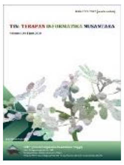

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A System Dynamics Model for Environmental Quality and Urban Quality of Life through Smart City Implementation

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Abstract−Smart city programs are increasingly adopted to enhance urban environmental performance through digital innovation and sustainable governance; however, solid waste accumulation and carbon dioxide (CO_2) emissions remain persistent challenges in rapidly expanding cities. This study evaluates the environmental impacts of smart city implementation in Surabaya by quantitatively examining waste stock dynamics and CO_2 emission behavior using a system dynamics approach. The analysis focuses on the environmental subsystem, particularly smart waste management and air emission control, which are modeled through a Causal Loop Diagram (CLD) and a Stock and Flow Diagram (SFD) to capture feedback mechanisms between waste generation, waste processing, stock accumulation, and emission growth. Simulation results for the 2020–2024 period show that the implementation scenario performs significantly better than the base model, achieving an average reduction of approximately 6–7% in waste stock and about 5% lower CO_2 emission levels by the end of the simulation horizon. These improvements are primarily driven by increased waste processing efficiency, which directly suppresses waste accumulation and indirectly slows emission growth. Nevertheless, the magnitude of environmental benefits is strongly influenced by technological readiness and the operational capacity of the environmental management system. Overall, the findings provide quantitative evidence that integrating waste management and emission control within smart city frameworks is essential for achieving measurable and sustainable improvements in urban environmental quality.

Keywords: Smart City; Environmental Quality; System Dynamics; Smart Waste Management; Urban Sustainability

1. INTRODUCTION

Smart City has been widely adopted as an urban development strategy to respond to increasingly complex environmental problems driven by rapid urbanization, population growth, and intensified economic activity. Urban areas are facing mounting pressures in the form of solid waste accumulation, air pollution, and inefficient resource use, which directly affect environmental quality and urban quality of life (Menajang et al., 2019). Conventional environmental management approaches, which are often sectoral and reactive, have proven inadequate in addressing these challenges due to their inability to cope with dynamic interactions, feedback effects, and long-term environmental accumulation processes. Consequently, the integration of information and communication technologies (ICT) into urban governance has been promoted to improve environmental performance through data-driven decision-making and sustainable management practices (Made & Mahayani, 2024).

Within the Smart City framework, the Smart Environment dimension plays a crucial role in enhancing urban sustainability by focusing on waste management efficiency, pollution control, energy use, and environmental monitoring. Prior studies suggest that smart waste management systems and digital-based environmental monitoring can reduce waste accumulation and pollution levels when supported by adequate infrastructure and institutional (Nunes et al., 2021). However, environmental outcomes are not solely determined by technological deployment. They are influenced by complex and interdependent factors, including population dynamics, behavioral patterns, policy effectiveness, technological readiness, and community participation, which interact over time and generate reinforcing and balancing feedback mechanisms within urban systems (Kartika Sari & Ibnu Rochim, 2025).

In the Indonesian context, Surabaya represents one of the most active metropolitan cities in implementing the Smart City concept. The enactment of the *Masterplan Smart City Kota Surabaya* in 2023 formalized the city's commitment to integrating digital solutions across governance, economic, social, and environmental dimensions. Initiatives such as smart waste management, digital environmental reporting, and community-based environmental programs demonstrate tangible efforts to improve urban environmental quality. Despite these developments and national recognition for public service innovation, empirical evaluations of how Smart City implementation quantitatively affects environmental quality particularly waste stock dynamics and CO_2 emissions remain limited. Most existing studies in Indonesia emphasize governance readiness, service efficiency, or descriptive assessments, while rigorous system-level environmental evaluations are still scarce (Daniswara et al., 2025).

Comparative reviews of previous research reveal that many studies assessing Smart City environmental initiatives rely on static indicators or linear analytical methods. These approaches typically assume independent and proportional relationships between variables, which limits their ability to represent feedback loops, time delays, accumulation effects, and nonlinear behavior inherent in urban environmental systems. In reality, waste generation and CO_2 emissions are dynamic processes that accumulate over time and are shaped by interrelated drivers such as population growth, transportation activity, waste processing capacity, and policy intervention effectiveness. As highlighted by (Liu et al., 2024), linear models are insufficient for capturing such complex system behavior, particularly when policy interventions generate delayed or indirect effects.

System dynamics offers a robust methodological alternative by enabling the modeling of complex systems through feedback structures and stock flow relationships. Previous applications of system dynamics in waste management and environmental studies have demonstrated its effectiveness in analyzing long-term policy impacts and identifying leverage points within environmental systems (Meiwanto Doktoralina et al., 2024). However, the application of system dynamics to evaluate integrated Smart City environmental strategies combining waste management and emission control within a single modeling framework remains limited, especially in the context of developing countries and Indonesian metropolitan cities. This gap indicates the need for research that explicitly links Smart City environmental interventions with dynamic waste and emission behavior using a quantitative, system-based approach.

