distinguishing between normal variations and potential problems, thereby ensuring a robust monitoring system.

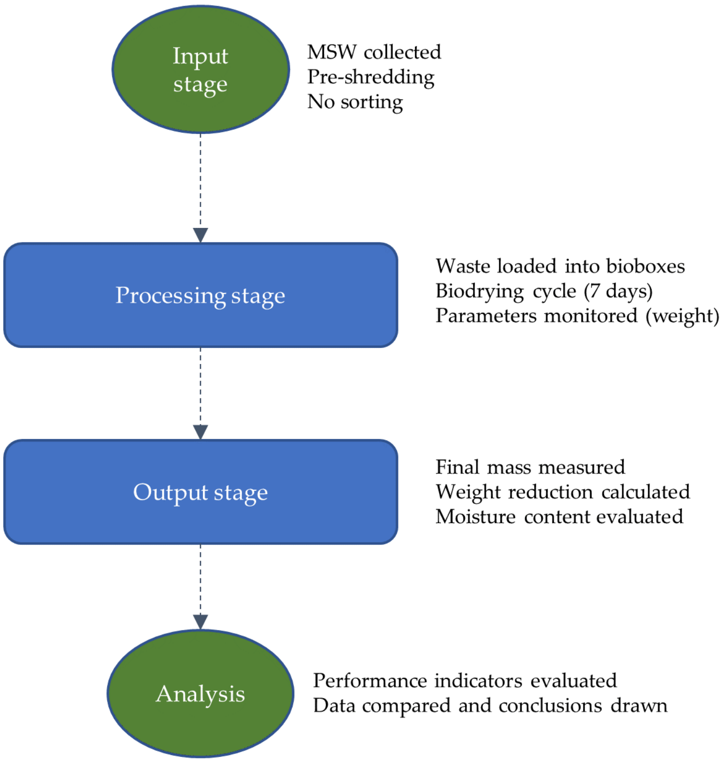

Figure 1. Overview of the study investigation, illustrating the key stages of the biodrying process. The figure includes (**1**) the input stage where municipal solid waste (MSW) is collected, pre-shredded, and loaded without sorting; (**2**) the processing stage where the waste is subjected to biodrying in Rotteboxes for a 7-day cycle, with parameters such as weight and temperature being monitored; (**3**) the output stage where the final mass, weight reduction, and moisture content are evaluated; and (**4**) the analysis stage, where performance indicators are calculated and conclusions are drawn.

Key metrics, including the mean and standard deviation (σ) of the weight reduction values, were calculated. Control limits were then established at three standard deviations above the upper control limit (UCL) and below the lower control limit (LCL) of the mean, defining the acceptable range for process variability. Data points falling outside of these control limits were flagged as potential indications of special cause variations, requiring further investigation to identify and address underlying factors. Given that the process aims to achieve a minimum moisture reduction of 30%, an additional SPC analysis was conducted with a lower control limit (LCL) explicitly set at 30%. This secondary analysis ensured that the process met its operational requirements and provided a complementary perspective on performance consistency.

3.2. Data Visualization

The weight reduction values were visualized on the control chart, with each point representing the weight reduction achieved in an individual Rottebox® during a single biodrying cycle. The chart prominently displays the mean, UCL, and LCL, enabling a clear assessment of the process's stability over time. Outliers—data points exceeding the 3-sigma limits—were easily identifiable, facilitating a rapid assessment of process deviations. Additionally, the control chart was examined for any emerging trends or cyclical patterns that might indicate underlying shifts in the process.

3.3. Process Stability Assessment

The stability of the biodrying process was determined by evaluating whether the weight reduction values remained consistently within the 3-sigma control limits. A stable process was defined by the absence of patterns, trends, or cycles that could suggest systemic or external influences. Any deviations, such as data points outside of the control limits or runs of values consistently above or below the mean, were flagged for further investigation. These deviations were analyzed as potential indicators of process instability or special cause variations, which could arise from factors such as inconsistent waste composition, operational changes, or environmental conditions.

This approach allowed for a robust assessment of the biodrying process, ensuring that variability was effectively monitored and controlled. The use of SPC tools not only provided insights into process performance, but also helped to identify opportunities for optimization, contributing to improved efficiency and operational reliability.

3.3.1. Statistical Software

All data analyses, including the generation of control charts, were performed using Python, leveraging the capabilities of the Matplotlib library (version 3.7.1) for data visualization. Descriptive and inferential statistics were calculated using the Pandas library (version 1.5.3), which provides efficient tools for data manipulation and statistical computations.

3.3.2. Study Assumptions

Several key assumptions underpinned the analysis to ensure the validity and consistency of the findings. First, it was assumed that the biodrying process operated under steady-state conditions, free from significant external influences that could impact the performance of the Herhoff Rotteboxes®. This included the presumption that factors such as ambient temperature, humidity, and operational parameters remained stable and did not introduce variability beyond normal process fluctuations. Furthermore, it was assumed that the initial composition and moisture content of the waste batches remained relatively uniform throughout the study period. Consistency in these characteristics was critical for enabling the direct comparison of weight reduction values across multiple cycles and Rotteboxes®. Variations in waste composition or moisture levels could otherwise confound the results, making it difficult to isolate the effects of the biodrying process itself. These assumptions provided a foundation for the statistical analyses conducted, ensuring that any observed variability in the process outcomes could be attributed primarily to the biodrying system rather than external or uncontrolled factors. However, it is acknowledged that deviations from these assumptions, such as unforeseen changes in waste composition or environmental conditions, could introduce variability and should be addressed in future studies for a more comprehensive understanding of process performance.

