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ANALYSIS OF DETERMINANT FACTORS OF CARBON EFFICIENCY IN INDONESIA BASED ON DOMESTIC WASTE MANAGEMENT USING CAUSAL MACHINE LEARNING

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Abstract

Introduction: *Domestic waste management, which is a provincial-level program, is expected to reduce greenhouse gas (GHG) emissions for the sustainability of climate control efforts in Indonesia. Given this context, it is necessary to conduct a carbon efficiency analysis in Indonesia based on domestic waste management efforts.* ***Methods:*** *This study used an observational research design with a cross-sectional time approach. This study predicted the reduction in carbon emissions based on domestic waste management using causal machine learning by analyzing data on GHG emissions and domestic waste management from all provinces in Indonesia. An advantage of causal machine learning is its ability to assess the impact of treatment (domestic waste management) on the results (GHG emissions), as well as mitigating the effects of confounding variables.* ***Results and Discussion:*** *Despite improvements in waste management, several provinces experienced increased waste production, particularly from domestic waste and plastic waste. Analysis using the R programming language revealed that waste management is a significant variable (p = 0.011). However, data limitations posed challenges to comprehensive analysis.* ***Conclusion:*** *Achieving carbon efficiency requires serious waste management efforts. All provinces and cities/regencies must actively participate in program implementation. Routine reporting is essential to monitor the progress toward reducing GHG emissions.*

INTRODUCTION

Greenhouse gas (GHG) emissions pose a significant challenge today, with major impacts on environmental conditions and global climate change (1–4). Climate change, which affects ecosystems, weather patterns, and the biosphere, is mostly caused by the increasing levels of gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are the main contributors to the greenhouse effect. This rapid increase in carbon emissions is attributed to industrial development in all sectors, energy consumption, especially from internal combustion vehicles, and human activities, especially in waste management (5–7).

GHG emissions originate from various sources, including natural processes (8), transportation (9–10), industrial facilities (11–12), agricultural activities (13–17), and land use change, especially deforestation for agricultural purposes. The main source of CO_2 emissions is the combustion of hydrocarbon fuels such as oil, coal, and gas produced by internal combustion vehicles and industrial engines (9,17–18). Meanwhile, CH_4 is released during the decomposition of organic matter under oxygen-deficient conditions (19–20), which commonly occurs during waste incineration. In addition, N_2O is mainly generated from the use of nitrogen fertilizers in agriculture (17,21).

GHGs create a “greenhouse effect” by trapping heat within the Earth’s atmosphere, preventing it from escaping into space (19,22–24). This process leads to global warming, which has implications for climate change, including rising sea levels due to melting polar

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ice caps, increased frequency and intensity of extreme weather events, and threats to biodiversity (25–27).

Given the environmental and climatic impacts, all countries face challenges to reducing their GHG emissions. Understanding each country's contribution to global emissions is a key aspect in developing effective strategies to mitigate climate change. Since each country is responsible for global emissions, assessing these contributions is an important step toward developing effective strategies to reduce GHG emissions. Attention is focused on small-scale carbon emitters that are carried out massively, namely households, which continuously produce waste and use fossil fuels in daily activities.

According to the Paris Agreement, the overall global temperature increase should be limited to 2°C in the 21st century, with a preferred target of 1.5°C, compared to the pre-industrial period. This serves as the basis for climate change mitigation efforts, making studies on GHG emissions from various countries an integral part of the global strategy (28). Indonesia, as the fourth most populous country in the world, faces significant challenges in domestic waste management. According to data from the Ministry of Environment and Forestry (KLHK), Indonesia produces approximately 67 million tons of waste annually, with more than 50% comprising domestic waste. This waste contributes to GHG emissions, which have an impact on global climate change.

Based on statistical data, global solid waste disposal generated approximately 1600 Mt of CO_2 in 2016, representing 3-5% of global GHG emissions. The fast-growing economy can significantly lead to increased consumption and total domestic waste volume (29). Municipal solid waste disposal produces air pollutants and contributes to global warming as most waste is thrown in landfills or incinerated (30). Additionally, CH_4 emissions from waste disposal are a major source of GHG emissions (31).

Quantifying GHG emissions from municipal solid waste treatment, which typically falls into two categories, is the subject of extensive scholarly research. Studies, using dots data (2), statistical data (32), and a time-series analysis of GHG emissions from historical municipal solid waste disposal using the IPCC methodology, have focused on GHG emissions at the national (33), regional (27), and city levels (34). Other studies have focused on N_2O and CH_4 emitted from municipal solid waste treatment (35). In China, municipal waste is managed through three primary methods: incineration, landfilling, and biological treatment. Of these, biological treatment mostly involves anaerobic treatment and composting (2). China has increasingly switched from sanitary landfills to incineration to reduce GHG emissions from municipal waste disposal, thereby increasing the percentage of incineration annually from 5.3% in 2010 to 62.1% in 2020 (35).