Based on these considerations, this study aims to evaluate the environmental impact of Smart City implementation in the City of Surabaya using a system dynamics approach. The specific objectives of this research are: (1) to develop a system dynamics model that captures the interactions between population growth, waste generation, waste processing, waste stock accumulation, and CO_2 emissions; (2) to compare waste stock and emission behavior between a base model and Smart City implementation scenarios over the 2020–2024 period; and (3) to assess the effectiveness of integrated smart waste management and emission control strategies in reducing environmental pressure. The contribution of this study lies in providing quantitative, system-level evidence on how Smart City environmental initiatives influence urban environmental quality, thereby offering a decision-support tool for policymakers in designing more effective and sustainable Smart City environmental strategies.

Smart City is commonly understood as an urban development paradigm that integrates information and communication technologies (ICT) to enhance the efficiency of city management while improving citizens' quality of life. Beyond technological advancement, recent studies emphasize that Smart City initiatives must be aligned with sustainability principles, particularly environmental sustainability, to ensure long-term urban resilience (Oktarina et al., 2023).

The environmental dimension of Smart City, often referred to as *Smart Environment*, focuses on addressing urban ecological challenges such as waste management, pollution reduction, energy efficiency, and environmental monitoring. ICT-enabled solutions such as smart waste systems, sensor-based monitoring, and data-driven environmental policies are expected to support more efficient resource use and reduce environmental degradation. However, the effectiveness of these initiatives depends not only on technology but also on governance capacity and community participation (Neirotti et al., 2022).

Environmental quality is a critical determinant of urban quality of life, influencing public health, comfort, and overall well-being. Poor waste management, air pollution, and environmental degradation can significantly reduce livability in urban areas. Previous research indicates that improvements in environmental quality contribute positively to citizens' physical and psychological well-being, making environmental sustainability a central component of urban development strategies (Sharifabadi & Ziaeian, 2023).

Within the Smart City context, environmental quality is often measured through indicators such as waste processing efficiency, pollution levels, and environmental cleanliness. The integration of digital technologies is expected to enhance these indicators by enabling real-time monitoring, faster decision-making, and more targeted environmental interventions. Nevertheless, environmental outcomes are shaped by dynamic interactions between policy implementation, technological readiness, and public behavior, which require a holistic analytical perspective.

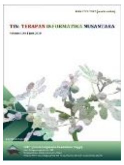
Smart waste management is one of the most prominent applications of Smart City initiatives in the environmental sector. It involves the use of digital technologies to optimize waste collection, processing, and disposal, aiming to reduce environmental impacts and operational inefficiencies. Studies have shown that smart waste systems can improve waste processing efficiency and reduce pollution when supported by adequate infrastructure and institutional capacity (Parmawati et al., 2023).

Community participation plays a crucial role in determining the success of smart environmental programs. Public awareness, behavioral change, and active involvement in waste separation and environmental programs significantly influence system performance. Without sufficient community engagement, technological solutions may fail to deliver sustainable environmental improvements (Artika & Chaerul, 2020). Therefore, environmental management in Smart Cities should be understood as a socio-technical system rather than a purely technological one.

System dynamics is a methodological approach designed to analyze complex systems characterized by feedback loops, nonlinearity, and time delays. It has been widely applied in environmental and urban studies to examine long-term policy impacts and dynamic interactions among system components (Zhang et al., 2025). In the context of Smart City environmental management, system dynamics allows researchers to capture the reciprocal relationships between technology adoption, environmental quality, and human behavior.

The modeling process typically begins with the development of a Causal Loop Diagram (CLD) to identify reinforcing and balancing feedback loops within the system. The CLD is then translated into a Stock and Flow Diagram (SFD), which enables quantitative simulation and scenario analysis. Through simulation, policymakers can explore how different environmental strategies influence system behavior over time and identify potential unintended consequences of policy interventions.

Based on the reviewed theories, this study conceptualizes Smart City environmental implementation as a dynamic system in which technological adoption, environmental management policies, and community participation interact to influence environmental quality and urban quality of life. Smart City initiatives are expected to improve



environmental performance through enhanced waste management efficiency and pollution reduction. However, these effects are mediated by feedback mechanisms that may either reinforce or limit long-term environmental benefits. By employing a system dynamics framework, this study aims to capture these interactions and provide a structured understanding of how Smart City environmental policies affect urban quality of life over time (Fakhriyat Noor et al., 2020). The proposed framework serves as the foundation for developing the causal loop and stock-flow models used in the analysis.

