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# System Dynamics-Based Policy Design for Circular Economy: Achieving Sustainability Under SDG 12

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Circular Economy; System Dynamics; SDGS 12; Waste Management; Public Health

***ABSTRACT***
*The purpose of this study is to assess the impact of circular economy waste management implementation in Indonesia on environmental quality, public health, and long-term economic growth, as well as to provide policy options based on SDG 12. The System Dynamics technique involved modelling four subsystems: population, waste management, environmental contamination, and public health. Secondary data were gathered from SIPSN, BPS, and relevant literature and analysed using the Causal Loop Diagram (CLD), Stock Flow Diagram (SFD), and Mean Absolute Percentage Error (MAPE) accuracy validation. According to the simulation results, increasing the implementation of the 3R concept (Reduce, Reuse, Recycle) by 20% over 20 years (2011-2030) could reduce managed waste generation by 6.38 million tonnes per year, increase the GDP contribution of the waste management sector by 261.6%, and reduce air (62.04 Mg/L) and water (38.86 Mg/L) pollution. Furthermore, ARI and diarrhoea cases dropped by 74.8%. Model validation yielded a relatively low error rate (MAPE 2.39-14.44%), showing the model's dependability as a policy planning tool. The study's findings emphasise the significance of improving infrastructure (waste bank, MRF), integrating digital technologies, fostering multisector collaboration, and providing continual education. The findings lead to the creation of a system dynamics-based policy model for achieving SDG 12 through an inclusive circular economy strategy.*

## INTRODUCTION

Global waste generation has increased from year to year. In 2018, the amount of waste generated was 2.01 billion tons; it is projected that in 2050, global waste generation will reach 3.4 billion tons/year

(The World Bank, 2021). Waste for developed countries is a crucial part to be handled; correct waste handling will provide benefits for the community and the waste management and recycling industry. However, for developing countries, waste management and environmental impacts have not been fully controlled properly, especially waste sourced from households (Sassanelli et al., 2020).

The cause of the global waste crisis is due to inefficient production, wasteful production and the lack of recycling of products that can be produced. Public consumption patterns also affect the generation of waste produced, especially in the form of the use of disposable products and excessive packaging, which can cause environmental pollution and a decrease in the quality of public health (Wilson et al., 2015). The dominant waste generation is household waste and plastic waste. The generation of plastic waste globally began in the 1950s, and in 2014, reached 8.3 billion tons, 2 billion tons are still recyclable, and the rest is sent to final disposal and pollutes the environment, including the ocean. Plastic waste is a top priority that must be recovered because it will have an impact on chemical pollution produced by inorganic plastic waste (Economist, 2021). There needs to be an appropriate strategy in waste management, both household waste and factory waste, applied by each country, especially the development of appropriate indicators is needed in monitoring waste management (Zhao, 2021).

The current occurrence of climate change is one of the impacts of less controlled waste management that has an impact on the decline of environmental quality and public health. The circular economy model is one of the concepts that is expected to mitigate and eliminate (zero/minimum waste) the negative impact of externalities. This economic concept aims to maintain product value and can be regenerated (Ogunmakinde, 2019). The three important things in this economic model are related to the potential of a new sustainable economy, innovative recyclable product and environmental resistance from waste (Andrews, 2015). The concept of circular economy is a concept of the development of the concept Sustainable Development, contained in the Sustainable Development Goals *(SDGs)* 12th is the goal of sustainable consumption and production in waste management (Banaite & Tamošiuniene, 2016).

Waste management needs to be managed correctly and organised, starting from the micro level, namely community awareness, which is carried out continuously, because if it is not done in the long term, it will result in public health disturbances, especially for densely populated communities (Guzzo et al., 2022). Based on the IPKM (Public Health Development Index), waste management is expected to be an instrument in monitoring and a comprehensive evaluation of the success of national health development, along with information on the negative impacts resulting from waste pollution (Kemenkes RI, 2018). The application of the circular economy concept with indicators of per capita waste generation, waste recycling rate, packaging waste recycling rate by type of packaging, organic waste recycling rate, and e-waste recycling rate can inclusively increase economic growth and GDP while reducing the exploitation of natural resources and ensuring greater environmental protection (Grdic et al., 2020). This aims to reduce the impact of waste on public health, which can potentially cause diseases such as ISPA (Acute Respiratory Tract Infection), early childhood cancer and leukaemia (Nwogwugwu & Ishola, 2019). How the community manages waste is a determining factor in public health and can reduce the potential for the proliferation of infectious disease sources caused by waste (Jerumeh, 2020).

