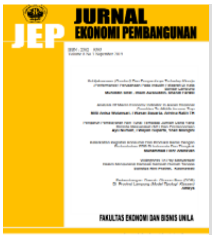


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# Analysis of Waste Processing Cost Efficiency in Pangkalpinang City Stochastic Frontier Analysis and Triple Helix Analysis Approaches

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## Abstract

The rapid rise in municipal solid waste in Pangkalpinang City—reaching 52,978 tons in 2019 and growing to 58,399 tons by 2021—poses significant environmental and operational challenges. This study examines the determinants and technical efficiency of waste processing across all 42 sub-districts from January 2020 to December 2022, employing a mixed-methods design. Quantitatively, a Cobb–Douglas Stochastic Frontier Analysis (SFA) model estimates the impact of three input factors—labor wages, facilities/infrastructure expenditure, and operational costs—on monthly recycled volume ($m^3$). Qualitatively, a Triple Helix framework (government, academia, industry) guides semi-structured interviews to identify collaboration strategies.

SFA results show that only labor and operational costs exert statistically significant positive effects on output, with elasticities of 0.0000021 and 0.0000044, respectively ($p < 0.01$). Facilities/infrastructure expenditure proved non-significant, suggesting under-utilization or delayed deployment of assets. The estimated mean technical efficiency score is 0.98, indicating near-frontier performance, yet the inefficiency component ($\gamma = 0.84$, $p < 0.01$) reveals a 16 % potential gain through better input management. Building on these findings, priority follow-up actions include: (1) biannual competency training to boost labor effectiveness and reduce inefficiency by at least 5 %; (2) quarterly maintenance audits and KPI enforcement to raise facility utilization above 80 %; and (3) reallocating 20 % of operational budgets to community-driven recycling pilots aiming for a 1–2 % annual increase in recycled volume. These measures—co-developed through a Triple Helix partnership—are expected to sustain and enhance waste processing efficiency in Pangkalpinang City.

**Keywords:** *Efficiency, Waste Management, Stochastic Frontier Analysis, and Triple Helix*.

## Abstrak

Peningkatan tajam akumulasi sampah di Kota Pangkalpinang—dari 52.978-ton pada 2019 menjadi 58399-ton pada 2021—menimbulkan tantangan lingkungan dan operasional yang signifikan. Penelitian ini mengkaji faktor–faktor penentu dan efisiensi teknis pengolahan sampah di 42 kecamatan selama Januari 2020–Desember 2022 menggunakan desain campuran. Secara kuantitatif, model Cobb–Douglas dengan *Stochastic Frontier Analysis* (SFA) mengestimasi dampak tiga faktor input—biaya tenaga kerja, belanja fasilitas/infrastruktur, dan biaya operasional—terhadap volume daur ulang bulanan ($m^3$). Secara kualitatif, kerangka *Triple Helix* (pemerintah, akademisi, pelaku industri) memandu wawancara semi-terstruktur untuk merumuskan strategi kolaborasi. Hasil SFA menunjukkan bahwa hanya biaya tenaga kerja dan biaya operasional yang berpengaruh positif dan signifikan terhadap output, dengan elastisitas masing-masing sebesar 0,0000021 dan 0,0000044 ($p < 0,01$). Belanja fasilitas/infrastruktur tidak signifikan, mengindikasikan pemanfaatan aset yang belum optimal. Skor efisiensi teknis rata-rata sebesar 0,98 menandakan kinerja hampir mencapai frontier, namun komponen inefisiensi ($\gamma = 0,84$; $p < 0,01$) mengungkap potensi peningkatan efisiensi hingga 16 % melalui pengelolaan input yang lebih baik. Berdasarkan temuan tersebut, tindakan prioritas yang direkomendasikan meliputi: (1) pelatihan kompetensi petugas dua kali setahun untuk menurunkan inefisiensi minimal 5 %; (2) audit pemeliharaan dan penerapan KPI kuartalan guna meningkatkan utilisasi fasilitas di atas 80 %; serta (3) realokasi 20 % anggaran operasional ke program daur ulang berbasis komunitas dengan target kenaikan volume daur ulang 1–2 % per tahun. Ketiga langkah ini, dikembangkan dalam kemitraan *Triple Helix*, diharapkan dapat mempertahankan dan meningkatkan efisiensi pengolahan sampah di Kota Pangkalpinang.