3.3.3. Limitations of This Study

This study does not incorporate the potential influence of external factors, such as seasonal variations in waste composition, fluctuations in ambient temperature and humidity, or changes in microbial activity, all of which can significantly impact the biodrying process. These factors are known to contribute to variability in drying efficiency and process stability, yet their effects were not directly measured or controlled in this analysis.

4. Results

4.1. Descriptive and Inferential Statistics and Data Distribution

To assess the normality of the data, the Kolmogorov–Smirnov (K-S) test was employed. The K-S test evaluates the maximum distance between the cumulative distribution function (CDF) of the sample data and the CDF of a specified theoretical distribution—in this case, the normal distribution. The parameters of the normal distribution (mean and standard deviation) were estimated directly from the dataset. The K-S test statistic was calculated as 0.0245, with an associated p-value of 0.9282. Since the p-value is significantly greater than the conventional threshold of 0.05, we rejected the null hypothesis, suggesting no statistically significant evidence of deviation from normality.

Analysis of Variance (ANOVA) and post hoc tests were deployed to examine the differences in drying efficiency across months and seasons, providing insights into the influence of seasonal variation on the biodrying process. ANOVA is a statistical technique used to compare means across multiple groups by analyzing the variability within groups relative to the variability between groups.

A multiple linear regression model (Equation (3)) was employed to explore the relationships between drying efficiency (the dependent variable) and three key predictor variables, as follows: the amount of waste loaded into the bioboxes, the operational month (representing seasonal variations), and the biobox number. This statistical technique is used to quantify how each predictor influences the outcome variable, drying efficiency, while controlling for the effects of the other predictors in the model. By isolating the contribution of each variable, regression analysis allows for a deeper understanding of the factors driving variability in the biodrying process.

The descriptive statistics on biodryig parsed per bioboxes are shown in Table 1.

Table 1. Summary of descriptive statistics for the percentage of moisture removed during the biodrying process across individual Herhof Rotteboxes®. The term "counts" refers to the number of biodrying cycles recorded for each Rottebox over the study period, with each cycle lasting approximately 7 days. The 25%, 50%, and 75% values correspond to the first quartile, median, and third quartile, respectively, representing the spread of the data.

Herhof Rottebox®	Count	Mean	Std	Min	25%	50%	75%	Max
1	38	0.25	0.05	0.14	0.22	0.25	0.3	0.37
2	43	0.24	0.07	0.08	0.19	0.24	0.28	0.4
3	41	0.24	0.05	0.15	0.21	0.24	0.27	0.35
4	41	0.23	0.05	0.12	0.2	0.23	0.26	0.39
5	39	0.27	0.07	0.12	0.23	0.26	0.31	0.5
6	40	0.25	0.05	0.12	0.22	0.25	0.28	0.36
7	40	0.25	0.05	0.14	0.2	0.25	0.29	0.33
8	40	0.25	0.05	0.16	0.21	0.25	0.29	0.34
9	40	0.25	0.05	0.14	0.21	0.24	0.29	0.38
10	39	0.25	0.07	0.1	0.21	0.25	0.28	0.46
11	40	0.25	0.06	0.14	0.2	0.25	0.28	0.42
12	38	0.23	0.07	0.05	0.19	0.25	0.27	0.34

4.2. Process Stability and Control

The X-bar control chart illustrated in Figure 2 shows the drying efficiency across the bioboxes over time, with the mean drying efficiency represented with a green dashed line and the control limits ($\pm 3\sigma$) marked with red dashed lines. The outliers, identified as points exceeding the control limits, are highlighted with red "X" markers.

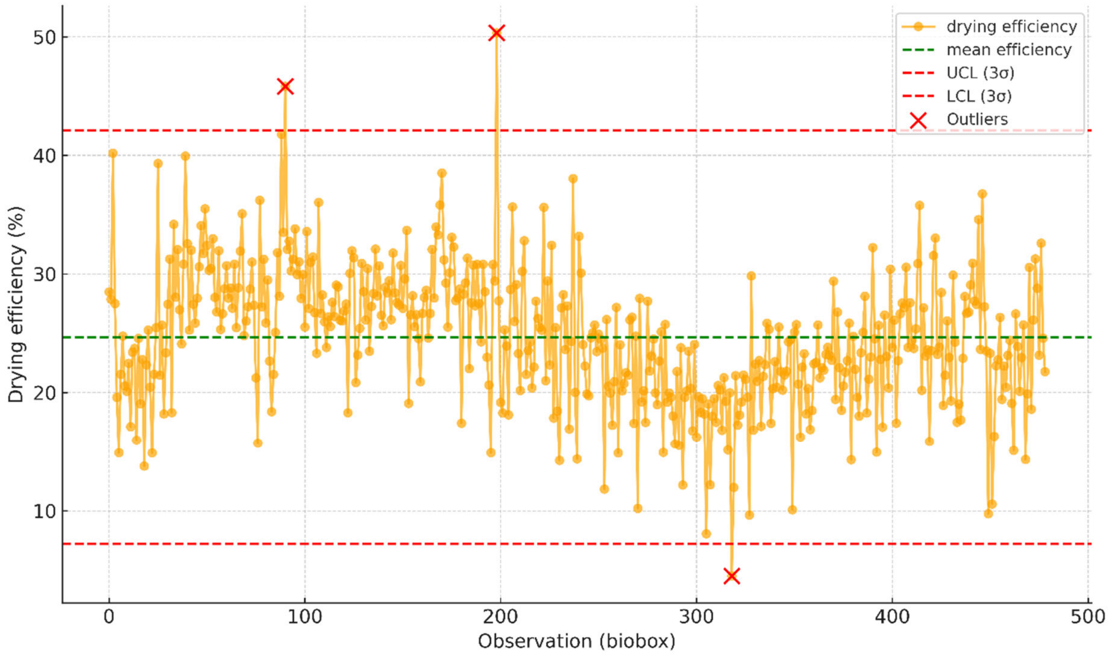

Figure 2. Control chart showing drying efficiency across observations for individual bioboxes. The range of 0–500 on the x-axis represents the sequential numbering of recorded observations, where each observation corresponds to a biodrying cycle for a specific biobox. The green dashed line indicates the mean drying efficiency (~28%), while the red dashed lines mark the upper and lower control limits ($\pm3\sigma$). Outliers exceeding the control limits are highlighted with red "X" markers.