This research is designed to explore the influence, elements, and linkages of the circular economy of waste management on environmental quality and public health in Indonesia in the SDGs pillar. Based on the background that has been described. The main contribution expected from this study is a deeper understanding of the urgency of the concept of circular economy in the context of waste management in Indonesia, which is reviewed from various perspectives, including the government, the business sector, academia, and environmental organisations. Furthermore, this study aims to show the potential application of a circular economy model in waste management to improve sustainable economic growth, environmental quality, and public health inclusively at the national level.

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# METHOD

The System Dynamics (SysDyn) method is a system analysis consisting of several sub-systems in society (real world), which is described as a set of elements that interact with each other. This method is a modelling method whose use is closely related to the question of the dynamics of several tendencies in complex systems. In the analysis of the SysDyn method, it is assisted by using the Powersim software, which helps to visualise the model created in the form of a Causal Loop Diagram (CLD) and Stock Flow Diagram (SFD). The population determined was the condition of waste in Indonesia with variable parameters in 4 (four) sub-models, namely (1) A population sub-model consisting of population variables, births and deaths; (2) Waste Management Sub Model which consists of waste volume, waste generation, managed waste and unmanaged waste; (3) The sub model of pollution consists of water pollution, water pollution control, water pollution load, air pollution, air pollution control and air pollution load; and (4) The sub-model of public health is the population infected with diseases (ISPA and diarrhea) and the decrease in the number of people infected with diseases (ISPA and diarrhea). Variables in the built sub-sub-model were also used to forecast as a basis for creating strategic scenarios. The data consisted of secondary data from SIPSN (National Waste Management Information System), BPS, and national and international journal articles. The data analysis used in calculating forecasting was carried out using the MAPE (Mean Absolute Precent Error) technique which is used to determine the level of forecasting accuracy in determining policy scenarios with stages, namely calculating Mean Absolute Deviation (MAD), Mean Square Error (MSE) and Mean Absolute Precent Error (MAPE) as the last stage with the requirements in Table 1 and Table 2.

Table 1
Mean Absolute Percent Error (MAPE) *Assessment Criteria*

| **MAPE Values** | **Criterion** |
|---|---|
| < 10% | Excellent |
| 10-20% | Good |
| 20-50% | Enough |
| >50% | Bad |

Table 2
MAD, MSE and MAPE Forecasting Accuracy Methods

| **No.** | **Method** | **Type** |
|---|---|---|
| 1 | Mean Absolute Deviation (MAD) | $\frac{1}{n}\sum_{i=1}^{n}[At - Ft]$ |
| 2 | Mean Square Error (MSE) | $\frac{1}{n}\sum_{i=1}^{n}[At - Ft]^2$ |
| 3 | Mean Absolute Percent Error (MAPE) | $\sum_{t=1}^{n}\frac{\lvert At - Ft\rvert}{At}\ x\ 100\%$ |

Where: *At* = actual value on data t; *Ft* = Predictive value b on data t; *n* = number of data periods

The model created is the result of a representation of the real world in the form of an object with a simplified process. Key assumptions in the paradigm SysDyn are the persistent density dynamics of

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any complex system, and are derived from the causal structure that makes up a system (Forrester, 2009). The process in the preparation of the model by the SysDyn is illustrated in Fig. 1.

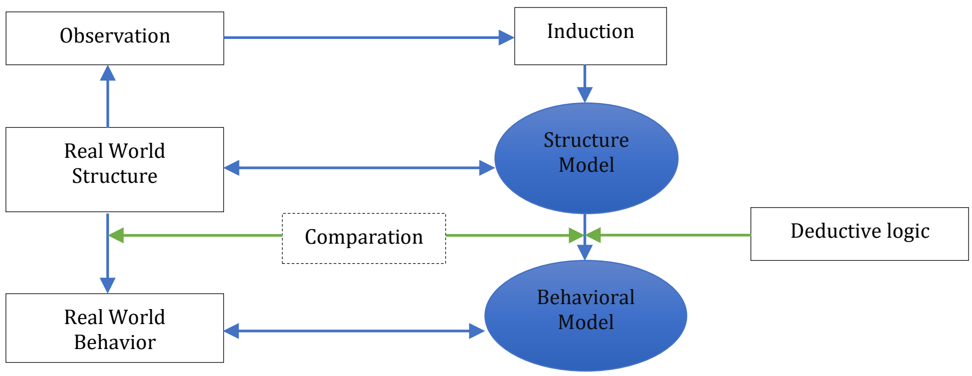


***Fig. 1*** *The process stages of the System Dynamics method by Saeed (1986)*

The visualisation method in the form of CLD can describe the qualitative variables in the approach of System Thinking, which can explain interdepartmental relationships in various situations and is effective for knowing mental models that show cause-and-effect relationships. The model is marked with a (+) sign, which means reinforcing (R), i.e. mutually reinforcing/weakening, and the sign (-) is balancing (B), which means that the relationship that provides balance is mutually balanced, that is, if condition A increases, it will cause condition B to decrease (Vennix, 1999). The Stock Flow Diagram (SFD) *is* useful to enable quantitative analysis of numerical data in understanding and estimating/predicting system behaviour over time.