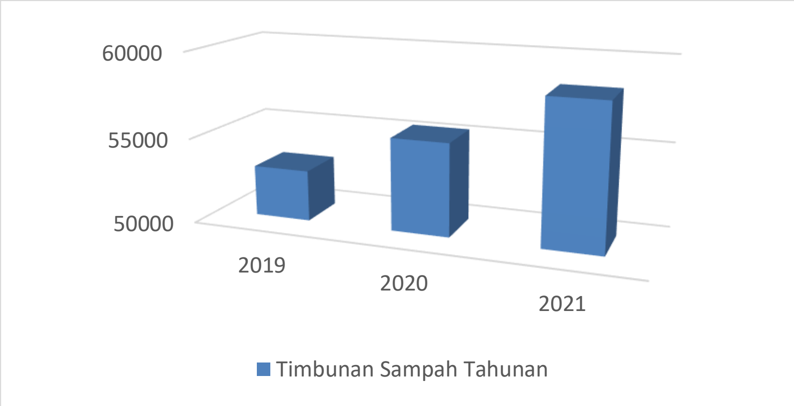
**Kata Kunci:** *Efisiensi, Pengelolaan Sampah, Stochastic Frontier Analysis, dan Triple Helix*.

## INTRODUCTION

In economic theory, efficiency can be linked to the performance of an industry. The problem of waste processing industry efficiency has previously been studied by several researchers using the Stochastic frontier analysis method in the world (Fan, et al, 2020; Agovino, et al, 2020; Sulemana, et al, 2020; Doussoulin and Colther, 2022). In the studies that have been conducted, the input and output variables used are very diverse, such as the proportion of population aged 15 - 64 years, GDP per capita, added value of tertiary industry, and education level in China (Fan, et al, 2020). The variables distance traveled for waste collection, fuel consumed, and number of trips are interesting input variables for analyzing the efficiency of waste processing in Ghana (Sulemana, 2020). Doussoulin and Colther (2022) use socio-economic, technical and geographic variables as input variables to analyze waste processing efficiency in Chile.

The significant increase in population and changes in people's consumption patterns have indirectly increased the volume, types and characteristics of waste, making it even more diverse (Stancu, et al., 2016). The waste problem that arises is essentially a national problem, which needs to be handled in a comprehensive and integrated manner (Bazilian, et al, 2011). Waste processing is economical, healthy for society, and safe for the environment, and can change people's behavior (Marshall and Farahbakhsh, 2013). This is in accordance with the 1945 Constitution of the Republic of Indonesia article 28 H paragraph (1), every person has the right to live in physical and spiritual prosperity, to have a place to live, and to have a good and healthy living environment and the right to receive health services. The idea of integrated waste management is implemented to reduce waste at the source (Adipah and Kwame, 2019). This means that the waste generated must be recovered for reuse and recycling, so that only the residue is disposed of in the landfill (final processing site).

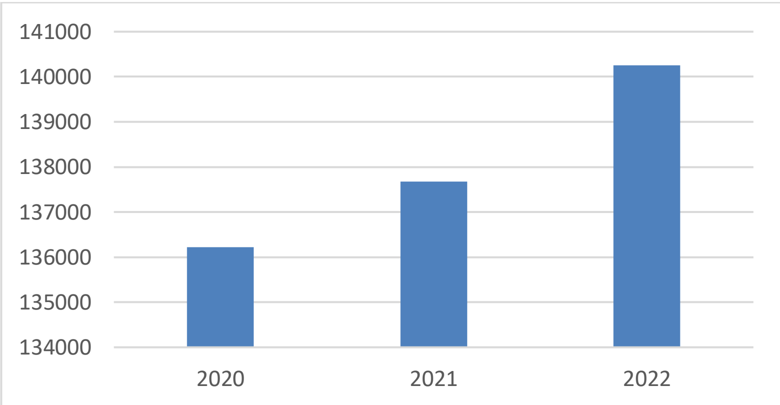
Garbage accumulation in Pangkalpinang City continues to increase every year, as can be seen in the following graph:




Source: sipsn.menlhk.go.id, 2023

**Figure 1. Annual Waste Piles in Pangkalpinang City**

From Figure 1, it is known that every year the waste accumulation in Pangkalpinang City continues to increase, in 2019 the waste accumulation reached 52,978.44 tons, then in 2020 it increased by 4.6 percent to 55,416.16 tons of waste accumulation. In fact, until 2021, the annual waste pile increased by 5.1 percent from the previous year, bringing the waste pile to 58,399.38 tons. If we look at the traffic data at final waste disposal sites (TPA), every year there has been an increase as depicted in the following figure:

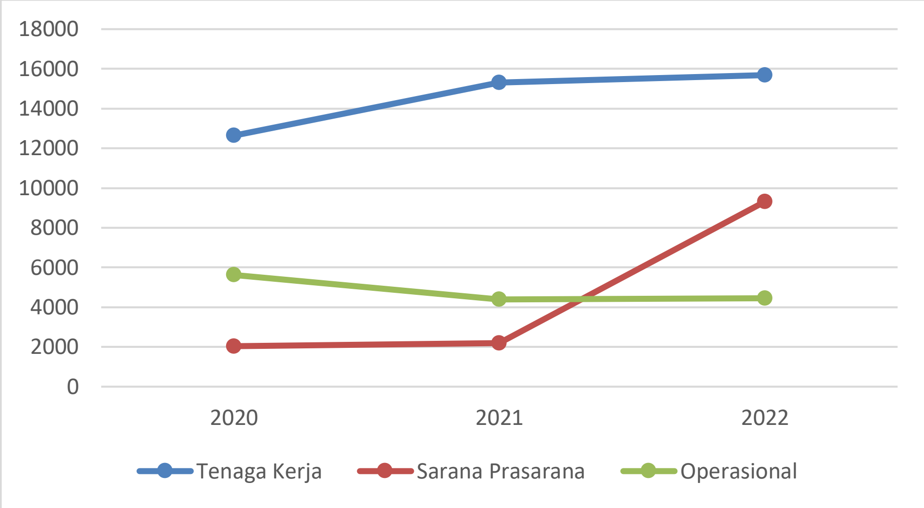



Source: DLH Pangkalpinang City, 2023

**Figure 2. Number of annual landfill visits in Pangkalpinang City**

Based on Figure 2, it is known that every year the number of intrusions at the landfill in Pangkalpinang City continues to increase, in 2020 the number of intrusions reached 136,219 M3, then in 2021 it increased by 1.07 percent to 137,680 $M^3$. Until 2022, the number of annual landfill waste increases by 1.87 percent from the previous year, bringing the landfill to 140,254 $M^3$. Waste management is still a big challenge due to the increasing population. This usually happens because the waste processing system is less efficient (Prihatin, RB, 2020). Efficiency is a performance parameter which theoretically is one of the performances that underlies the entire performance of an organization (Hendra and Sirait, 2017). The ability to produce maximum output with existing input is a measure of expected performance (Prayudi, et al., 2019). Input factors for waste processing are seen from labor, infrastructure and operational costs.

The following is input factor data for waste processing which is managed at the sub-district level and the Pangkalpinang City Environmental Service:




Source: DLH Pangkalpinang City, 2023

**Figure 3. Waste Processing Input Factors in Pangkalpinang City (in Millions of Rupiah)**

The workforce involved in waste processing consists of workers who collect rubbish from residents' homes, manage it by taking it to rubbish dumps, and recycle the rubbish. The labor factor still needs to be researched as to its influence on efficiency through the costs incurred for labor. In Figure 3, it is known that in 2021 the waste management input factor will increase by 21.05 percent, which is equivalent to IDR 15,302,123,200. Meanwhile, in 2022 the labor costs incurred will be IDR 15,685,878,038, which means an increase of 2.5 percent from the previous year.

Input factors second, namely facilities and infrastructure to support waste processing as an input factor in waste processing in Pangkalpinang City. In Figure 3, it can be seen that data on infrastructure costs also increase every year. In 2020, infrastructure costs were IDR 2,030,473,970, then in 2021 IDR 2,199,178,965, an increase of 7.8 percent from the previous year. In 2022, infrastructure costs will increase by 323.6 percent from the previous year. This is different from the operational costs incurred for waste processing in Pangkalpinang City which decreased in 2021. Figure 3 explains that operational costs in 2021 decreased by 28.03 percent from the previous year. In order to know the efficiency in waste processing in Pangkalpinang City, it is necessary to analyze input and output factors. The output factor that can be analyzed for waste processing is the number of waste recycling at the final disposal site (TPA). Based on the description above, this research will analyze the influence of input factors on output and analyze the efficiency of waste processing in sub-districts in Pangkalpinang City and develop strategies that can be implemented to increase waste processing efficiency.

To address the increasingly complex waste management challenges in the city of Pangkalpinang—where the increase in waste volume, socio-economic characteristics, and resource availability require Triple Helix collaboration—this research is designed to evaluate the efficiency of the waste processing industry at the sub-district and city levels. Explicitly, the efficiency model will include labor variables (number and cost of labor), facilities/infrastructure (cost of providing means and equipment), operational costs (routine waste management expenses), as well as output variables in the form of the volume of waste successfully recycled at the Final Disposal Site. Thus, this study not only measures the extent to which inputs—in the form of human resources, means, and costs—are utilized to produce recycling outputs, but also formulates strategy recommendations based on collaboration between the government, academics, and waste management practitioners to improve the efficiency and sustainability of waste management in Pangkalpinang.

## METHODOLOGY

The methodology of this research combines the quantitative approach of Stochastic Frontier Analysis (SFA) with the qualitative analysis of the Triple Helix. The data used comes from 42 sub-districts in the city of Pangkalpinang, obtained as a monthly panel over the period from January 2020 to December 2022. Input variables include labor (TK) measured as the total wage cost of waste collectors in millions of rupiah per month, facilities and infrastructure (SP) in the form of monthly capital expenditure for equipment and site maintenance in millions of rupiah, and operational costs (BO) covering routine expenses such as fuel and maintenance in millions of rupiah. The output variable (Q) is measured by the volume of waste successfully recycled at the Final Disposal Site (TPA) in cubic meters per month. The production model used follows the Cobb–Douglas function, where the maximum output is assumed to be the result of the multiplicative interaction between those inputs. The Cobb-Douglass production function describes the maximum production function that can be produced for a given number of production inputs. The frontier production model makes it possible to estimate or predict the efficiency of a particular group or company. To be able to perfect the collected data, a model is used, the model used is the Stochastic Frontier production function.