2. RESEARCH METHODOLOGY

This study employs a system dynamics approach to analyze the impact of Smart City environmental implementation on environmental quality and urban quality of life in the City of Surabaya. Similar system dynamics approaches have been applied in Indonesian cities to evaluate waste management performance (Artika & Chaerul, 2020; Labibah, 2025). The system dynamics method is selected due to its ability to represent complex feedback structures, accumulation processes, and time delays that characterize urban environmental systems, particularly in waste generation and emission dynamics.

The model development began with problem identification and system conceptualization based on environmental conditions in Surabaya. Rapid population growth influences the number of households and vehicles, which in turn increases household waste generation and vehicle emissions. These dynamics form the core structure of the model, where environmental pressure accumulates through waste stock (Stok Sampah) and air emission stock (Emisi Udara)**.** The system boundary focuses on waste generation, waste processing, emission generation, and emission reduction mechanisms, while external macro-level factors are treated as exogenous variables.

A Causal Loop Diagram (CLD) was first developed to identify causal relationships and feedback mechanisms among key variables. The CLD highlights reinforcing loops related to population growth, waste generation, and emission accumulation, as well as balancing loops associated with waste processing and emission reduction policies. These feedback structures were then translated into a Stock and Flow Diagram (SFD) to enable quantitative simulation. In the SFD, *Stok Sampah* accumulates waste from household sources and other waste contributors through the inflow *Sampah Masuk*, while waste is reduced through the outflow *Pengolahan Sampah*. Similarly, *Emisi Udara* accumulates emissions from vehicle activities, waste processing, and other emission sources through *Penambahan Emisi*, and is reduced through *Pengurangan Emisi*.

Table 1 presents the mathematical formulation of the environmental sub-model implemented in Vensim PLE. Stock variables are represented using integral functions, while flow variables determine the rate of accumulation and reduction of waste and air emissions. Policy interventions related to Smart City initiatives are incorporated through variables affecting waste processing and emission reduction rates.

Table 1. Mathematical Equations for the Environmental SFD Sub-Model (Waste and Emissions)

Variabel	Model Equation in Vensim PLE
Stok Sampah (ton)	INTEG (Sampah Masuk - Pengolahan Sampah, 8464000)
Sampah Masuk (ton/year)	(Total Sampah Rumah Tangga + Total sumber sampah lainnya)*Persentase Sampah Masuk TPA
Pengolahan Sampah (ton/year)	IF THEN ELSE(Stok > 0, Pengolahan Sampah lainnya + Smart City untuk Pengolahan Sampah,0)
Emisi Udara (CO2)	INTEG (Penambahan Emisi - Pengurangan Emisi, 16650000)
Penambahan Emisi (ton CO2/year)	Emisi dari Pengolahan Sampah + Emisi dari sumber lainnya + Total Emisi Kendaraan
Pengurangan Emisi	Emisi Udara * (Pengurangan Emisi Lainnya + Smart City Untuk Pengurangan Emisi)

The model formulation involved defining mathematical relationships among variables using linear and nonlinear functions to represent real-world behavior. Parameters such as average household waste generation, waste processing efficiency, vehicle emission rates, and emission reduction effectiveness were determined based on secondary data and literature-supported assumptions. The simulation was conducted using Vensim to observe system behavior over a defined simulation period.

Model verification was carried out to ensure that the model structure was logically consistent and free from computational errors, including dimensional consistency checks and successful model execution. Validation was performed by examining whether the simulated behavior of waste stock and emission stock followed realistic trends observed in Surabaya's environmental conditions, ensuring that the model adequately represents the real system dynamics.

Model parameters were obtained from secondary data sources, including reports from the Surabaya City Environmental Agency (DLH Kota Surabaya), Statistics Indonesia (BPS), and national environmental studies. Average household waste generation rates were derived from DLH Surabaya annual waste reports, while vehicle emission parameters were based on emission factors published by the Ministry of Environment and Forestry (KLHK) and previous empirical studies. Additional assumptions were adopted from system dynamics-based waste management literature to ensure model consistency.

Scenario analysis was integrated directly into the model through two policy intervention variables embedded in the SFD. The first scenario, Smart Waste 2.0, represents the implementation of digital-based waste management systems, including smart waste processing, digital environmental reporting, and community-supported waste programs. In the model, Smart Waste 2.0 directly influences the *Pengolahan Sampah* flow, increasing waste processing efficiency and indirectly reducing emissions originating from waste treatment activities.