## RESULTS AND DISCUSSION

An analytical study of waste management policies in Indonesia using *the SysDyn* model aims to understand the interaction between waste management, environmental quality and public health to represent aspects of the SDGs. The model is simplified into three sub-models: population, circular economy waste management, and air, water, and public health pollution. The relationship between the sub-models is visualised in Fig. 2.

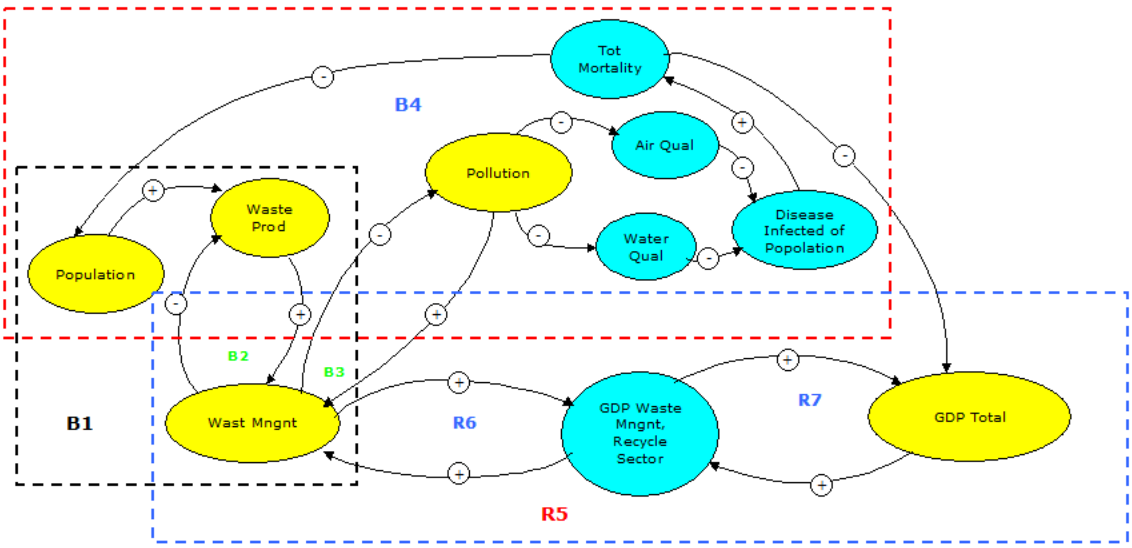


***Fig. 2*** *Causal Loop Diagram of the affinity between sub-models*

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Fig. 2 can explain the mutual and interrelated relationship between sub-models that form a large model of the Circular Economy in waste management in Table 3.

Table 3
Explanation of the Feedback Diagram Between Sub Model

| CLD | Information |
|---|---|
| **Loop B1** (Loop B1; Loop B1.1; Loop B1.2; Loop R3) – Balancing (-) | Describe the relationship between the waste management sub-model and the population in Indonesia. In the loop, it is described that an increase in the population has the potential to increase the generation of waste produced; the generation of managed waste has a positive effect on the quality of the environment. Waste management carried out by the community by composting household organic waste, recycling and the establishment of waste banks in each line of society, both unit and parent waste banks, will have an impact on reducing the pile of waste in the landfill (Final Processing Site). Waste management starting from the community will have a positive effect if all facilities, infrastructure, and support are provided by the government and the private sector, as well as assistance and training in community waste management in an optimal and sustainable manner. The managed waste will affect the improvement of environmental quality, both air quality and water quality. Improving air quality and water quality will have a positive effect on the quality of public health. Thus, Loop 1 occurs as a generating/growth/reinforcing interaction (Kristianto et al., 2024a). Loop B1.1 (negative) describes waste management, describing the relationship between sub-models of environmental quality, namely air quality, water quality and waste management. In the loop, it is described that if waste generation is not managed, there will be an increase in the amount of pollutants produced from waste that will affect environmental conditions in the long term. Waste that is burned or stockpiled will have an impact on the environment. These negative influences explain that if the generation of waste continues to increase and is not managed, the decline in environmental quality will continue to occur. One of the steps and strategies that can be taken is with strict regulations with the concept of reward and punishment in China, rewards will be given in the form of incentives both to the community and industry in managing waste, while punishment for EU countries, Australia and Brazil is given by paying penalties for industry and society and supervision is carried out by the community and institutions independent who collaborate with the government who can directly provide complaint reporting with digitalized facilities that are carried out strictly and education in synergy with stakeholders, including academics, environmental activists and the informal sector (Yang et al., 2021; Xu et al., 2021). Thus, loop B1.2 results in a negative feedback interaction (goal seeking/balancing). |