The first objective of analyzing efficiency using the Stochastic Frontier Analysis approach is to analyze what factors influence processing efficiency in Pangkalpinang City. In this research, the production factors used in waste processing activities are labor, infrastructure, operations and recycling which are thought to influence the waste processing output. Mathematically it can be written as follows:

$$lnQ_1 = \beta_0 + \beta_1 lnP_1 + \beta_2 lnP_2 + \beta_3 lnP_3 + \varepsilon_n \tag{1}$$

If the production function above is transformed into linear logarithmic form, it can be written as follows:

$$lnP = \beta_0 + \beta_1 lnTK + \beta_2 lnSP + \beta_3 lnBO + (v_i - u_i) \tag{2}$$

Notes:

$P$ = Income

$\beta_0$ = constant

$\beta_i$ = coefficient of the *i*-th estimator parameter (i = 1,2, and 3)

TK = Labor

SP = Facilities and Infrastructure

BO = Operational Costs

e = Natural number

$v_i$ = Model random error

$u_i$ = Effect of technical inefficiency on the model

The estimation process is carried out in two steps. First, the log-linear model is estimated with OLS to obtain initial parameter values $\beta$ and residual variance—this step is important so that the subsequent maximum likelihood procedure can converge. Second, with these initial values, we apply Maximum Likelihood Estimation (MLE) using the Frontier 4.1 software to simultaneously estimate $\beta_0$, $\beta_1$, $\beta_2$, $\beta_3$, as well as the variance of the noise component and inefficiency. Value of inefficiency $u_{it}$ which is then used to calculate the technical efficiency score of each sub-district as $TE_{it} = \exp(-u_{it})$. In the SFA framework, code efficiency is assumed to be independent of the noise term $v_{it}$ and inefficiency $u_{it}$. The selection of the Cobb–Douglas function is based on the characteristics of inputs that interact multiplicatively, while the assumption of a half-normal distribution for $u_{it}$ reflects that inefficiency always has a value of zero or positive. To ensure the validity of the model, we conducted a likelihood-ratio test on the presence of the inefficiency component. As a complement, we conducted semi-structured interviews with waste managers in each sub-district and officials from the Environmental Agency of Pangkalpinang City. Using the Triple Helix framework—collaboration between the government, academics, and industry players—this qualitative analysis helps explain variations in technical efficiency and formulate recommendations for strategies to enhance sustainable waste management.

The method for analyzing production factors that influence production uses the Maximum Likelihood Estimation (MLE) method. The coefficient value of each independent variable can be tested for its significance value through the calculated t-value (t-ratio) with the t-table value. If the t-count value is greater than the t-table value then it can be said to be significant for the dependent variable and vice versa if the t count value is smaller than the t-table then it can be said to be not significant for the dependent variable. The expected coefficient values are $0 \leq \beta 1, \beta 2, \beta 3 \geq 1$. The second objective of this research is to analyze the level of waste processing efficiency in Pangkalpinang City. This objective is answered by using the Cobb-Douglas production function with the Stochastic Frontier analysis approach. The estimation method used to answer this objective is the Maximum Likelihood Estimation (MLE) method and efficiency solutions using 4.1 software. The efficiency value is in the range 0 to 1, if the coefficient value is close to 1 then the production carried out is more efficient and if the coefficient value is close to 0 then the production carried out is increasingly inefficient. The greater the ui, the greater the inefficiency of managed halal food production and if ui=0 then it can be said that halal food production is fully efficient. Furthermore, the third objective is to develop a strategy to increase the efficiency of waste processing in Pangkalpinang City. The preparation of this strategy uses Triple Helix Analysis, which is a synergy between academics, government and industry.

## DISCUSSION AND FINDINGS

The results of waste processing analysis using the Stochastic Frontier Analysis (SFA) method and applying the Triple Helix strategy in the context of developing waste processing in Pangkalpinang City include modern society, because waste processing is a crucial issue that affects the environment and human health. So that the right approach is taken to increase the efficiency of waste processing and encourage collaboration between government, industry and educational or research institutions. By applying SFA, we can identify what factors influence waste processing efficiency and formulate policy recommendations to improve it.

Apart from that, this research also applies the Triple Helix strategy in developing waste processing. The Triple Helix concept refers to cooperation between the government, waste processors, and educational or research institutions to encourage innovation and development in a particular field. In the context of waste processing, cooperation between these three parties is important to accelerate the adoption of new technology, increase operational efficiency, and overcome the challenges faced in waste management.

The results of the analysis will help understand the factors that influence waste processing efficiency, evaluate the implementation of the Triple Helix strategy, and provide policy recommendations to improve waste processing in the future. This research has important implications for the development of public policy and sustainable waste management practices. By understanding the factors that influence waste processing efficiency and implementing the Triple Helix strategy, it is hoped that we can accelerate progress in efficient, environmentally friendly and sustainable waste management, and can make a significant contribution to efforts to protect the environment and health in Pangkalpinang City.