The second scenario, Smart Carbon Monitoring, represents Smart City initiatives focused on emission control through real-time air quality monitoring and data-driven emission reduction policies. This scenario affects the *Pengurangan Emisi*flow by strengthening emission reduction mechanisms supported by AQMS, Smart PJU LED, RTH berbasis GIS, and PLTSa Benowo. Smart Carbon Monitoring enables faster detection of emission sources and improves the effectiveness of emission mitigation actions.

Both scenarios were simulated independently to evaluate their respective impacts on waste accumulation and emission dynamics. The simulation results provide a basis for comparing the effectiveness of Smart Waste 2.0 and Smart Carbon Monitoring in improving environmental quality and supporting urban quality of life in Surabaya.

3. RESULT AND DISCUSSION

This section presents the outcomes of the system dynamics modeling conducted in this study. It explains the results obtained from the development of the Causal Loop Diagram (CLD) and Stock and Flow Diagram (SFD), followed by model verification and validation processes. The results section also describes how the constructed model behaves under the defined simulation settings and provides the basis for subsequent analysis of policy interventions. Each stage of the modeling results is discussed in the following subsections.

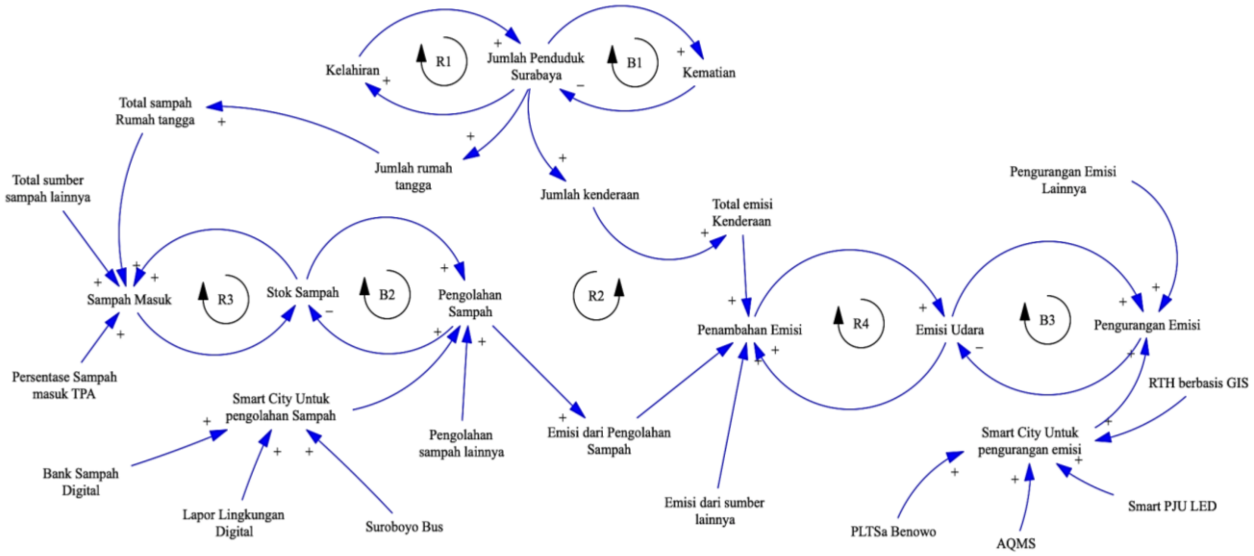


Figure 1. Causal Loop Diagram

Figure 1 illustrates the Causal Loop Diagram (CLD) that represents the dynamic interactions among population growth, waste generation, waste management, and air emission control within the urban system of Surabaya. Population dynamics are captured through reinforcing and balancing loops, where birth rates increase the total population and death rates moderate its growth, subsequently influencing the number of households and vehicles. An increase in households and other urban activities leads to higher waste inflows, which contribute to waste stock accumulation. This accumulation forms a reinforcing loop that intensifies environmental pressure when waste processing capacity is insufficient. Balancing mechanisms are introduced through waste treatment activities supported by Smart City initiatives, such as digital waste banks, environmental reporting systems, and improved waste processing technologies, which reduce waste stock over time. On the emission side, population growth and vehicle use increase emission inflows from transportation, waste processing, and other urban sources, reinforcing the growth of air emission stock. Emission reduction is controlled through balancing loops enabled by Smart City–based interventions, including PLTSa Benowo, real-time air quality monitoring systems (AQMS), smart public lighting (PJU LED), and GIS-based green open space development. Overall, the CLD demonstrates how environmental conditions emerge from the interaction between reinforcing pressures and balancing policy interventions, highlighting Smart City strategies as critical leverage points for improving urban environmental quality and sustainability.