| CLD | Information |
| --- | --- |
| **Loop B2** (Loop B2; Loop B1; Loop R3)- Balancing (-) | Describing waste management, air pollution, water pollution and public health, this loop explains that low waste management that occurs in the community has the potential to cause pollution, specifically in this study is air pollution and water pollution, with the behavior of people piling garbage in the ground, throwing garbage in rivers and burning garbage in settlements can potentially increase the burden of pollution in the environment that can be Reduce air quality and water quality which ultimately harms public health (Chowdhury & Baksh, 2020). A decrease in air quality and water quality will have the potential to increase the number of people infected with diseases such as ISPA (air pollution) and diarrhoea (water pollution). Increasing the potential for people to contract diseases results in a decrease in the quality of public health, which can lead to death, so the overall relationship between these sub-models will form negative feedback (goal seeking/balancing). |
| **Loop R3** (Loop R3; Loop R3.1; Loop R3.2; Loop B1)- Reinforcing (+) | Describing the contribution of waste management to the sector's GDP and total Sector GDP (water procurement, waste management, waste and recycling), the waste management sector is currently a concern of the government, because it is hoped that with the increasing generation of waste generated by the community, it can contribute to the country. Waste management can contribute to the sector's GDP (Gross Domestic Product) by implementing the waste to be recycled into resources in the production process, both for raw materials and energy sources (Grdic et al., 2020). The concept of the circular economy is considered more sustainable because it can reduce environmental burdens that cause pollution, improve the quality of the environment and improve public health (Shi et al., 2020). In addition to being more environmentally friendly, the circular economy system is also able to provide added economic value, provide jobs that can increase per capita income, contribute to development, and efforts to mitigate climate change (Kristianto et al., 2023). |

**Model Structure And Sub Model**
In building a model consisting of predetermined sub-sub-models, the structure used is to describe the real system in the actual conditions of people's behaviour. The behaviour is described in a variable to be studied and formulated to be simulated by considering time changes. The sub-sub-models built are the population sub-model, the circular economy sub-model and the SDGs sub-model, represented by air quality, water quality and public health.

**Population Sub Model (Social Aspect)**
The basic structure of the population sub-model is composed of two *feedback* loops that affect the stock of the number of populations, as shown in Fig. 3.


***Fig. 3*** *Population sub-model feedback structure*
Source: Data processed with the Powersim 10 application

The growth of the population in an area can be explained through two feedback mechanisms. A reinforcing loop occurs when population growth encourages further growth, so the population tends to increase over time. In contrast, negative feedback loops (goal-seeking loops) such as outward migration play a role in reducing the population towards a certain equilibrium point. In addition to

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natural factors such as births and deaths, inward migration also contributes to population accumulation. Population growth can have an impact on increasing per capita income, which in turn has implications for increasing the volume of waste generation. Significant inward migration has the potential to increase the generation of waste, which, if not managed properly, will reduce the quality of the environment. Deteriorating environmental quality has a negative relationship with public health status, especially through the increase in deaths from diseases arising from environmental pollution. In this context, environmental quality and public health are also affected by the level of education.

**Circular Economy Sub Model (Economic Aspect)**

The increase in population growth rate directly contributes to the increase in waste generation. Waste comes from various sources, such as households, markets, offices, and public facilities. The volume of generation is influenced by the population and the generation per capita, with a positive relationship (Kristianto et al., 2024b). The imbalance between managed and unmanaged waste has an impact on environmental quality and public health, requiring adaptive and sustainable management strategies. The picture is illustrated in Fig. 4.