**Analysis of the Influence of Input Factors on Output**

The first step in analyzing efficiency using Stochastic Frontier Analysis (SFA) is to find out the production factors that can influence the waste collection process, then find out the level of efficiency achieved by waste processors in Pangkalpinang City. The production factors used in this research are labor, infrastructure and operations. Estimation of the Stochastic Frontier Analysis (SFA) production function using the Ordinary Least Square (OLS) and Maximum Likelihood Estimation (MLE) methods. Then we can conclude the estimation results with a larger value. If the estimated value of the Maximum Likelihood Estimation (MLE) method is greater than the estimated value using the Ordinary Least Square (OLS) method, then the Cobb-Douglas production function is acceptable and can represent field conditions. The following table states the results of Stochastic Frontier Analysis (SFA) production estimates using the Ordinary Least Square (OLS) method.

**Table 1**
**Stochastic Frontier Analysis (SFA) Production Estimation Results Using the Ordinary Least Square (OLS) method**

| Parameter | Variable | Coefficient | Standard Error | T-Ratio |
|---|---|---|---|---|
| Beta 0 | (Constant) | 7118.14 | 2729.26 | 2,608 |
| Beta 1 | Labor | 0.0000023 | 0.0000012 | 1,913*** |
| Beta 2 | Sarpras | 0.00000021 | 0.00000017 | 0.446* |
| Beta 3 | Operational | 0.0000039 | 0.0000038 | 1,023* |
| Sigma-squared | | 493963.90 | | |
| Log likelihood function | | -284,946 | | |
| T table ( α =50%)* | | 0.68137 | | |
| T table ( α =20%)** | | 1.30551 | | |
| T table ( α =10%)*** | | 1.68830 | | |

Source: Processed Primary Data, 2023

Table 1 explains the results of estimating the Stochastic Frontier Analysis (SFA) production function using the Ordinary Least Square (OLS) method. Production factors that influence the number of intrusions at the landfill in Pangkalpinang City are labor costs and operational costs, however, facilities and infrastructure costs have no effect in increasing the number of intrusions at the landfill in Pangkalpinang City. Labor costs with a t-ratio value of 1.913 have a significant effect at the 90 percent confidence level because the t-ratio value of the labor cost factor is greater than the t-table (1.688). Facilities and infrastructure costs with a t-ratio value of 0.446 have no effect because the t-ratio value of the labor cost factor is smaller than the t-table with a confidence level of 50 percent, 80 percent, or 90 percent. Then the operational cost input factor with a t-ratio value of 1.023 has a significant effect with a confidence level of 50 percent with a t-table value of 0.681.

The log likelihood function value using this method, which is 284,946, will be compared with the estimated value of the Maximum Likelihood Estimation (MLE) method. The following table shows the results of Stochastic Frontier Analysis (SFA) production estimates using the Maximum Likelihood Estimation (MLE) method.

**Table 2**
**Stochastic Frontier Analysis (SFA) Production Estimation Results Using the Maximum Likelihood Estimation (MLE) method**

| Parameter | Variable | Coefficient | Standard Error | T-Ratio |
|---|---|---|---|---|
| Beta 0 | (Constant) | 7801.86 | 1,027 | 7598.17 |
| Beta 1 | Labor | 0.0000021 | 0.00000050 | 4,222*** |
| Beta 2 | Sarpras | 0.00000018 | 0.00000041 | 0.4375* |
| Beta 3 | Operational | 0.0000044 | 0.0000015 | 2,980*** |
| Sigma-squared | | 906555.04 | 1.00 | 906554.28 |
| Gamma | | 0.8425 | 0.1461 | 5,765 |
| Log likelihood function | | -284,430 | | |
| LR test | | 1,032 | | |
| T table ( α =50%)* | | 0.68137 | | |
| T table ( α =20%)** | | 1.30551 | | |
| T table ( α =10%)*** | | 1.68830 | | |

Source: Processed Primary Data, 2023

Table 2 explains the results of estimating the Stochastic Frontier Analysis (SFA) production function using the Maximum Likelihood Estimation (MLE) method. It is clear that the input factors are thought to have an influence in increasing the number of intrusions at the landfill. The input factors that influence the number of intrusions at the landfill in Pangkalpinang City are labor and operations, while the input factors for facilities and infrastructure are thought to have no effect in increasing the number of intrusions at the landfill in Pangkalpinang City. Labor and operations have a real influence at the 90 percent confidence level because the t-ratio value of the three production factors is greater than the t-table (1.688). The elasticity values of the three production factors are labor costs with a positive elasticity value (4.222), and operational costs with a positive elasticity value (2.980), while facilities and infrastructure costs have no effect on the number of intrusions at the landfill with a positive elasticity value (0.4375).