The analysis reveals a mean drying efficiency of approximately 28%, with the upper and lower control limits set at ±3 standard deviations (σ) from the mean. These control limits define the boundaries within which the process is expected to operate under normal conditions, providing a clear framework for assessing process stability. The biodrying process demonstrates statistical control, as the majority of data points fall within the established control limits. However, several outliers—extreme drying efficiency values—are apparent on the chart, indicating occasional occurrences of special cause variation. These deviations suggest that certain cycles may have been influenced by irregular factors, such as variations in waste composition, operational inconsistencies, or environmental conditions. Although the process is generally stable, it consistently underperforms relative to the desired lower specification limit of 30% drying efficiency. This indicates a need for further optimization of the biodrying process to achieve higher and more consistent efficiencies. Addressing the factors contributing to outliers and overall underperformance could enhance both the stability and effectiveness of the system, ensuring it meets operational and environmental goals.

4.3. Biobox Performance Variability

Figure 3 presents a boxplot illustrating the distribution of drying efficiency across the 12 bioboxes, offering a detailed visualization of their individual performance.

While the range of drying efficiencies shows slight variations between bioboxes, statistical analysis using an Analysis of Variance (ANOVA) test confirms that these differences are not statistically significant (p value = 0.188). Thus, the observed variability in drying efficiency across the bioboxes can be attributed to random fluctuations rather than any systemic differences in performance. This finding suggests that all 12 bioboxes operate with comparable efficiency under similar conditions, emphasizing the consistency of the biodrying process across the system. Such consistency is critical for ensuring reliable performance in waste management operations and underscores the effectiveness of the system design in maintaining uniformity across the bioboxes.

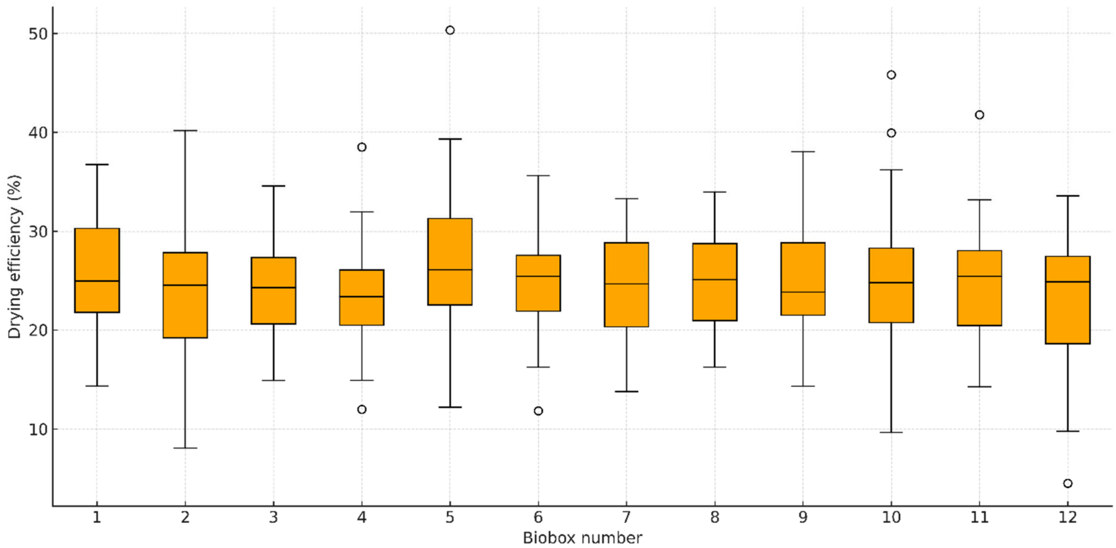

Figure 3. Boxplot showing the distribution of drying efficiency across 12 bioboxes. The boxes represent the interquartile range (IQR), the horizontal line within each box represents the median (50th percentile), and the whiskers indicate the range of values within 1.5 times the IQR. Small circles represent outliers, which are values that fall outside this range, observed for certain bioboxes due to variability in the drying efficiency data. While slight variations in efficiency are observed, an ANOVA test confirms no statistically significant differences in performance among the bioboxes, indicating consistent operation.

4.4. Influence of Amount of Waste Loaded into the Bioboxes on Drying Efficiency

Figure 4 illustrates the relationship between the amount of waste filled into the bioboxes and the resulting drying efficiency.

Figure 4. Scatter plots illustrating the relationship between the amount of waste filled into bioboxes and drying efficiency. The left panel shows the distribution of data points, while the right panel includes a fitted linear regression line (slope = 0.59), indicating that for every additional ton of waste filled, drying efficiency increases by approximately 0.59%. A moderate positive correlation (r = 0.41) is observed, suggesting that larger waste loads are associated with slightly higher drying efficiencies.