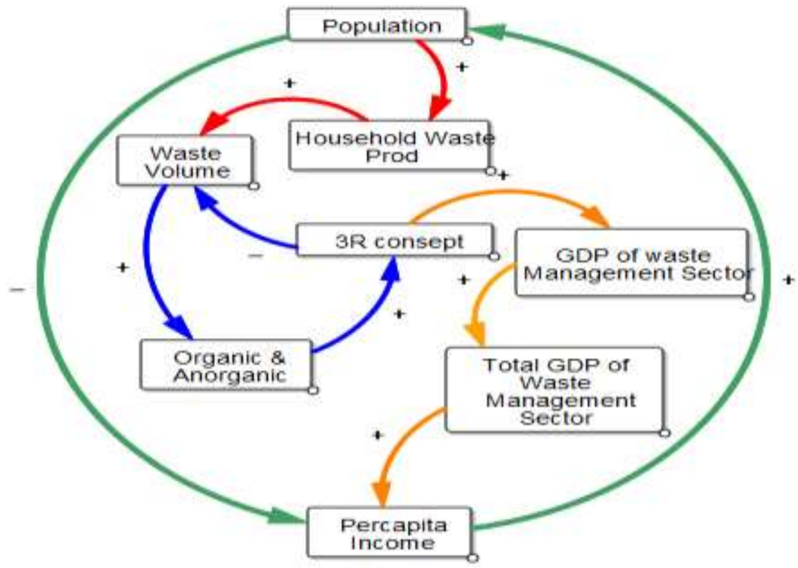


***Fig. 4** Causal Loop Diagram Sub Model of the Circular Economy*
Source: Data processed with the Powersim 10 application

The circular economy sub-model in waste management describes the causal relationship between population growth, waste generation, 3R (Reduce, Reuse, Recycle)-based management strategies, and their implications for economic sectors. The increase in population directly encourages an increase in household waste generation, which then contributes to the accumulation of the amount of waste by type, both organic and inorganic (Adamo et al., 2020). Both contribute to an increase in the overall volume of waste (Retuerto et al., 2021). In the circular economy approach, interventions are carried out through three main strategies, namely Reduce (reducing waste from sources), Reuse (reusing goods), and Recycle (reprocessing materials). These three strategies form a balancing loop that functions to control the growth of waste volume. Economically, the recycling strategy has a positive impact on the GDP of the recycling and waste management sector, as well as increasing the total GDP in the water supply, waste management, and recycling sectors. This contribution also has an impact on increasing per capita income, which shows the economic potential of sustainable waste management practices (Dos Muchangos et al., 2016). Thus, this model shows that the implementation of a circular economy in waste management not only reduces environmental burden but also creates economic added value through the growth of the recycling sector, job creation, and improved community welfare (Fehr et al., 2020). The control loop is key in maintaining a balance between population growth dynamics, waste volume, and sustainable management efforts based on the principle of circularity.

**Sub Model of Air Quality, Water Quality and Public Health (Environmental Aspect)**
Low environmental quality is closely related to the lack of public awareness and participation in waste management (Sethy et al., 2019). This involvement contributes to an increase in the volume of waste from the source, which ultimately worsens the level of environmental pollution. Increased pollution, both to the air and water, negatively impacts the overall quality of the environment. To overcome this problem, it is necessary to strengthen regulations related to waste management at the source, so that waste generation can be controlled more effectively. This can be illustrated in Fig. 5 of the CLD sub-model of air quality, water quality and public health.