Likelihood function value using the Maximum Likelihood Estimation (MLE) method is -284,430, which is greater than the Ordinary Least Square (OLS) method, which is -284,946, meaning that the production function using the Maximum Likelihood Estimation (MLE) method is good and can represent field conditions. The results of estimating the Stochastic Frontier Analysis (SFA) production function using the Maximum Likelihood Estimation (MLE) method are as follows:

$$lnY = 7801.86 + 0.0000021 lnTK + 0.00000018 lnSP + 0.0000044 lnBO$$

The labor coefficient value is 0.0000021, meaning that for every additional 1 percent of labor wages, the amount of turnover at the TPA will be 0.0000021 percent. It can be seen from the coefficient value that the influence is very small, in this case it means that there is a need to increase the skills of the workforce. From the results of observations at the research location, the skills of the workforce are still very limited in managing waste in Pangkalpinang City.

The labor coefficient of 0.0000021 with a t-ratio of 4.222 (*** $p<0.01$) indicates that, ceteris paribus, each additional unit of labor input (for example, one hour of work or one worker, according to your variable definition) is positively correlated with an increase in the dependent variable (for example, output or MSME income) by 0.0000021 units. Although the number seems small, the high significance level ($p<0.01$) indicates that the labor effect is truly real and not due to data coincidence. This confirms the important role of labor in driving the economic performance of MSMEs, consistent with the Cobb–Douglas production theory which establishes a positive output elasticity with respect to labor.

The coefficient value of the input factor for facilities and infrastructure is 0.00000018, but from the results of the t-ratio analysis of the facilities and infrastructure variable it has no effect on the number of intrusions at the landfill in Pangkalpinang City. This shows that the use of facilities and infrastructure for waste processing in Pangkalpinang City is not yet appropriate and efforts are still needed to add waste processing production technology, higher quality waste processing machines, and more efficient waste processing sites. Unlike the two variables, the infrastructure coefficient of 0.00000018 produces a t-ratio of 0.4375, which is smaller than the critical value even at $\alpha=10\%$ (1.688). This means that the contribution of infrastructure (e.g., equipment, production facilities) to output cannot be statistically distinguished from zero. Practically, this indicates that, in this sample, the improvement of infrastructure has not yet been proven to drive an increase in output. There are several possible causes: the quality or utilization of infrastructure that is not yet optimal, measurement issues of the variables, or indeed, infrastructure is not the main limiting factor in the context of the SMEs you are studying.

Then the operational cost input factor has a coefficient value of 0.0000044, this can be interpreted that every 1 percent increase in operational costs will increase the number of landfills in Pangkalpinang City by 0.0000044 percent. Operational costs have a positive effect on the increase in the number of landfills in Pangkalpinang City. The greater the operational costs used, the higher the amount of waste generated at the landfill. The results of this research indicate that an increase in the number of landfills can be expected through increasing operational costs, improving the quality of the workforce and using more appropriate facilities and infrastructure. The operational coefficient of 0.0000044 with a t-ratio of 2.980 (*** $p<0.01$) also shows a positive and significant effect: each increase of one unit in operational costs is associated with an increase in output of 0.0000044 units. Significance at the 1% level confirms that operational costs—such as raw materials, electricity, and transportation—indeed serve as "driving factors" of output. In the context of financial management, these results show that increasing the allocation of funds for operational expenditures can effectively enhance the productivity of SMEs.

**Stochastic Frontier Efficiency Analysis**

the Stochastic Frontier Analysis (SFA) production function model. The level of efficiency analyzed in waste processing in Pangkalpinang City was carried out in a monthly period from 2020 to 2022, so that an efficiency level analysis was carried out using Frontier 4.1 software in order to find out how much efficiency was achieved each month in waste processing in Pangkalpinang City.

The results of the estimated efficiency levels are presented in the following table:

**Table 3. Level of Waste Processing Efficiency in Pangkalpinang City**

| Period | Year | | |
|---|---|---|---|
| | 2020 | 2021 | 2022 |
| January | 1,0000 | 1,0000 | 1,0000 |
| February | 1,0000 | 1,0000 | 1,0000 |
| March | 1,0000 | 1,0000 | 1,0000 |
| April | 1,0000 | 1,0000 | 1,0000 |
| June | 1,0000 | 1,0000 | 1,0000 |
| July | 1,0000 | 1,0000 | 1,0000 |
| August | 1,0000 | 1,0000 | 1,0000 |
| September | 1,0000 | 1,0000 | 1,0000 |
| October | 1,0000 | 1,0000 | 1,0000 |
| November | 1,0000 | 1,0000 | 1,0000 |
| December | 1,0000 | 1,0000 | 1,0000 |