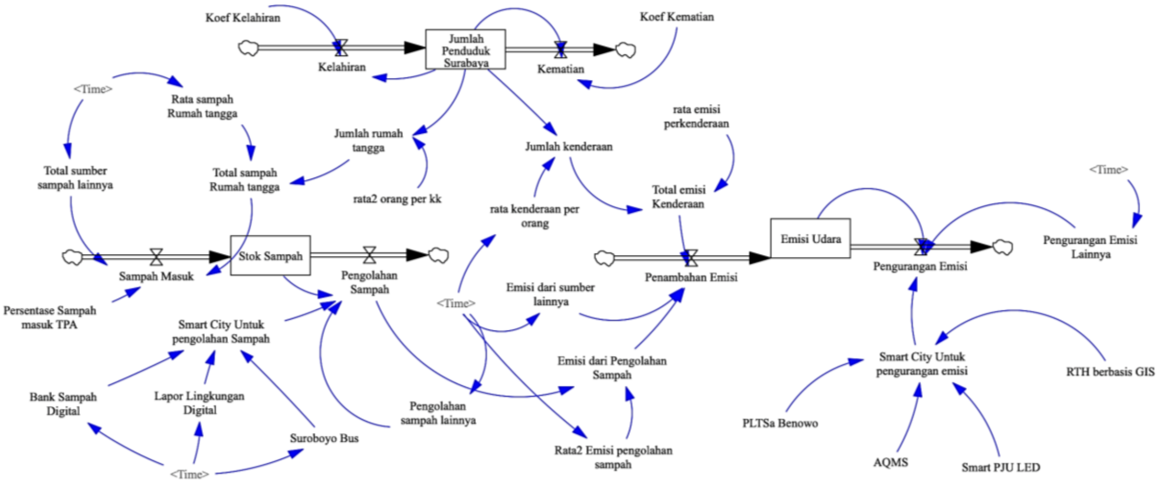
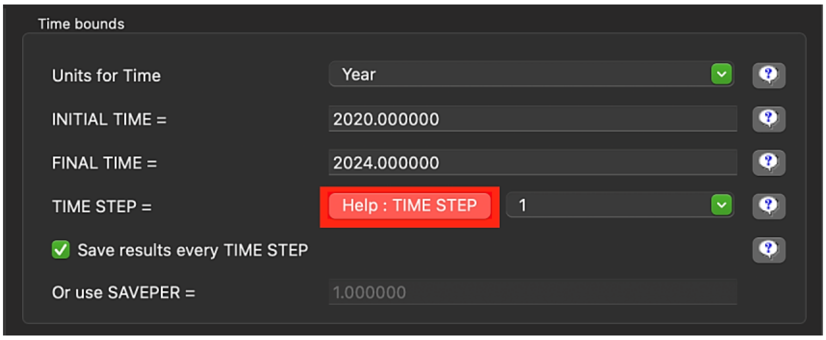


Figure 2. Stock Flow Diagram

The Causal Loop Diagram illustrates the dynamic relationships among population growth, waste generation, waste processing, and emission dynamics in the City of Surabaya. An increase in population leads to higher household numbers and vehicle usage, which subsequently increases waste generation and air emissions. These processes form reinforcing mechanisms that intensify environmental pressure over time (Pramesti et al., 2020). Waste accumulation is controlled through waste processing activities supported by Smart City-based waste management, while emission accumulation is mitigated through emission reduction mechanisms enabled by Smart Carbon Monitoring and other Smart City environmental initiatives (Neirotti et al., 2022). The diagram highlights that environmental conditions are determined by the interaction between reinforcing pressures and balancing interventions, emphasizing the role of Smart City strategies as leverage points in improving environmental quality.


Time bounds

Units for Time: Year

INITIAL TIME = 2020.000000

FINAL TIME = 2024.000000

TIME STEP = 1

☑ Save results every TIME STEP

Or use SAVEPER = 1.000000

Figure 3. Simulation Time Setting

The model simulation was conducted using a yearly time unit, with an initial time set at 2020 and a final time at 2024. A time step of one year was applied to capture gradual changes in waste accumulation and emission dynamics over the simulation period. This time horizon was selected to reflect medium-term environmental trends and to observe the dynamic effects of Smart City environmental interventions on waste stock and air emissions over time. After defining the simulation settings, the model was executed by clicking the Run button on the Vensim toolbar, as shown in Fig. 3, to generate dynamic simulation outputs for all stock and flow variables.