In the left panel, the scatter plot illustrates the relationship between the amount of waste filled into the bioboxes and drying efficiency (%). Each data point represents an observation, revealing the distribution and variability of drying efficiency across different input volumes. The plot highlights a general trend where higher tonnage corresponds to slightly improved drying efficiency, though the variation in data points suggests other factors may also contribute to this relationship. In the right panel, the scatter plot includes a linear regression line that quantifies the relationship between tonnage filled and drying efficiency (%). The regression line, derived from a statistical model, demonstrates a positive trend, indicating that drying efficiency increases slightly as the amount of waste filled into the bioboxes rises.

The regression analysis reveals a moderate positive correlation (r = 0.41) with a statistically significant relationship ($p < 0.00001$), suggesting that higher input tonnage contributes to slightly improved drying efficiency. This improvement is likely due to enhanced heat retention and thermal dynamics during the biodrying process, which are more effective in larger waste loads. Together, these visualizations offer a clear depiction of the interaction between waste tonnage and process efficiency, providing critical insights for optimizing biobox loading strategies in biodrying operations.

A multiple linear regression model was constructed to predict drying efficiency based on the following three key predictors: the amount of waste loaded into the bioboxes ("Loaded (t)"), the biobox number, and the month of operation. The target variable was the percentage of water removed during the biodrying process. To ensure a robust evaluation of the model, the dataset was divided into training (80%) and testing (20%) subsets. The regression equation derived from the analysis is as follows:

$$Dry.effic.(\%) = 0.46 * (Loaded\ (t)) - 0.034 * (Biobox\ no.) - 0.36 * (Month) + 49.96 \quad (3)$$

The analysis produced an R-squared value (R^2) of 0.25, indicating that the model explains 25% of the variability in drying efficiency ("*Dry. Effic.*"). While this suggests some predictive power, a significant portion of the variability remains unexplained, pointing to the influence of additional factors not included in the model. The Mean Squared Error (MSE) of 34.90 reflects the average squared difference between the predicted and actual drying efficiencies. Among the predictors, "*Loaded* (*t*)" had the strongest positive influence, with a coefficient of 0.46. This indicates that for every additional ton of waste filled, drying efficiency increased by approximately 0.46%. The "*Month*" variable showed a small negative impact (−0.36), suggesting that drying efficiency slightly decreases in later months, potentially due to seasonal variations. The biobox number ("*Biobox no*.) had a negligible negative influence (−0.034), demonstrating minimal variation in performance across different bioboxes. This model highlights the importance of operational factors such as input tonnage and seasonality in influencing biodrying efficiency. However, the relatively low R^2 value underscores the need to incorporate additional predictors, such as ambient temperature, humidity, and waste composition, to improve the model's accuracy and provide a more comprehensive understanding of the biodrying process.

4.5. Seasonal Variations in Drying Efficiency

The analysis of seasonal trends shown in Figure 5 revealed significant variations in drying efficiency across the months.

The ANOVA test showed a highly significant difference in efficiency between months ($p < 0.00001$). The line plot indicated that the lowest efficiencies were observed in the summer and fall months, particularly in July, August, September, and October. This suggests that environmental factors, such as temperature and humidity, may play a role in drying efficiency.

The drying efficiency by season is shown in the bar plot in Figure 6.

According to the analysis, spring had the highest average drying efficiency (28.4%), followed by winter (25.5%). Summer and fall had the lowest efficiencies, both averaging around 22.6%. It can be concluded that drying efficiency is generally lower during the warmer months, which aligns well with the findings of the seasonal trends analysis.

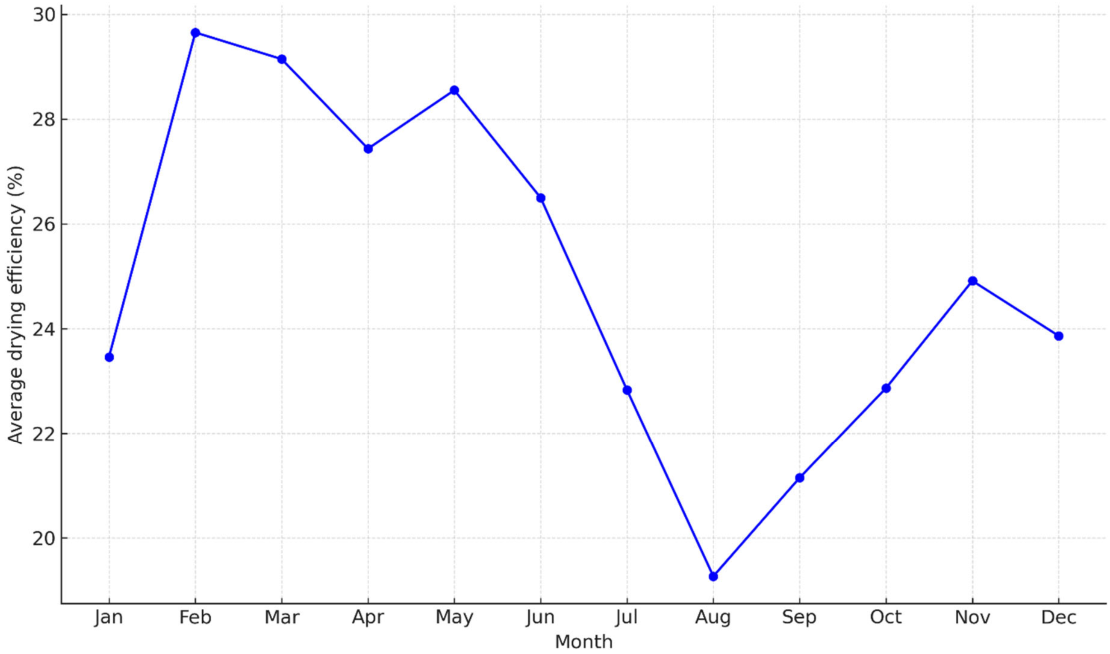

Figure 5. Monthly variation in average drying efficiency (%). The plot illustrates the average drying efficiency for each month, highlighting seasonal trends in the biodrying process. Data points represent the mean drying efficiency calculated across all observations within each month.