The alarming increase in climate change requires immediate and extensive mitigation efforts to reduce domestic and global emissions. Although contributing to a small percentage, waste accumulation that produces methane remain a critical concern in emission reduction efforts (36). Up to 8 million tons of waste were generated daily in Indonesia's biggest cities in 2019. Being the world's largest archipelagic nation and one of the significant GHG emitters, Indonesia is particularly susceptible to the adverse effects of climate change (37). In response, through its revised Nationally Determined Contribution (NDC) statement, the Government of Indonesia (GoI) has reaffirmed its commitment to reducing GHG emissions. By 2030, Indonesia has set a conditional reduction target of up to 41% and an unconditional reduction target of 29% compared to the business-as-usual scenario (38). Following the forestry, agriculture, and energy sectors, the solid waste sector is the fourth largest national priority for reducing GHG emissions. Emission sources in Indonesia consist of forest and land conversion (50%), energy (34%), waste (7%), agriculture (6%), and industrial processes (3%). Therefore, the waste sector is the third largest source of GHG emissions in Indonesia and to achieve the reduction targets, the waste sector must be a primary concern. GHG emissions from Indonesia's waste sector are equivalent to 127 billion tons of CO_2, which ranks the country as the third largest emitter in the global waste sector (37). As a result, efficiency in domestic waste management is key to reducing carbon impacts and meeting emission reduction targets. This study employed a causal machine learning method by estimating the causal impact of domestic waste management on GHG emissions across provinces in Indonesia. The analysis included data on waste management and GHG emissions consisting of carbon and nitrogen. In addition, the impact of various features on the impact scale was assessed (2,18), thereby facilitating a broader contextual discussion on its implications for domestic waste management planning in Indonesia (39).

The increasingly worrying climate conditions in Indonesia have prompted the government to implement various efforts to restore climate conditions as expected. One of these efforts is the management of domestic waste produced by households. Provincial-level domestic waste management is expected to reduce GHG emissions for the sustainability of climate control efforts in Indonesia. Research on domestic waste has been widely conducted, but has not yet addressed the causality model that demonstrates an impact on GHG emissions (40).

The use of causal machine learning methods in carbon efficiency analysis provides an innovative approach to understanding the causal relationships between various waste management factors and their impacts on carbon emissions (1,41–42). Unlike traditional statistical methods that only show correlations, this method allows for the identification and understanding of deeper causal relationships, thereby informing the formulation of effective policies. This approach is valuable as understanding and mitigating GHG emissions is essential to preventing further environmental degradation and combating climate change. By analyzing domestic waste management across provinces, this study aims to identify the most effective household-level interventions for reducing GHG emissions. Furthermore, the significance of this study lies in its potential to provide input for policies that are critical to achieving targets set by global agreements such as the Kyoto Protocol and the Paris Agreement (43).

METHODS

Data Source

This study used an observational research design with a cross-sectional time approach, in which data were collected simultaneously. A quantitative analytical approach was applied, using machine learning techniques for data analysis. The variables included in this study were carbon emissions in Indonesia (CO_2), waste piles, plastic waste, sources of household/ domestic waste, and waste handling carried out across various provinces in Indonesia. The data were obtained from the websites of Climate Watch and the Ministry of Environment and Forestry of the Republic of Indonesia covering the period from 2019 to 2021. Further details are provided in the following table.

Table 1. Research Data Sources

Variable	Data Source
CO_2 Emission	https://www.climatewatchdata.org/ghg-emissions?end_year=2021&regions=IDN&start_year=2018
Waste Piles	https://sipsn.menlhk.go.id/sipsn/public/data/timbulan
Plastic Waste	https://sipsn.menlhk.go.id/sipsn/public/data/komposisi
Domestic Waste Source	https://sipsn.menlhk.go.id/sipsn/public/data/sumber
Waste Handling	https://sipsn.menlhk.go.id/sipsn/public/data/capaian

Panel Data Regression Analysis

Panel data regression analysis is a statistical method that combines cross-sectional data and time series data, where observations are made on multiple entities (e.g. individuals, companies, countries) over a specific period (44). This method enables the capture of more complex dynamics while controlling for unobserved factors through fixed effects and random effects models. For data analysis, this study used RStudio, an open-source platform for statistical analysis (45). The stages of analysis were as follows:

The first step involved loading the necessary packages in RStudio, specifically the "plm" package, and organizing the dataset in a panel format as illustrated below.

```
library(plm)
library(performance)
library(normtest)
```

The following step involved testing panel data regression models using pooled ordinary least squares (OLS), fixed effects, and random effects models.

```
pooled <- plm(model, paneldata, model = "pooling")
fixed <- plm(model,paneldata,model = "within", effect = "individual")
random <- plm(model, paneldata, model = "random", effect = "individual")
```

Following the model testing, the Hausman test was conducted to select the most appropriate model among the three models.

```
hausman_panel <- phtest(fixed.random)
```