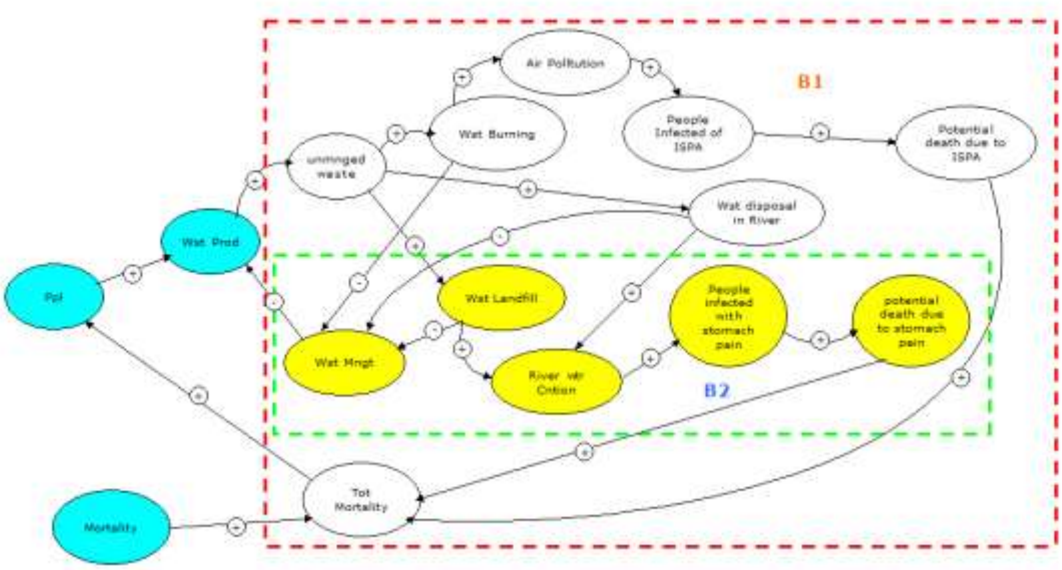


***Fig. 5*** *Causal Loop Diagram Sub Model Environmental Quality*
Source: Data processed with the Powersim 10 application

Fig. 5 illustrates the complex relationship between population, waste management, environmental pollution, and public health. Population increase is positively correlated with waste generation, which, if not managed properly, causes waste to go unmanaged. This unmanaged waste triggers two main feedback loops: loop B1 (air pollution) and loop B2 (river water pollution). Loop B1 shows how burned waste causes air pollution, increases the risk of ISPA, and potentially increases mortality. Loop B2 shows how garbage dumped into rivers pollutes water, increases the risk of diarrhoea, and potentially increases death. Effective waste management has a negative relationship with unmanaged waste generation, garbage hoarding, and water pollution, making it a key factor in reducing these negative impacts (González-Arqueros et al., 2021). Natural deaths also contribute to total deaths. This diagram emphasises the importance of comprehensive waste management to protect public health and the environment.

**Model Validation Test**
Validation of forecasting models is carried out through prediction accuracy testing, which is essential given the inherent complexity and uncertainty in decision-making systems. This study focuses on the selection of optimal forecasting models for time series data. The process of systematically estimating future phenomena based on historical time series data requires an appropriate forecasting model to minimise the deviation between the predicted value and the actual value. Evaluation of prediction accuracy was carried out using Mean Squared Error (MSE) and Mean Absolute Percentage Error (MAPE) metrics. The feasibility of the forecasting model was assessed based on the MAPE criteria that had been set. The Exponential Smoothing method can be applied as an approach to determine

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predictive values (Douglas et al., 2020). Based on the results of the validity test model, the measurement of the level of forecasting accuracy in Table 4 uses the MAPE (Mean Absolute Percent Error) Technique.

Table 4
Model validation test with the MAPE Technique

| No | Variables in the model | MAPE (%) | Criterion |
|---|---|---|---|
| 1 | Population Model | 3,75 | Excellent |
| 2 | Household Waste Generation Model | 14,44 | Good |
| 3 | Model PDB Sector | 11,47 | Good |
| 4 | Recycling Rate Model | 2,39 | Excellent |
| 5 | Water Pollution Model | 2,39 | Excellent |
| 6 | Air Pollution Model | 4,41 | Excellent |
| 7 | Public Health Model | 3,62 | Excellent |

Source: data processed by the exponential smoothing method (2022)

In general, it can be said that the model that has been built has very small errors and considering that the purpose of this model is as a tool to conduct behavioral analysis in circular economy waste management in relation to air pollution, water pollution and public health in the long term, the confidence level of this model is very good and the model can be declared valid for use.

**Policy Scenario Determination**

The scenario assumption assumes that the implementation of the 3R concept in household waste management will increase by 20% in 20 years (2011-2030). This increase can have a positive impact on the environment, such as a reduction in the amount of waste and an increase in recycling rates.

Thus, this policy scenario estimates that while there is still work to be done to achieve higher targets, the implementation of the 3R concept can still have a positive impact on air quality, water quality, and public health. To achieve better outcomes from this scenario, effective cooperation between the government, the private sector and the community is needed in promoting and implementing the 3R concept in household waste management. This can be done through educational programs and campaigns that focus on increasing public awareness and participation. The determination of the scenario with a target increase of 7% uses the following assumptions:

- The population growth rate of 0.0123% was obtained from historical data from the research, with the base year of 2011 of 245,100,000 people/year, compared to 2020 of 273,500,000 people/year.
- The birth rate of 0.02% was obtained from historical data from the research, with the base year of 2011, of 618,000 people/year.
- Average population: 259,691,144 inhabitants
- Average household waste generation: 38,099,840 tons/year
- Average amount of household waste addition: 10,716,661 tons/year
- Target percentage of implementation of the 3R (Reduce-Reuse-Recycle) concept of household waste: 20%