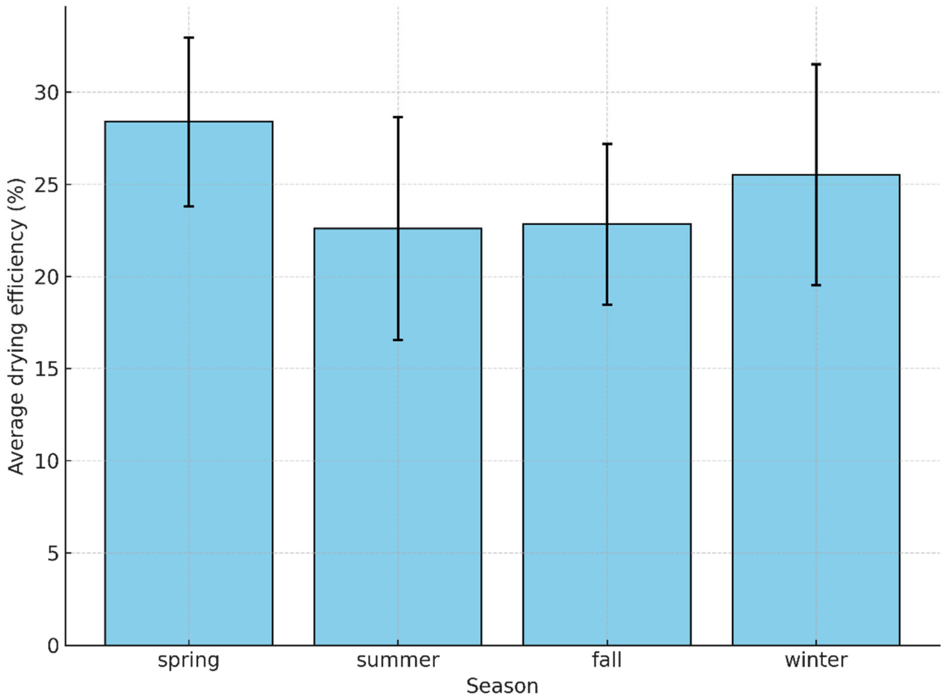

Figure 6. A bar plot comparing the average drying efficiency across the four seasons. Spring exhibits the highest average efficiency (28.4%), while summer and fall have the lowest, both around 22.6%. This indicates lower efficiency during the warmer months, likely due to environmental factors.

5. Discussion

The results of this study demonstrate the effectiveness and stability of the biodrying process using Herhoff Rotteboxes®. By applying Statistical Process Control (SPC) techniques, particularly control charts, we were able to monitor the key performance indicator—weight reduction—and assess the consistency of the process over multiple biodrying cycles. The analysis provides valuable insights into both the stability and the efficiency of the process, with implications for optimizing waste management operations.

5.1. Process Stability and Control

The X-bar control chart (Figure 1) demonstrates that the biodrying process using Herhoff Rotteboxes® exhibits overall stability, with most data points falling within the upper and lower control limits. This stability is crucial for maintaining consistent performance in waste management operations. However, the presence of occasional outliers exceeding the control limits suggests instances of special cause variation that warrant further investigation. These outliers could be attributed to factors such as variations in waste composition, environmental conditions, or operational parameters, which have been shown to influence biodrying performance [4,21–24]. The mean drying efficiency of approximately 28%, although promising, falls below the desired lower specification limit of 30%. Other studies have achieved drying efficiencies higher than 30%, but with longer drying times [25–27]. This underperformance indicates the need for process optimization. Similar challenges in achieving target drying efficiencies have been reported in other biodrying studies and were related to aeration rates, waste characteristics, and other factors [28,29].

5.2. Biobox Performance Variability

The boxplot analysis (Figure 3) reveals slight variations in drying efficiency across the 12 bioboxes, although the differences are not statistically significant. This relative consistency in performance across the bioboxes is advantageous for overall process management. However, the lack of significant differences also suggests that there might be systemic factors affecting all bioboxes similarly, which could be targeted for overall process improvement.

5.3. Influence of Amount of Waste Loaded into the Bioboxes on Drying Efficiency

The moderate positive correlation (r = 0.41) between the amount of waste filled into the bioboxes and drying efficiency (Figure 4) is a noteworthy finding. This relationship suggests that larger tonnages of waste loaded into the bioboxes tend to achieve slightly higher drying efficiencies. These findings are in agreement with the study by Bosily et al., which also found that the efficiency of the biodrying process is influenced by various geotechnical factors, such as the initial moisture content, organic content, bulk density, dry density, particle density, and porosity [30]. One possible explanation for the observed finding is that the biological component of municipal solid waste (MSW) has a relatively high density [31]. Consequently, bioboxes loaded with higher-density material may contain a greater proportion of biological material. This results in higher temperatures during aerobic degradation, which in turn enhances convective drying of the material [32–34]. This observation aligns with the findings of Velis et. al [3], who noted that the scale of operation could influence biodrying performance. The statistical significance of this correlation ($p < 0.00001$) underscores its importance in process optimization. Waste management facilities might consider optimizing the loading of bioboxes to maximize efficiency, balancing this against other operational constraints and safety considerations.