Based on the testing of the panel data regression model and assumptions, the final stage involved generating predictions using the selected model.

```
#model GLS
gls <- pggls (Emisi_CO2 ~ Timbunan_sampah + Jenis_sampah + Sampah_RT + Penangan_sampah + lag(Emisi_CO2), data=paneldata, model="within")
summary(gls)
residgls <- gls$residual
summary(residgls)

#pcse
ols <- lm(model, panel)
pcse <- pcse(ols, groupN=panel$no, groupT=panel$tahun)
pcse <- pcse(ols, groupN=panel$No, groupT=panel$Tahun)
pcse <- pcse(ols,groupN = panel$No, groupT = panel$Tahun)
summary(pcse)
summary(ols)
pcse <- pcse(ols,groupN = panel$No, groupT = panel$Tahun)
View(data_uji_regresi_panel)
```

```
#pcse
ols <- lm(model, panel)
pcse <- pcse(ols,groupN = panel$No, groupT = panel$Tahun)
pcse <- pcse(ols,groupT = panel$Tahun)
pcse <- pcse(ols,groupN = panel$No, groupT = panel$Tahun)
pcse <- pcse(ols,groupN = panel, groupT = panel)
pcse <- pcse(ols,groupN = panel$No, groupT = panel$Tahun)
summary(pcse)
```

After the testing was completed, regression analysis results were generated to identify which variables had an influence based on the panel data approach.

RESULTS

Carbon Emissions in Indonesia Based on the CO_2 Status

Table 2. CO_2 Emission in Indonesia

Indicator	Year	Average	Standard Deviation	Min	Max
	2019	1,919.32	0	1,919.32	1,919.32
CO_2 Emission	2020	1,481.59	0	1,481.59	1,481.59
	2021	1,484.66	0	1,484.66	1,484.66

Between 2019 and 2021, carbon emissions in Indonesia showed a downward trend. In 2020, emissions reduced by 22.8%. Although carbon emissions increased slightly in 2021, they remained lower than those recorded in 2019.

Domestic Waste Management in Indonesia

Based on the results of thematic analysis using QGIS shown in the Figure 1, in general, the data on waste management by the Ministry of Environment and Forestry indicated an improvement over the years. Despite the overall positive trend, no province achieved a waste management rate exceeding 80% of the total waste generated.

Based on the results of thematic analysis shown in Figure 2, the data on waste piles by the Ministry of Environment and Forestry increased over the years. The highest level of waste pile between 2019 and 2021 was recorded in the Special Capital Region of Jakarta Province, illustrating the high level of urbanization in the capital city, which contributes to increased waste piles. In addition to the Special Capital Region of Jakarta Province, other provinces on Java Island reported significant waste piles. This is reasonable considering that the population of Java Island accounted for 54.4% of the total population in Indonesia in 2021. Several provinces with low levels of waste piles tend to be those with many immigrants such as the provinces on the islands of Kalimantan, Sulawesi, and Papua. However, the overall trend of waste piles across various provinces in Indonesia worsened, especially in West Java Province in 2021, which experienced a two-fold increase compared to the previous year. Although the amount of waste pile is highly dependent on the population size, an analysis of the proportion of waste pile per person per day revealed that the highest rates in 2019, 2020, and 2021 were recorded in the Special Capital Region of Jakarta (0.16 kg in both 2019 and 2020) and West Papua (0.14 kg in 2021).

Based on the results of thematic analysis shown in Figure 3, the data on household waste sources by the Ministry of Environment and Forestry indicated relatively low numbers between 2019 and 2021. For instance, Banten Province reported the highest household waste in 2019 at 933 tons per year. This accounted for only 0.33% of the total waste generated in the same year.

Based on the results of thematic analysis shown in Figure 4, the percentage of plastic waste composition by the Ministry of Environment and Forestry ranged from 0% to 40% between 2019 and 2021. Based on the data obtained from National Waste Management Information System (SIPSN), the average percentages of plastic waste composition in Indonesia in 2019, 2020, and 2021 were 15.04%, 16.89%, and 16.06%, respectively.