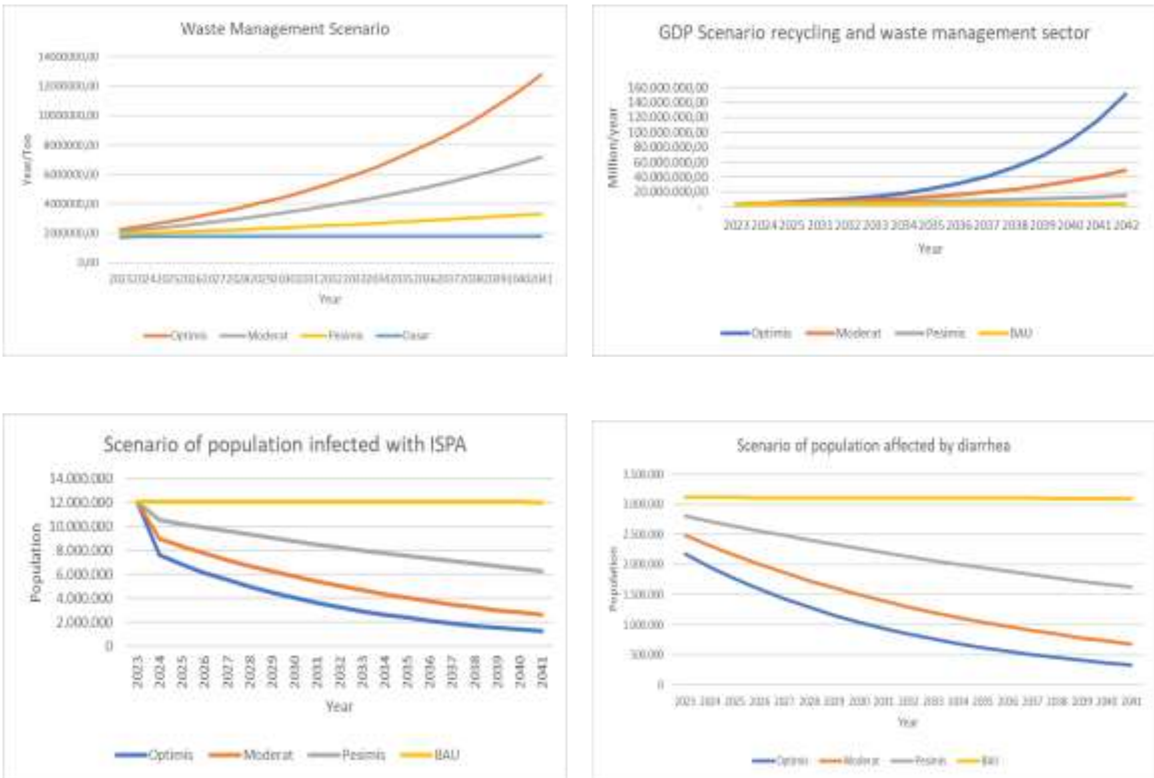
This can be projected from the results in the following explanation based on the scenario carried out, namely the implementation of the household waste management *3R* (reduce, reuse, recycle) concept: The target scenario of 20% with the base year 2011 is 1,764,001 tons/year. If this scenario is achieved, the waste reduction with the 3R concept will be 6,379,558 tons/year by 2030.

a. Contribution of the implementation of the 3R concept to the GDP of the water supply, waste management, waste and recycling sectors: This shows that if the moderate target is achieved, the sector will contribute Rp 13,877,801 billion/year in 2030 to the national GDP, an increase from the GDP of the 2011 base year of Rp 3,837,327.69 billion/year.
b. Water pollution conditions: If this scenario is achieved, then the implementation of the 3R

(Reduce, Reuse, Recycle) concept of household waste management will reduce water pollution by 38.86 Mg/L from 2011, which is 51.94 Mg/L, to 13.08 Mg/L by 2030.Air pollution conditions: This shows that if a moderate scenario is achieved, it can reduce air pollution by 62.04 Mg/L within 20 years.

c. The condition of the population infected with ARI: This shows that if a moderate scenario is achieved, it can reduce the number of people affected by POIA due to waste pollution by 0.044,298 people within 20 years. The population affected by ISPA will decrease from 12,089,203 people in 2011 to 3,044,905 people in 2030.
d. Condition of the population infected with diarrhoea: If the target scenario is achieved in the implementation of the 3R concept, it can reduce the number of people affected by diarrhoea due to waste pollution by 2,329,908 people within 20 years. The population affected by diarrhoea will decrease from 3,114,308 people in 2011 to 784,400 people in 2030.