The multiple linear regression model developed to predict drying efficiency revealed several important insights into the biodrying process. With an R-squared value of 0.25, the model explains 25% of the variability in drying efficiency, indicating that, while it captures some key factors, there are likely additional variables influencing the process that were not included in this analysis. Among the predictors, the amount of waste loaded into the bioboxes had the strongest positive influence, with a coefficient of 0.46. This suggests that, for every additional ton of waste filled, drying efficiency increased by approximately 0.46%, aligning with the earlier observed moderate positive correlation (r = 0.41) between waste load and efficiency. There are several other studies that have also analyzed the influence of different parameters on the biological treatment of waste (anaerobic digestion and biodrying), but they did not specifically address the effect of bulk densities of waste on biodrying efficiencies [35,36]. The model also captured a slight negative impact of the "Month" variable (−0.36), supporting the observed seasonal variations in efficiency. Interestingly, the biobox number had a negligible negative influence (−0.034), confirming the earlier finding of consistent performance across the different bioboxes. While the model provides valuable insights, its relatively low explanatory power suggests that other factors, such as waste composition, ambient temperature, humidity, and microbial activity, may have a more significant impact on the biodrying process [21,23,26,37]. Future research should aim to incorporate these additional variables in order to develop a more comprehensive predictive model for optimizing biodrying operations.

5.4. Seasonal Variations in Drying Efficiency

The significant variations in drying efficiency across the months (Figure 5) and seasons (Figure 6) provide valuable insights into the environmental factors affecting the biodrying process. The lower efficiencies observed during summer and fall months (July to October) suggest that ambient temperature and humidity play crucial roles in the biodrying process. This seasonal effect aligns with observations by Zhang et al. [12], who reported that environmental conditions significantly impact biodrying performance. Other authors observed similar findings during the biological treatment of waste [38,39]. The highest average drying efficiency in spring (approximately 28%) compared to the lowest in the summer and fall (around 22%) indicates a need for seasonal adjustments in process parameters. This finding is particularly important for waste management facilities operating in regions with distinct seasonal variations. Operators might consider modifying aeration rates, retention times, or other operational parameters during warmer months to compensate for reduced efficiency.

5.5. Process Optimization Opportunities

The consistent underperformance relative to the 30% target efficiency, coupled with the observed seasonal variations, highlights several opportunities for process optimization, as follows:

Seasonal adjustments: Implementing adaptive control strategies that account for seasonal variations in temperature and humidity could help to maintain a more consistent performance year-round. This can include adjustments to the biodrying times, as suggested by some studies [4,40], or mixing fresh waste with landfilled waste, as suggested by the study of Widyarsana et al. [41]. The study tested different ratios, identifying a 1:1 mixture as the most effective, achieving a moisture reduction of 9–29.1%.

Waste characterization: Given the potential influence of waste characteristics on drying efficiency, more detailed characterization of incoming waste streams could provide valuable insights for process optimization. This approach is supported by Sugni et al. [14], who emphasized the importance of waste properties in biodrying outcomes.

Advanced process control: The implementation of more sophisticated control strategies, such as those suggested by Tom et al. [16], could help to reduce variability and improve overall efficiency. This might include real-time monitoring and adjustment of aeration rates based on temperature and moisture content data.

Optimized loading: The positive correlation between waste volume and drying efficiency suggests that optimizing the loading of bioboxes could improve overall performance. However, this must be balanced against practical constraints and safety considerations.

5.6. Limitations and Future Research Directions

While this study provides valuable insights into the biodrying process using Herhoff Rotteboxes®, several limitations should be acknowledged, as follows:

This study does not account for detailed waste composition or initial moisture content, which could provide a more nuanced understanding of process performance. Environmental parameters, such as ambient temperature and humidity, were not directly measured, limiting our ability to quantify their impact on the process. The analysis focuses on weight reduction as the primary performance indicator, while other factors, such as calorific value improvement or biological stability, were not assessed.

Future research could address these limitations by incorporating detailed waste characterization and tracking of initial moisture content to better understand their influence on drying efficiency. Additionally, monitoring and analyzing environmental parameters alongside process data could help to quantify their impact and develop predictive models for process performance. Expanding the range of performance indicators to include factors such as calorific value improvement, which is crucial for waste-to-energy applications, would also be beneficial. Furthermore, investigating the microbial dynamics during the biodrying process could optimize biological activity and potentially enhance drying efficiency.

In conclusion, this study demonstrates the effective application of SPC techniques to monitor and analyze the biodrying process in Herhoff Rotteboxes®. The findings highlight the overall stability of the process while identifying the key factors influencing drying efficiency. By addressing the identified areas for optimization and conducting further research, waste management facilities can enhance the efficiency of biodrying operations, contributing to improved resource recovery and reduced environmental impact in municipal solid waste management.

6. Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the author used ChatGPT/data Analyst module in order to analyze the data and create the visualization presented in this paper. After using this tool/service, the author has thoroughly reviewed and revised the material and assumes full responsibility for the content of this publication.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are available upon request and approval by the author.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. Bhatsada, A.; Patumsawad, S.; Towprayoon, S.; Chiemchaisri, C.; Phongphiphat, A.; Wangyao, K. Modification of the Aeration-Supplied Configuration in the Biodrying Process for Refuse-Derived Fuel (RDF) Production. *Energies* **2023**, *16*, 19. [CrossRef]
2. Latosinska, J.; Zygadlo, M.; Debicka, M. The Biological Drying of Municipal Waste in an Industrial Reactor—A Case Study. *Energies* **2022**, *15*, 9. [CrossRef]
3. Velis, C.A.; Longhurst, P.J.; Drew, G.H.; Smith, R.; Pollard, S.J.T. Biodrying for mechanical-biological treatment of wastes: A review of process science and engineering. *Bioresour. Technol.* **2009**, *100*, 2747–2761. [CrossRef] [PubMed]
4. Payomthip, P.; Towprayoon, S.; Chiemchaisri, C.; Patumsawad, S.; Wangyao, K. Optimization of Aeration for Accelerating Municipal Solid Waste Biodrying. *Int. J. Renew. Energy Dev.* **2022**, *11*, 878–888. [CrossRef]
5. Psaltis, P.; Komilis, D. Environmental and economic assessment of the use of biodrying before thermal treatment of municipal solid waste. *Waste Manag.* **2019**, *83*, 95–103. [CrossRef]

6. Zaman, B.; Oktiawan, W.; Hadiwidodo, M.; Sutrisno, E.; Purwono, P. Calorific and greenhouse gas emission in municipal solid waste treatment using biodrying. *Glob. J. Environ. Sci. Manag.* **2021**, *7*, 14. [CrossRef]
7. Siddiqui, S.A.; Ucak, I.; Jain, S.; Elsheikh, W.; Redha, A.A.; Kurt, A.; Toker, O.S. Impact of drying on techno-functional and nutritional properties of food proteins and carbohydrates—A comprehensive review. *Dry. Technol.* **2024**, *42*, 592–611. [CrossRef]
8. Tun, M.M.; Juchelková, D. Drying methods for municipal solid waste quality improvement in the developed and developing countries: A review. *Environ. Eng. Res.* **2019**, *24*, 529–542. [CrossRef]
9. Itsarathorn, T.; Towprayoon, S.; Chiemchaisri, C.; Patumsawad, S.; Phongphiphat, A.; Bhatsada, A.; Wangyao, K. The effect of aeration rate and feedstock density on biodrying performance for wet refuse-derived fuel quality improvement. *Int. J. Renew. Energy Dev.* **2023**, *12*, 1091–1103. [CrossRef]
10. Tambone, F.; Scaglia, B.; Scotti, S.; Adani, F. Effects of biodrying process on municipal solid waste properties. *Bioresour. Technol.* **2011**, *102*, 7443–7450. [CrossRef]
11. Zhang, D.Q.; He, P.J.; Jin, T.F.; Shao, L.M. Bio-drying of municipal solid waste with high water content by aeration procedures regulation and inoculation. *Bioresour. Technol.* **2008**, *99*, 8796–8802. [CrossRef] [PubMed]
12. Zhang, D.Q.; He, P.J.; Shao, L.M. Sorting efficiency and combustion properties of municipal solid waste during bio-drying. *Waste Manag.* **2009**, *29*, 2816–2823. [CrossRef] [PubMed]
13. Rada, E.C.; Venturi, M.; Ragazzi, M.; Apostol, T.; Stan, C.; Marculescu, C. Bio-Drying Role in Changeable Scenarios of Romanian MSW Management. *Waste Biomass Valoriz.* **2010**, *1*, 271–279. [CrossRef]
14. Sugni, M.; Calcaterra, E.; Adani, F. Biostabilization-biodrying of municipal solid waste by inverting air-flow. *Bioresour. Technol.* **2005**, *96*, 1331–1337. [CrossRef]
15. Adani, F.; Baido, D.; Calcaterra, E.; Genevini, P. The influence of biomass temperature on biostabilization-biodrying of municipal solid waste. *Bioresour. Technol.* **2002**, *83*, 173–179. [CrossRef]
16. Tom, A.P.; Pawels, R.; Haridas, A. Biodrying process: A sustainable technology for treatment of municipal solid waste with high moisture content. *Waste Manag.* **2016**, *49*, 64–72. [CrossRef]
17. Zawadzka, A.; Krzystek, L.; Ledakowicz, S. Autothermal biodrying of municipal solid waste with high moisture content. *Chem. Pap.* **2010**, *64*, 265–268. [CrossRef]
18. Foronda, K.D.C.; Garces, D.C.G.; Rendon, L.R.; Alvites, Y.Y.M.; Sagra, J.P.R.; Mendoza, G.L.O.; Sossa, J.W.Z. Electrohydrodynamic Drying in Agribusiness: Literature Review. *Front. Sustain. Food Syst.* **2022**, *5*, 13. [CrossRef]
19. Croatian Agency for the Environement and Nature. *Creating a Unique Methodology for the Analysis of the Composition of Municipal Waste, Determining the Average Composition of Municipal Waste in the Republic of Croatia and Making Projections on the Amount of Municipal Waste*; Croatian Agency for the Environment and Nature: Zagreb, Croatia, 2015; p. 90.
20. Traven, L. The potential for a combined heat and power (CHP) generation from municipal solid waste: A case study of Croatia. *Case Stud. Chem. Environ. Eng.* **2023**, *8*, 100450. [CrossRef]
21. He, P.J.; Zhao, L.; Zheng, W.; Wu, D.; Shao, L.M. Energy Balance of a Biodrying Process for Organic Wastes of High Moisture Content: A Review. *Dry. Technol.* **2013**, *31*, 132–145. [CrossRef]
22. Huiliñir, C.; Villegas, M. Simultaneous effect of initial moisture content and airflow rate on biodrying of sewage sludge. *Water Res.* **2015**, *82*, 118–128. [CrossRef] [PubMed]
23. Yuan, J.; Zhang, D.F.; Li, Y.; Li, J.; Luo, W.H.; Zhang, H.Y.; Wang, G.Y.; Li, G.X. Effects of the aeration pattern, aeration rate, and turning frequency on municipal solid waste biodrying performance. *J. Environ. Manag.* **2018**, *218*, 416–424. [CrossRef] [PubMed]
24. Kechaou, N.; Ammar, E. Biodrying process: A sustainable technology for treatment of municipal solid wastes organic fraction. In Proceedings of the 21st International Drying Symposium (IDS), Valencia, Spain, 11–14 September 2018; pp. 1953–1960.
25. Bilgin, M.; Tulun, S. Biodrying for municipal solid waste: Volume and weight reduction. *Environ. Technol.* **2015**, *36*, 1691–1697. [CrossRef] [PubMed]
26. Yang, B.Q.; Hao, Z.D.; Jahng, D. Advances in biodrying technologies for converting organic wastes into solid fuel. *Dry. Technol.* **2017**, *35*, 1950–1969. [CrossRef]
27. Yuan, J.; Li, Y.; Wang, G.Y.; Zhang, D.F.; Shen, Y.J.; Ma, R.N.; Li, D.Y.; Li, S.Y.; Li, G.X. Biodrying performance and combustion characteristics related to bulking agent amendments during kitchen waste biodrying. *Bioresour. Technol.* **2019**, *284*, 56–64. [CrossRef]
28. Quan, H.Y.; Zhu, T.; Ma, F.; Zhang, K.; Zhu, Y.A.; Wang, Y.Z.; Lyu, Z. Enhanced bio-drying effect in low-temperature: Characteristics of sludge hyperthermophilic aerobic bio-drying by inoculating with thermophilic bacteria and full-scale operation. *Dry. Technol.* **2023**, *41*, 1977–1990. [CrossRef]
29. Ramirez, A.A.; Godbout, S.; Léveillée, F.; Zegan, D.; Larouche, J.P. Effect of temperature and air flow rate on carbon and nitrogen compounds changes during the biodrying of swine manure in order to produce combustible biomasses. *J. Chem. Technol. Biotechnol.* **2012**, *87*, 831–836. [CrossRef]
30. Bosilj, D.; Petrović, I.; Hrnčić, N.; Kaniški, N. Biodrying of municipal solid waste-correlations between moisture content, organic content, and end of the biodrying process time. *Environ. Sci. Pollut. Res.* **2024**, *1*, 1–14. [CrossRef]