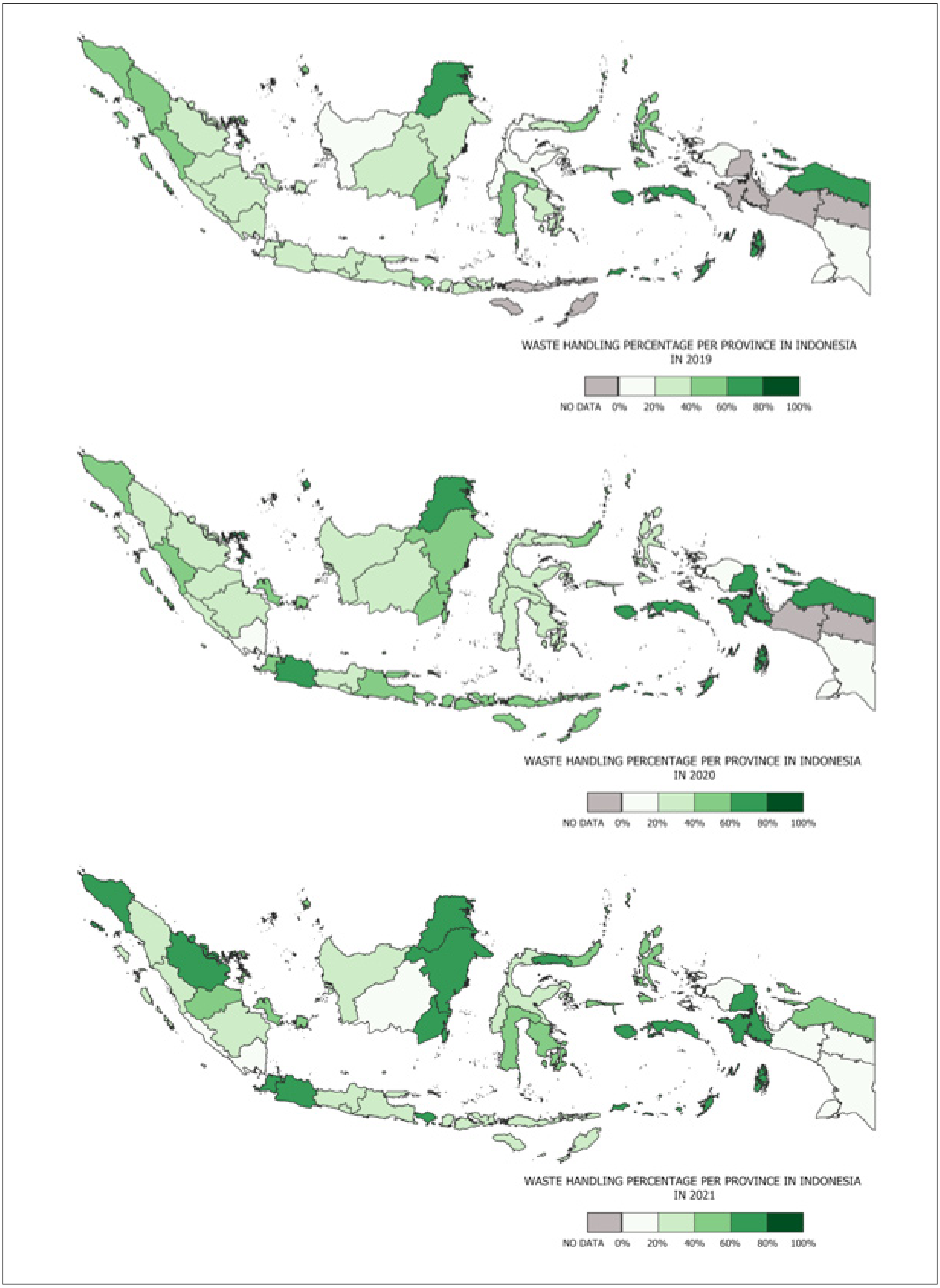

Figure 1. Percentages of Waste Handling Across Provinces in Indonesia Between 2019 and 2021