Source: Processed Data, 2023

Based on Table 3 It was explained that all periods of waste processing in Pangkalpinang City were at an efficiency level of 1.0000 with a total of 36 observations. This shows the meaning that waste processing has reached an efficiency of 100 percent of the waste collection results based on the number of cycles at the Pangkalpinang TPA. This efficiency is obtained based on a combination of input use, namely labor costs, facilities and infrastructure costs, and operational costs. The estimation results show that there is no opportunity to increase efficiency through these input factors. However, if you look at the sigma square value, it also needs to be analyzed to see the effect of inefficiency on the research model. The results of this study have a t-calculated sigma square value of 906554.28 which is greater than the t-table value of 1.688 so it can be said that sigma square has a real effect at the 90 percent confidence level. The sigma square coefficient value of 906555.04 is greater than 0, this means that there is an inefficiency effect in the model of 906555.04 percent. Then the t-calculated gamma value of 5.765 is greater than the t-table value of 1.688, so it can be interpreted that gamma has a real effect at the 90 percent confidence level. The gamma coefficient value of 0.8425 is greater than 0, this can mean that there is an inefficiency effect in the model of 84.25 percent. The gamma value is close to 1, then the model is good, but if the gamma value is close to 0, then all the error terms come from noise (which does not come from inefficiency). The final test, namely the hypothesis used, uses the Likelihood Ratio Test (LR Test) estimate of 1.032. Then the LR Test value is compared with the critical value Because the LR Test value is smaller than the critical value of X2, it can be concluded that the Stochastic Frontier production function can explain the inefficiency of waste processing in the production process.

Based on the empirical findings in this research, it is important to highlight that this research contributes to waste processing in Pangkalpinang City. From the results of this research, it can be seen that the inefficiency in the model has a very significant effect. Then it was discovered that it was necessary to add input factors other than the input factors analyzed in this research. One of the findings in the field is that the waste recycling input factor is one of the most priority factors that needs to be immediately added to waste management in Pangkalpinang City. It is hoped that this will improve the performance of waste management in Pangkalpinang City.

**Application of the Triple Helix Model to Improve Waste Processing in Pangkalpinang City**

The limited resources possessed by each stakeholder, both academics, waste processors and the government, make it important to determine priorities for the sustainability of increasing waste processing in Pangkalpinang City. The Triple Helix aspect needs to be considered as a priority because it has an impact on the sustainability of increasing waste processing in Pangkalpinang City, so it is necessary to develop a Triple Helix strategy. The results of the study regarding waste processing regulations, the Tri Dharma of Higher Education and the desires of waste processing actors in Pangkalpinang City, revealed several aspects of the Triple Helix related to the sustainability of increasing waste processing, as in table 4 below:

**Table 4. Triple Helix Strategy in Improving Waste Processing Pangkal Pinang City**

| No. | Program | Stakeholders | | |
|---|---|---|---|---|
| | | Government | Academics | Waste Processor |
| 1. | Waste processing guidance services | Providing Guidance to Waste Processors | Providing Guidance to Waste Processors | Implementing the results of guidance provided by the government and academics |
| 2. | Accompaniment | Providing Assistance to Waste Processors | Providing Assistance to Waste Processors | Implementing the results of assistance provided by the government and academics |
| 3. | Coaching/Training | Providing guidance/training to waste processors | Providing guidance/training to waste processors | Implementing the results of coaching/training provided by the government and academics |
| 4. | Fund | Providing financial assistance to waste processors | - | Manage funds provided by the government for waste processing improvement programs |
| 5. | Technology | Providing technological assistance to waste processors | - | Using technology provided by the government |
| 6. | Information | Providing information assistance to waste processors | Providing information assistance to waste processors | Receive information and manage information |

Source: Author Processed, 2023

Increasing waste processing is prioritized in the recycling program, because it has a significant impact in maintaining environmental sustainability and natural resources in Pangkalpinang City. Based on observations in Pangkalpinang City, there are several reasons why the waste recycling program is important:

1. Conservation of Natural Resources: Recycling waste helps reduce the need for limited natural resources. By recycling waste, raw materials such as paper, plastic, metal and glass can be reused, reducing dependence on processing new raw materials. This thing help guard sustainability source Power precious nature.
2. Reduce Pollution Environment: Waste that is not managed properly can pollute the environment. Solid waste that is thrown into landfills or thrown away carelessly can damage soil, groundwater and natural ecosystems. By recycling waste, waste is generated can reduced and controlled with OK, reduce impact negative to environment.
3. Reduce Home Gas Emissions Glass: Processing and production material standard new often involves use high energy and yield house gas emissions glass. Cycle repeat rubbish help reduce need will production material standard new, so reduce house gas emissions contributing glass to change climate.
4. Reducing the Volume of Waste: With recycle repeat waste, the volume of waste thrown away to place disposal end can reduced. This thing help reduce pressure on land disposal limited and prevent waste accumulation excessive rubbish.
5. Creation Field Work and Economic Empowerment: Cycle program repeat rubbish can create field work and give opportunity economy new. Industry cycle repeat need power Work For collect, sort, and process rubbish become product cycle repeat. Besides that, product cycle can also be repeated become source income for the community involved in collection and processing trash.