31. Cline, C.; Anshassi, M.; Laux, S.; Townsend, T.G. Characterizing municipal solid waste component densities for use in landfill air space estimates. *Waste Manag. Res.* **2020**, *38*, 673–679. [CrossRef]
32. Ab Jalil, N.A.; Basri, H.; Basri, N.E.A.; Abushammala, M.F.M. Biodrying of municipal solid waste under different ventilation periods. *Environ. Eng. Res.* **2016**, *21*, 145–151. [CrossRef]
33. dos Reis, R.F.; Cordeiro, J.S.; Font, X.; Achon, C.L. The biodrying process of sewage sludge—A review. *Dry. Technol.* **2020**, *38*, 1247–1260. [CrossRef]
34. Zawadzka, A.; Krzystek, L.; Stolarek, P.; Ledakowicz, S. Biodrying of Organic Fraction of Municipal Solid Wastes. *Dry. Technol.* **2010**, *28*, 1220–1226. [CrossRef]
35. Rossi, E.; Pecorini, I.; Iannelli, R. Multilinear Regression Model for Biogas Production Prediction from Dry Anaerobic Digestion of OFMSW. *Sustainability* **2022**, *14*, 17. [CrossRef]
36. Lwin, Y.N.N.; Bhatsada, A.; Towprayoon, S.; Patumsawad, S.; Sutthasil, N.; Wangyao, K. Aeration Optimization for the Biodrying of Market Waste Using Negative Ventilation: A Lysimeter Study. *Clean Technol.* **2024**, *6*, 1519–1536. [CrossRef]
37. Dhiman, S.; Khanna, K.; Kour, J.; Singh, A.D.; Bhardwaj, T.; Devi, K.; Sharma, N.; Kumar, V.; Bhardwaj, R. Landfill bacteriology: Role in waste bioprocessing elevated landfill gaseselimination and heat management. *J. Environ. Manag.* **2024**, *354*, 17. [CrossRef]
38. Kawai, M.; Purwanti, I.F.; Nagao, N.; Slamet, A.; Hermana, J.; Toda, T. Seasonal variation in chemical properties and degradability by anaerobic digestion of landfill leachate at Benowo in Surabaya, Indonesia. *J. Environ. Manag.* **2012**, *110*, 267–275. [CrossRef]
39. Chu, X.Q.; Wu, G.X.; Wang, J.Q.; Hu, Z.H. Dry co-digestion of sewage sludge and rice straw under mesophilic and thermophilic anaerobic conditions. *Environ. Sci. Pollut. Res.* **2015**, *22*, 20143–20153. [CrossRef]
40. Ihia, O.A.; Khomsi, D.; Hassani, N.S.A. Simulation and optimization model for mechanical biological treatment biodrying process: Validation with experimental results. *Euro-Mediterr. J. Environ. Integrat.* **2024**, *9*, 1207–1225. [CrossRef]
41. Widyarsana, I.M.W.; Sevina, R. Study on the Quality Improvement of Mixed Municipal Solid Waste by Greenhouse Blackout Tarp with Biodrying System. *J. Ecol. Eng.* **2024**, *25*, 200–209. [CrossRef]