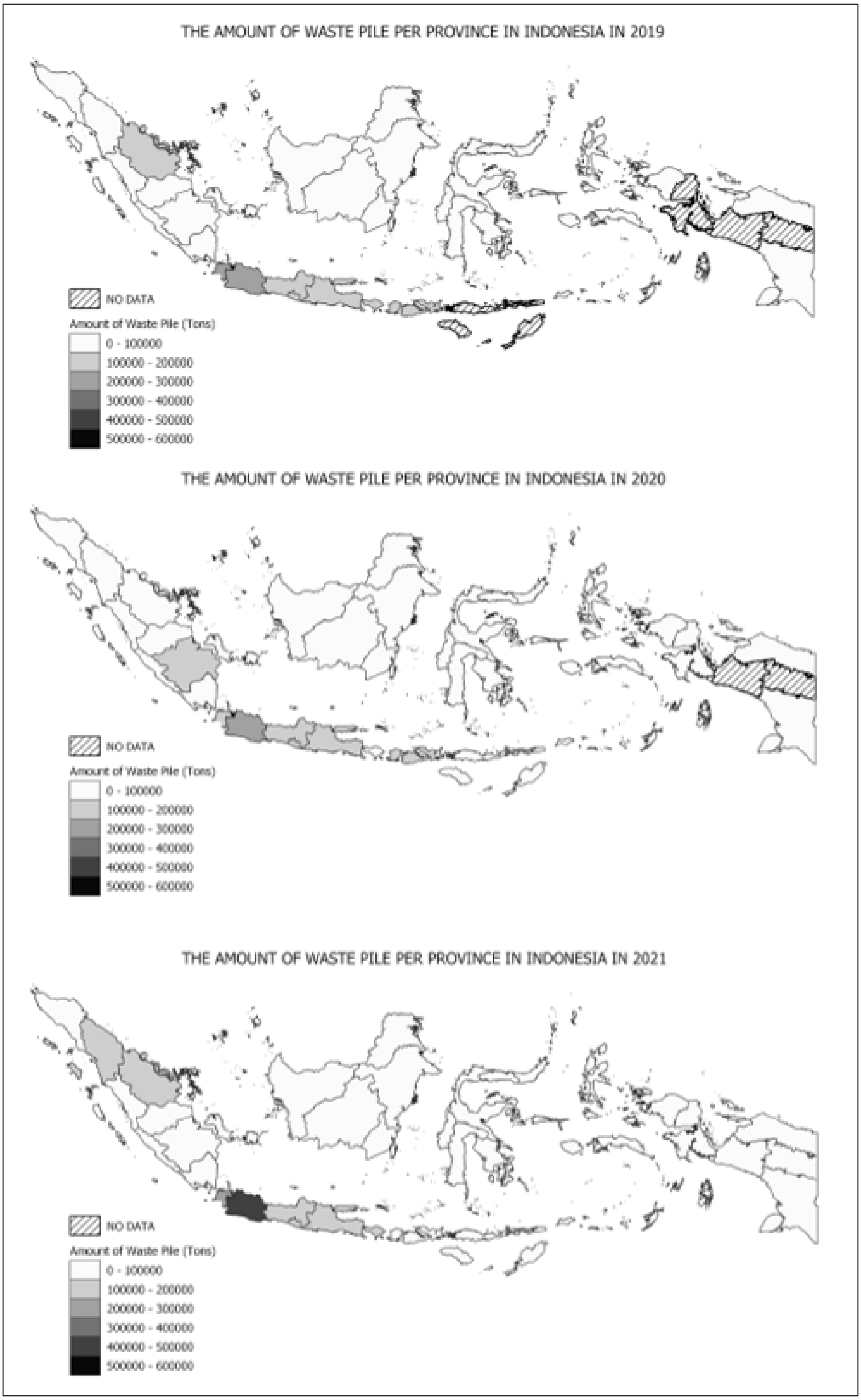

Figure 2. Trends in the Amount of Waste Pile Across Provinces in Indonesia Between 2019 and 2021