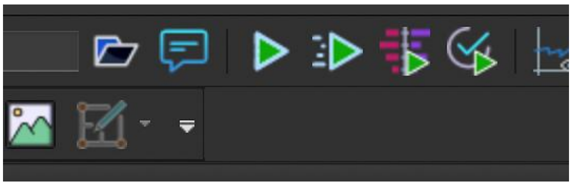
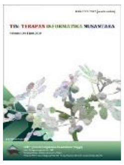


Figure 4. Simulation Run Interface

Table 2. Validation of Waste Stock Using MAPE

No	Aktual	Simulasi	Error	Nilai Absolut Error	Nilai Absolut Error Bagi Nilai Aktual
	A	**S**	**A-S**	**|A-S|**	**|(A-S)/A|**
1	8.464.000	8.464.000	0,0	0	0,000
2	8.442.000	8.458.210	-16210,0	16210	0,002
3	8.410.000	8.466.080	-56080,0	56080	0,007



No	Aktual	Simulasi	Error	Nilai Absolut Error	Nilai Absolut Error Bagi Nilai Aktual
	A	**S**	**A-S**	**|A-S|**	**|(A-S)/A|**
4	8.370.000	8.433.600	-63600,0	63600	0,008
5	8.325.000	8.393.460	-68460,0	68640	0,008
				Total	0,02
				MAPE	0,49

The accuracy of the simulation model for waste stock was evaluated using the Mean Absolute Percentage Error (MAPE) by comparing simulated values with actual waste data. The results show that the total absolute percentage error is low, resulting in a MAPE value of 0.49%**,** which is well below the commonly accepted threshold of 10%. This indicates that the simulation model closely represents actual waste dynamics and demonstrates a high level of accuracy in capturing waste accumulation behavior over the observed period. Therefore, the waste stock model is considered valid and suitable for further scenario analysis.

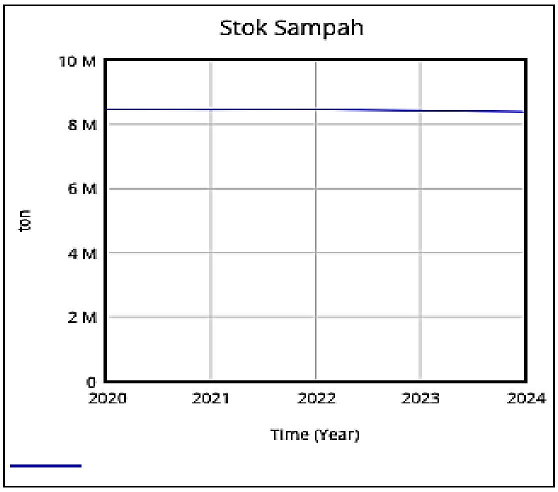
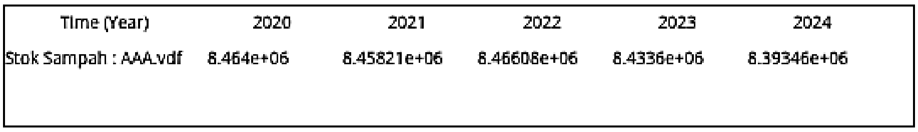


Figure 5. Validation Chart



Time (Year)	2020	2021	2022	2023	2024
Stok Sampah : AAA.vdf	8.464e+06	8.45821e+06	8.46608e+06	8.4336e+06	8.39346e+06

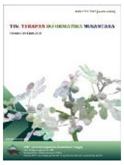
Figure 6. Validation Table

The validation results of the waste stock simulation are presented in Fig. 5 and Fig. 6. The validation chart shows that the simulated waste stock follows a trend similar to the actual data over the observed period, indicating consistent model behavior. The validation table further confirms this result through quantitative comparison between actual and simulated values. The low error magnitude, as indicated by the MAPE value, demonstrates that the model accurately represents waste stock dynamics and is suitable for subsequent scenario analysis (Gul-E-Hina & Haydar, 2023).

Table 2. Validation of CO2 Emission Model Using MAPE

No	Aktual	Simulasi	Error	Nilai Absolut Error	Nilai Absolut Error Bagi Nilai Aktual
	A	S	A-S	|A-S|	|(A-S)/A|
1	16.650.000	16.650.000	0,0	0	0,000
2	16.800.000	16.827.000	-27000,0	27000	0,002
3	17.000.000	17.029.000	-29000,0	29000	0,002
4	17.250.000	17.264.800	-14800,0	14800	0,001
5	17.450.000	17.587.600	-14800,0	14800	0,008
				Total	0,01
				MAPE	0,24

The validation results presented in Table 2 show a close agreement between actual and simulated CO_2 emission values for the period 2020–2024. Although minor differences are observed, the relative error remains very small, as indicated by the MAPE value of 0.24%. This low error level demonstrates that the simulation model is able to accurately represent the emission dynamics of the system. Therefore, the model is considered valid and reliable for further scenario analysis related to Smart City-based emission reduction strategies.