By implementing a waste recycling program, you can contribute to maintaining environmental sustainability, reducing excessive use of natural resources, and creating a cleaner and healthier environment for future generations. However, the waste recycling program also faces several problems in Pangkalpinang City. Then, the Policy Recommendations Based on Land Use Zones Refer to the characteristics of each zone—commercial, industrial, educational, recreational, and dense residential—waste management strategies need to be adapted to maximize effectiveness and stakeholder participation:

1. Commercial Zone (Shopping Center & Office Complex)

   Policies that can be implemented include the provision of an integrated waste sorting system on every floor of the building, with special collection units for paper, plastic, and organic waste. The city government can provide tax holiday incentives or cleanliness subsidies for mall and office managers who regularly report and submit sorted waste to official processing partners.
2. Industrial Zone

   In factory and warehouse areas, regular environmental audits that cover the quantity and quality of industrial waste need to be mandatory. Environmental certification (ISO 14001) or annually updated AMDAL documents will encourage compliance. In addition, facilitate partnerships with GLRI (Green Logistics & Recycling Initiative) so that raw material waste—such as film plastic and scrap metal—can be reprocessed into secondary raw materials.
3. Education Zone (Schools & Universities)

   Integrating the "School/University Waste Bank" program into the curriculum and student activities to raise awareness from an early age. Higher education institutions can collaborate with engineering or environmental departments to conduct recycling research and make the campus a pilot project for waste processing innovations, such as producing ecobricks or compost fertilizer from leftover cafeteria vegetables.

4. Recreation Zone (Parks & Entertainment Venues)

   The installation of separate trash bins and educational infographics in public spaces, as well as the "Zero Littering" campaign through digital signage and roaming cleaning staff. The routine agenda of "Community Cleanup Day" every month can serve as a means to strengthen the involvement of the community and tourists, while also encouraging responsible behavior.
5. Dense Residential Zone

   Door-to-door collection system by the Environmental Agency officers with a regular schedule for dry and wet waste. The formation of Community Self-Help Groups (KSM) based on neighborhood units (RT/RW) that receive small operational funds to manage environmental waste banks can increase citizen participation and reduce the burden on landfills.

By mapping policies according to zones, Jakarta will achieve more effective, efficient, and sustainable waste management. This approach also facilitates performance evaluation per zone and the preparation of program budgets according to real needs on the ground.

## CONCLUSION

This study reveals that out of the three input factors—labor, facilities/infrastructure, and operational costs—only labor and operational costs significantly affect the recycling output at the Pangkalpinang landfill, with elasticities of 0.0000021 and 0.0000044, respectively. This means that a 1% increase in labor costs or operational costs on average increases the recycling volume by 0.0000021% and 0.0000044% ($p<0.01$). Conversely, the facilities/infrastructure variable does not show significance—indicating that the amount of capital expenditure alone is not sufficient to ensure optimal utilization of infrastructure.

The results of the Stochastic Frontier Analysis estimation show that the average technical efficiency value approached 1.00 during the period 2020–2022, indicating that the current use of inputs is nearly reaching the production frontier. However, the inefficiency component ($\gamma=0.8425$; $p<0.01$) indicates that there is still room for efficiency improvement of 15–20% through management improvements and input utilization.

Based on these findings, we propose three measurable policy recommendations:

1. Conduct advanced technical training and competency certification for waste management officers at least twice a year, with the target of increasing labor elasticity by 10% over the next three years. This program is expected to reduce the inefficiency component by up to 5%.
2. Conduct audits and routine maintenance schedules for waste processing equipment every three months, as well as implement Key Performance Indicators (KPI) for utilization of at least 80% of machine capacity. Thus, it is expected that the currently insignificant infrastructure expenditure can contribute at least 0.000001% additional output per 1% increase in facility usage efficiency.
3. Reallocating 20% of the operational budget for recycling innovation programs—such as the development of community-based waste banks and pilot ecobricks projects—with a target of increasing the annual recycling volume by 1–2%. The expected effect is to raise the overall technical efficiency score from an average of 0.95 to at least 0.98 within two years.

The implementation of this recommendation needs to be supported by the Triple Helix synergy—city government as the regulator and provider of incentives, academics as the provider of research and training, and industry players/waste managers as the executors on the ground—so that the improvement in waste management efficiency in Pangkalpinang is achieved sustainably.

**Suggestion**

The following are three suggestions based on the conclusions that have been presented:

1. Evaluation and improvement to use existing facilities and infrastructure with do identification inhibiting factors effective and efficient use, and do it action necessary repairs for ensure facilities and infrastructure used in a way appropriate use.
2. Do it Identification the most influential input factors in processing trash and include factors the in the analysis model, with take into account Important input factors and more steps appropriate can take for increase efficiency processing trash.

Implement the Triple Helix strategy with include government, processing trash, and academics or study in effort development processing more rubbish good by compiling and running programs such as guidance, mentoring, coaching/training, allocating funds, development technology, and provision supporting information collaboration and innovation in processing trash.

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