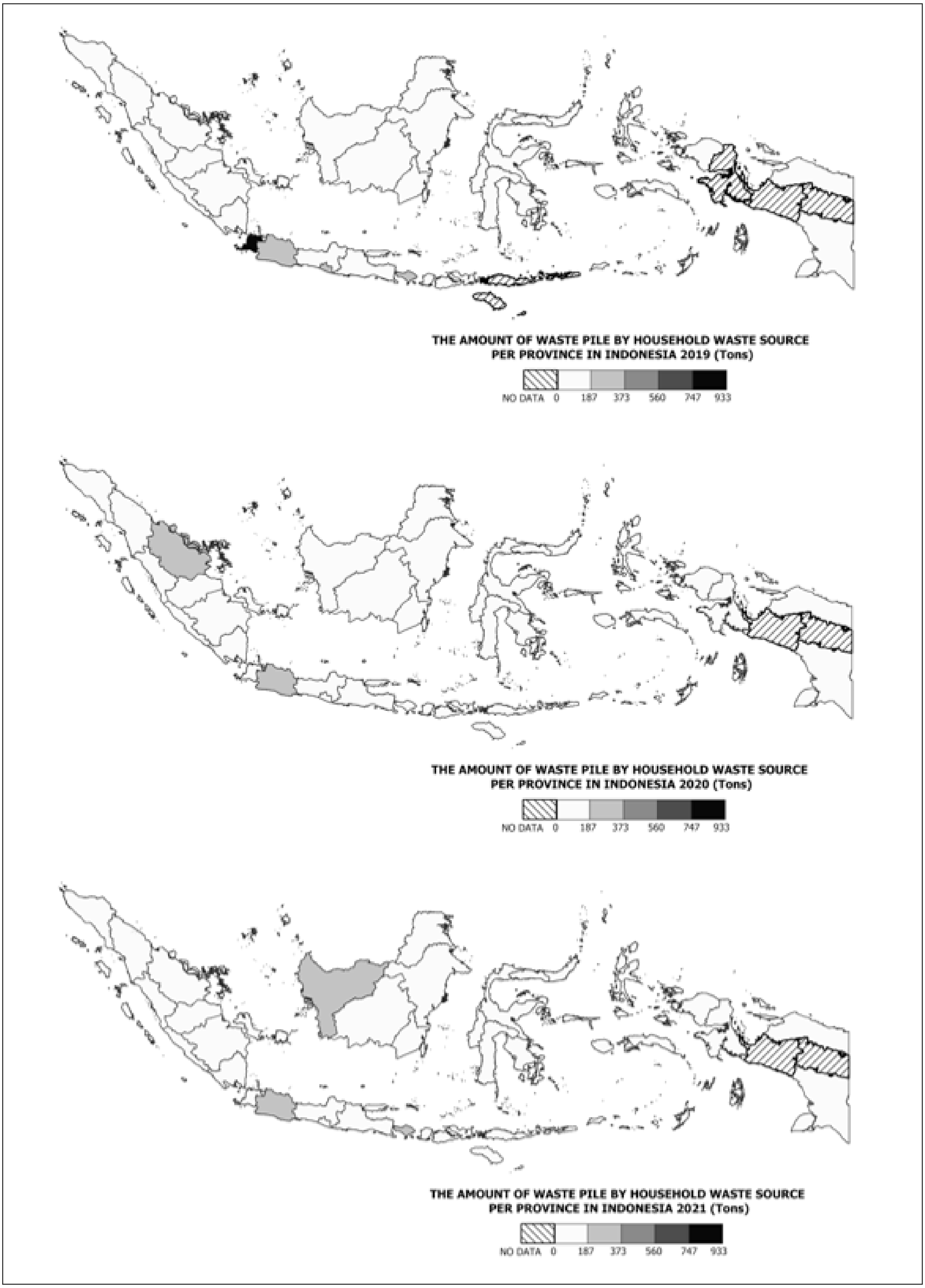

Figure 3 Trends in the Amount of Waste Pile by Household Waste Source Across Provinces in Indonesia Between 2019 and 2021

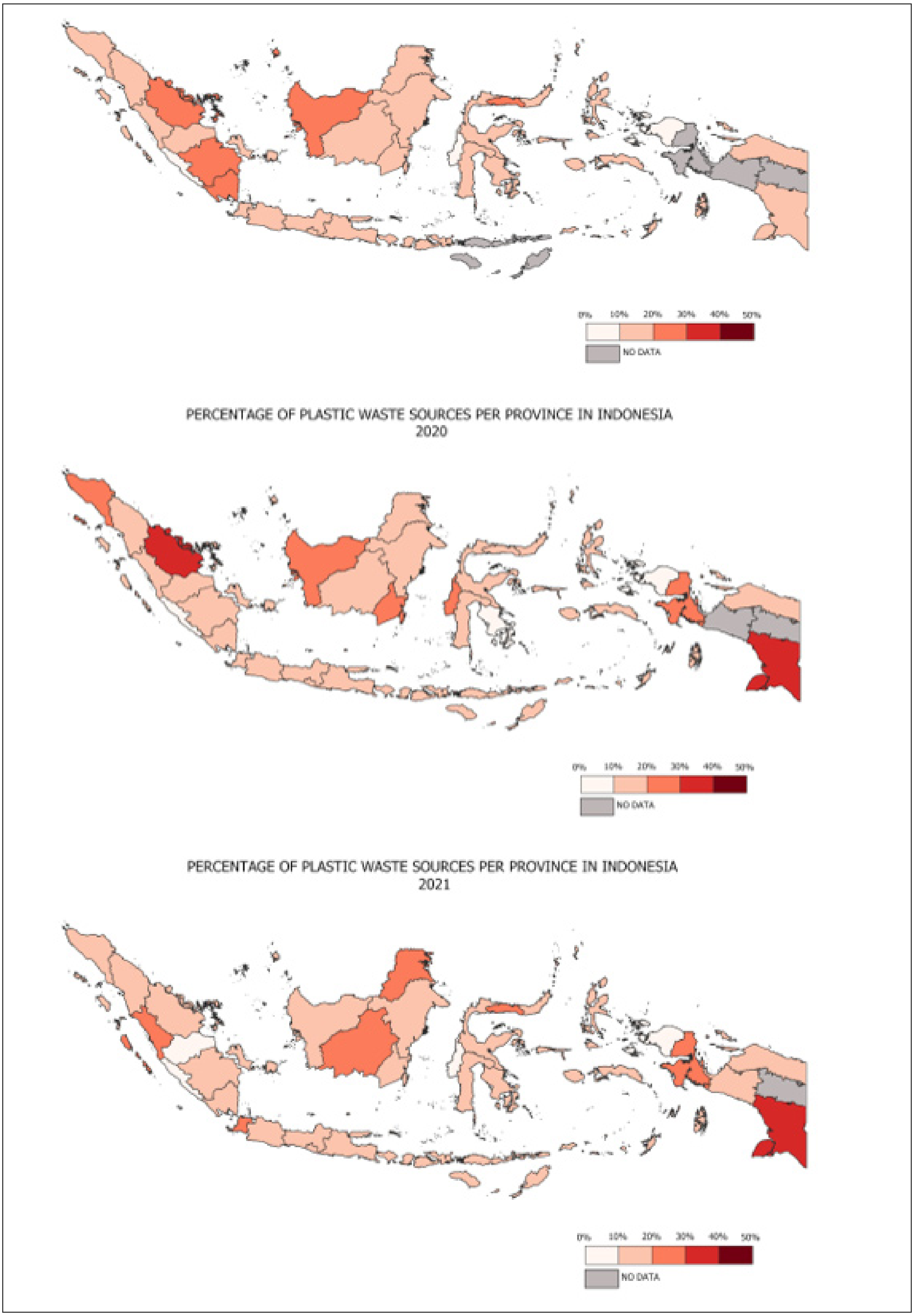

Figure 4. Percentages of Plastic Waste Source Across Provinces in Indonesia Between 2019 and 2021