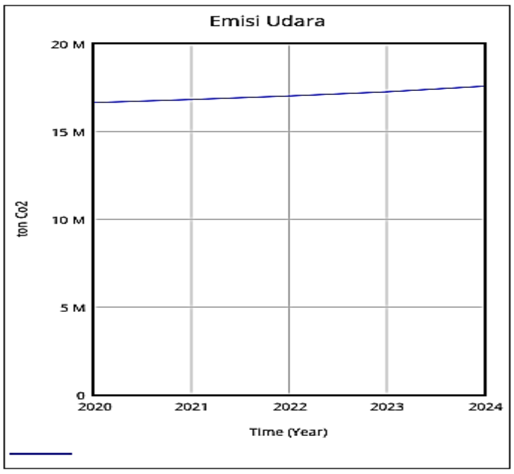
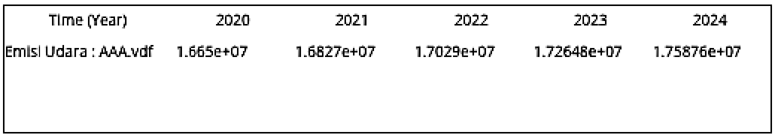


Figure 7. CO_2 Emission Validation Chart



Time (Year)	2020	2021	2022	2023	2024
Emisi Udara : AAA.vdf	1.665e+07	1.6827e+07	1.7029e+07	1.72648e+07	1.75876e+07

Figure 8. CO_2 emission validation results

The simulation results of the base model illustrate the behavior of CO_2 emissions under existing environmental conditions without additional policy interventions. Based on the simulation output, CO_2 emissions increase gradually from approximately 16.6 million units in 2020 to around 17.6 million units in 2024. This increasing trend reflects the influence of population growth and rising urban activities on air emission levels. The relatively stable growth pattern indicates that, under current conditions, emission levels continue to rise over time, highlighting the persistence of environmental pressure in the absence of stronger emission control measures (Sapanli et al., 2023). These results provide a reference point for evaluating the effectiveness of future policy scenarios.

3.1 Scenario Result Analysis

At this stage, a comparative analysis of the developed scenarios is presented to evaluate their effects on system behavior under the same simulation period. Unlike projection-based scenarios that extend the simulation horizon, the scenarios in this study are analyzed within the existing time frame of 2020–2024. This approach allows a direct comparison between the base model and the implemented scenarios by isolating the impact of policy interventions without introducing additional temporal uncertainty. To better reflect real-world conditions, the model incorporates additional variables related to waste sources and air emission processes. The results highlight differences in waste and emission dynamics attributable to scenario assumptions rather than changes in the simulation period.

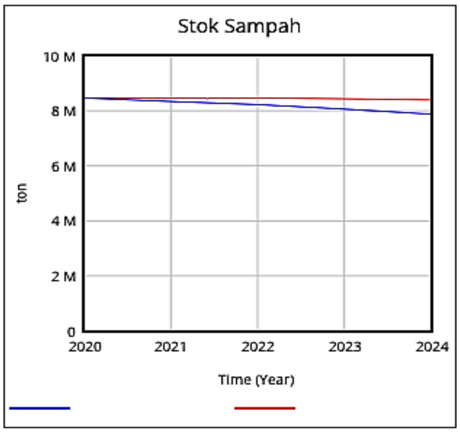
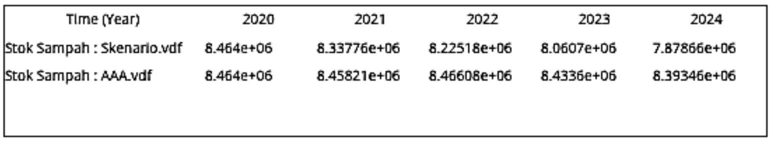


Figure 9. Waste Stock Under Base Model and Scenario



Time (Year)	2020	2021	2022	2023	2024
Stok Sampah : Skenario.vdf	8.464e+06	8.33776e+06	8.22518e+06	8.0607e+06	7.87866e+06
Stok Sampah : AAA.vdf	8.464e+06	8.45821e+06	8.46608e+06	8.4336e+06	8.39346e+06

Figure 10. Waste Stock Data for Base Model and Scenario

Figures 9 and 10 present a comparison of waste stock values between the implementation scenario (blue) and the base model (red) for the period 2020–2024, shown respectively in graphical and numerical forms. Both models begin with the same initial waste stock of 8.464.000 tons in 2020. Under the implementation scenario, waste stock decreases steadily from 8.337.760 tons in 2021 to 7.878.660 tons in 2024, indicating a more effective reduction trend. In contrast, the base model exhibits a slower decline, with waste stock values decreasing from 8.458.210 tons in 2021 to 8.393.460 tons in 2024. The consistent gap between the two models observed in both the chart and the numerical data confirms that the implementation scenario achieves lower waste stock levels over time, demonstrating the positive impact of enhanced waste management interventions in reducing waste accumulation.