Descriptive Data Analysis Results

Table 3. Descriptive Data Analysis Results

Indicator	Year	Average	Standard Deviation	Min	Max
Waste Piles	2019	84,057.54	106974.66	12,090.99	589,875.53
	2020	77,981.50	101014.69	10,010.27	595,322.83
	2021	85,974.89	103909.11	6,155.36	494,454.86
Plastic Waste	2019	15.04	5.95	0.00	26.00
	2020	16.89	8.02	0.00	40.00
	2021	16.06	7.66	0	40
Domestic Waste Source	2019	96.40	161.87	0.00	933.48
	2020	67.89	82.29	0.00	427.47
	2021	69.64	70.91	0	258.04
Waste Handling	2019	37.02	16.56	4.53	76.62
	2020	41.92	18.15	9.40	75.64
	2021	44.4	20.87	1.07	74.865

Waste piles in Indonesia fluctuated between 2019 and 2021. In 2020, a decrease of 6,076.04 metric tons in waste piles was observed, indicating a reduction in waste generated across various sectors of the country. However, in 2021, waste generation increased by 7,993.39 metric tons nationwide. Notably, plastic waste showed a decrease in 2021, and domestic waste generated by households also showed a downward trend. This problem was accompanied by improvements in waste management with achievements increasing over the years.

Determinant Factors of Carbon Efficiency in Indonesia Based on Domestic Waste Management

In panel regression analysis, various models were tested to determine the most appropriate model for prediction. The models tested included: (1) pooled; (2) fixed effects; and (3) random effects. Based on the comparison of these models, the Hausman test was conducted to identify the model that best fit the data for prediction.

Table 4. Panel Regression Analysis Results

Independent Variable	Sig Value of Pooled Model	Sig Value of Fixed Effects Model	Sig Value of Random Effects Model
Waste Pile	0.675	0.731	0.674
Plastic Waste	0.338	0.199	0.336
Domestic Waste Source	0.195	0.372	0.192
Waste Handling	0.101	0.011	0.099

The fixed effects model was selected because there was one significant prediction. This model serves as the basis for testing the actual data. The following table presents the results of the model comparison using the Haussmann test.

Table 5. Hausmann Test Results

Chi-Squared Value	df	p-Value
5.587	4	0.2322

Based on the results of the Hausman test, it was found that the significance value was more than alpha, indicating no difference between the models. However, since the fixed effects model had one significant variable, it was chosen for further analysis. The following stage involved testing the prediction model using the OLS approach.

Table 6. OLS Test Results

Dependent Variable	Estimate	p-Value
Intercept	1.732+03	0.000
Waste Piles	-9.553-05	0.675
Plastic Waste	-2.759+00	0.338
Domestic Waste Source	2.603-01	0.195
Waste Handling	-1.843+00	0.102

Based on the results of the prediction model test, no significant variables were observed, leading to the conclusion that none of the four variables (waste pile, plastic waste, household/domestic waste, and waste handling) had a significant impact on CO_2 emissions.

DISCUSSION

Carbon Emissions in Indonesia Based on CO_2 Status

Between 2019 and 2021, carbon emissions in Indonesia showed a downward trend. A 22.8% reduction in emissions was observed in 2020. Although carbon emissions increased slightly in 2021, they remained lower than those recorded in 2019. The COVID-19 pandemic in early 2020 brought significant changes in community activities (46–48), with a substantial reduction in various activities. While the pandemic resulted in numerous losses from a medical side and social perspective, it brought about environmental benefits. Previous studies have shown that, during the COVID-19 pandemic, environmental quality improved significantly (49–51). The reduction in human activities that generate carbon emissions undoubtedly contributed to the reduction in the amount of carbon emissions in the environment. The existence of a pandemic that requires people to stay at home, rest fossil fuel vehicles, and factory machines that produce carbon exhaust has greatly reduced carbon emissions in the air (28,52–53).

Domestic Waste Management in Indonesia

Based on the target of the Government of Indonesia as stated in the Presidential Regulation No. 97 of 2017 concerning the National Policy and Strategy (*Jaktranas*) for Household Waste Management and Household-like Waste, Indonesia aims to manage at least 70% of household waste and household-like waste by 2025 (54).

The number of provinces that achieved this target increased from 2019 to 2021, namely one province in 2019, three provinces in 2020, and five provinces in

2021. The five provinces were the Special Capital Region of Jakarta, Bali, East Kalimantan, South Kalimantan, and Gorontalo. In addition, 10 (26.3%) provinces achieved waste management rates of 60-80% in 2021. These provinces included Aceh, Riau, Banten, the Special Capital Region of Jakarta, Bali, North Kalimantan, East Kalimantan, South Kalimantan, Maluku, and West Papua. The government awarded the title of Adipura Regency/City to regions with good waste management performance at the source. Of the 58 regencies/cities that received the 2022 Adipura award, 18 (31%) were from the six aforementioned provinces. Furthermore, the Ministry of Environment and Forestry awarded the Adipura title to four regencies/cities with the best waste management performance, namely South Jakarta City (the Special Capital Region of Jakarta Province), Bandung City (West Java Province), Banyumas Regency (Central Java Province), and Klungkung Regency (Bali Province) (55).

The World Bank's "What a Waste 2.0" report projects that waste piles will increase annually, with a percentage increase of 28.8% every 10 years. However, Indonesia's waste generation per capita remains still below the global average of 0.74 kg/person/day. This is because Indonesia's status as a lower-middle-income country, as higher per capita income typically correlates with increased waste generation. Despite this, only a few provinces in Indonesia are able to manage 60-80% of their waste, as shown in Figure 1 above (56).

Based on the Regulation of the Minister of Environment and Forestry No. 6 of 2022 concerning the National Waste Management Information System, waste sources are categorized into even types: households, commercial areas, industrial areas, special areas, social facilities, public facilities, and other facilities (57). Banten Province recorded a significant amount of household waste in 2019, which drastically decreased in 2020 and 2021. One contributing factor was the series of earthquakes that occurred in 2019. These natural disasters not only caused fatalities but also led to an influx of volunteers assisting in disaster response, which significantly increased the amount of waste, especially household waste. In addition, the largest source of household waste over the years was West Java Province. This is because the province has the largest population in Indonesia (58).

The amount of plastic waste in Indonesia exceeds the global average by 12% (56). This plastic waste is a significant contributor to GHG emissions (CO_2), surpassing emissions from vehicles. It is estimated that CO_2 emissions from plastic waste are equivalent to those produced by 190 million vehicles in New York (59–60). Based on the map in Figure 4, two provinces, namely the Special Capital Region of Jakarta and Southwest Papua, produced the lowest plastic waste of 0-10% below the global average. The Special Capital Region of Jakarta is one of the provinces that has implemented a legal prohibition on the use of plastic bags for shopping, as stated in the Regulation of the Governor of the Special Capital Region of Jakarta Province No. 142 of 2019 concerning the Obligation to Use Environmentally Friendly Shopping Bags. Other provinces such as South Kalimantan and Bali have also implemented similar regulations (61), but their percentages of plastic waste remain above 10%. Factors such as education levels and income are key in reducing plastic use. Despite these efforts, plastic remains a staple everyday life due to its affordable price and strong durability, contributing to its high economic value in society. Of the three pioneering provinces that have made restrictions on the use of plastic, only the Special Capital Region of Jakarta has succeeded in reducing the composition of plastic waste to below 10%. Meanwhile, West Papua Province is one of the provinces with the lowest level of plastic waste sources. This is largely because the number of regencies and cities that have conducted data collection is limited, with only Raja Ampat being included in the dataset (62).

The amount of waste in Indonesia fluctuated between 2019 and 2021. In 2020, a decrease in waste generation occurred due to the COVID-19 pandemic. Restrictions on community activities imposed by government regulations resulted in a reduction in waste production across the country (63). However, in 2021, waste generation increased nationally. The total domestic waste data suggests that the source of the waste did not come from household activities. The increasing medical activities carried out in health facilities likely contributed to the increase in waste generation (64–65). Notably, plastic waste showed a decrease in 2021, indicating a growing public awareness of the need to reduce plastic consumption and replaced it with reusable alternatives (59–60). Fortunately, these problems have been met with improvements in waste management carried out by each region over the years. This includes efforts to reduce waste piles, sort waste by source and type, and handle waste according to its type (39).

Determinant Factors of Carbon Efficiency in Indonesia Based on Domestic Waste Management

Based on the fixed effects model prediction, it was found that the waste management variable had the potential to yield significant results, while other variables namely waste piles, plastic waste, and household/domestic waste, did not yield significant results. Even after conducting the Haussmann Test, not all variables demonstrated significant results. This does not imply that all efforts in handling domestic waste are ineffective in reducing carbon emissions, but suggests that issues with the data components may be influencing the results. As shown in Figures 1 to 4, there are instances of zero achievements or "no data" in waste management, indicating that not all provinces were able to provide the necessary data for the Ministry's website. Therefore, after the analysis, no significant results were obtained, which can be considered as a research limitation.

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AUTHOR CONTRIBUTIONS

AHZF: conceptualization, methodology, data collection, and writing-original draft. MI: validation and writing-reviewing. KUNEM: validation, writing-reviewing, and editing.

CONCLUSION

Waste management in the form of monitoring waste accumulation shows fluctuating results. Notably, there has been a decrease in plastic waste and domestic waste. Additionally, the waste management program has shown positive improvements. Therefore, carbon efficiency can achieved by handling and managing waste seriously. Routine reporting is essential to monitor the progress of the program's achievement.

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