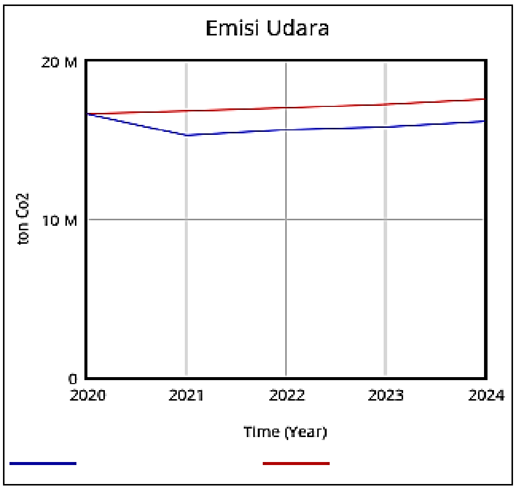
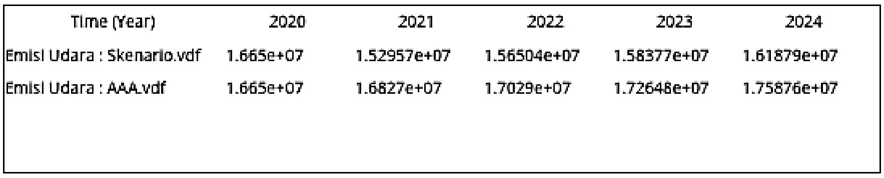


Figure 11. CO₂ Emission Under Base Model and Scenario



Time (Year)	2020	2021	2022	2023	2024
Emisi Udara : Skenario.vdf	1.665e+07	1.52957e+07	1.56504e+07	1.58377e+07	1.61879e+07
Emisi Udara : AAA.vdf	1.665e+07	1.6827e+07	1.7029e+07	1.72648e+07	1.75876e+07

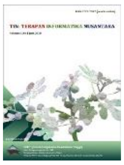
Figure 12. CO₂ Emission Data for Base Model and Scenario

Figures 11 and 12 present a comparison of CO₂ emission levels between the implementation scenario (blue) and the base model (red) for the period 2020–2024, shown respectively in graphical and numerical forms. Both models start from similar emission levels in 2020. Under the implementation scenario, CO₂ emissions remain consistently lower than those of the base model throughout the simulation period. In contrast, the base model exhibits higher emission values and a more pronounced increasing trend over time. The consistent gap between the two curves observed in both the chart and the numerical data indicates that the implementation scenario is more effective in controlling emission growth. This result demonstrates that improvements in waste management and emission-related interventions contribute to reducing air emission levels compared to existing conditions.

Although the simulation period in this study is limited to 2020–2024 due to data availability, the system dynamics structure allows extension to longer horizons. The feedback mechanisms embedded in the model indicate that sustained implementation of Smart Waste 2.0 and Smart Carbon Monitoring could generate compounding environmental benefits over longer periods, such as 2030 or 2045. In particular, reinforcing feedback between improved waste processing efficiency and emission reduction mechanisms suggests that long-term environmental improvements may be more pronounced than those observed within the current simulation period (Aromi et al., 2024).

4. CONCLUSION

This research confirms that a system dynamics framework is effective for explaining the complex interactions among population growth, waste generation, waste processing, and urban air emissions, as evidenced by the model's strong validation performance and low error values. Simulation outcomes show that the Smart City implementation scenario consistently yields better environmental performance than existing conditions during the 2020–2024 period, reflected in lower waste accumulation and slower growth of CO₂ emissions. These results indicate that coordinated improvements in waste processing efficiency and emission control measures are capable of reducing environmental pressure in urban systems. Policy implications derived from the model emphasize the strategic importance of prioritizing advanced waste processing technologies, expanding PLTSa Benowo capacity, strengthening vehicle emission controls, deploying real-time air quality monitoring in high-traffic areas, and reinforcing community-based waste segregation to enhance the effectiveness of Smart Waste 2.0. Although the model provides robust insights, its reliance on aggregated, non-spatial



data limits the ability to capture intra-urban variations, suggesting that future studies should integrate GIS-based spatial analysis, disaggregate emission sources, extend simulation horizons, and incorporate real-time monitoring data to improve precision and support more targeted, long-term urban environmental decision-making.

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