The still high source of waste from households from year to year shows that waste management in the community is still lacking. It is not enough just to know about waste management and its impact if it is not done correctly, but to attitudes and actions. There needs to be community realisation of waste handling; without this realization the existence of a waste management system becomes less optimal. This scenario is moderate and can be illustrated in the projections from 2023 to 2042 in Fig. 6.



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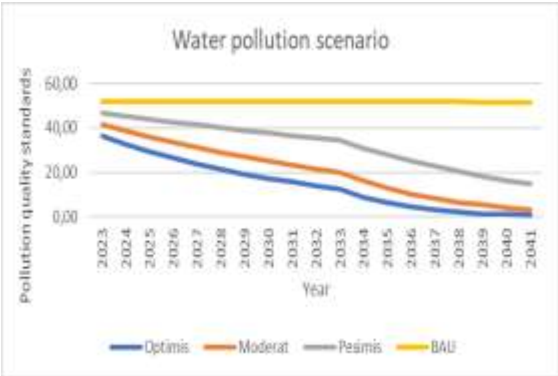


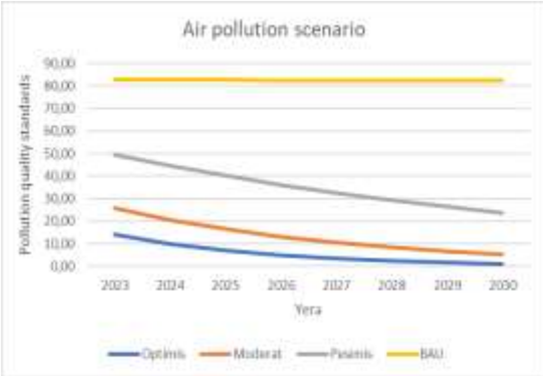


***Fig. 6*** *Projected Waste management scenario, GDP of the waste management and recycling sector, population infected with ISPA and Diarrhoea diseases, Water and air pollution*
Source: SIPSN, BPS, KLHK (2023), processed

The proposed policy scenario looks quite comprehensive and involves various parties in efforts to achieve better and sustainable waste management. Here is a brief explanation of each of these policy strategies:

1. Establishment of Unit and Main Waste Banks from the Village to the District Level. Through the establishment of a waste bank, communities at the village to sub-district levels can be empowered to manage waste better and have economic value. That way, it not only reduces the volume of waste produced but also provides economic benefits for the community.
2. The development of an Integrated National Level Digital Information System (SID) at the SID Village Level can help in monitoring and managing waste more effectively and efficiently. With the SID that is integrated at the village level, information about the volume and type of waste produced can be collected properly. In addition, SID can also help in regulating and monitoring waste transportation and safe waste disposal locations.
3. TPS3R Only Village Level TPS3R (Integrated, Integrated, Managed and Environmentally Friendly Waste Management Place) located only at the village level can help in waste management at the local level. With TPS3R, waste can be sorted, processed, and recycled better and more safely.
4. Project-Based Green Curriculum from Elementary School to College Level. Project-based green curriculum can help in building environmental awareness and teaching good waste management skills from an early age. Through a green curriculum, the young generation can be trained to become agents of change who care about the environment.
5. Scenarios in the construction of MRF (Material Recovery Facility) at the regional/district level and PPP (Government and Business Entity Cooperation) of national companies, as well as the provision of garbage transport motorcycles without dump trucks, can be carried out with the following steps:
   - Effective and efficient MRF construction. MRF is a waste management facility that aims to separate recycled materials from the waste produced. In the construction of the MRF, it is necessary to consider a strategic location so that it is easily accessible to waste hauliers and residents. In addition, it is also necessary to consider the technology that will be used so that the waste management process can run effectively and efficiently.
   - The implementation of PPP with national companies. PPP is a form of cooperation between the government and business entities that aims to increase investment in the public sector. In this case, the government can collaborate with national companies to build an MRF. The national companies involved can provide technology and management support so that the waste management process can run well.
   - The use of garbage transport motors, The use of garbage transport motors can be a more efficient alternative in transporting garbage. Garbage transport motors can reach narrower

areas and are difficult for dump trucks to reach. In addition, the use of garbage transport motors can reduce operational costs because they are more fuel-efficient.
- Provision of adequate facilities and infrastructure. To support this moderate scenario, it is necessary to provide adequate facilities and infrastructure, such as good road access, safe and controlled temporary waste disposal sites, and modern and environmentally friendly waste processing facilities.

In its implementation, this policy scenario requires good coordination and cooperation between the government, national companies, and the community. With this moderate scenario, it is hoped that waste management can run more effectively and efficiently, so that it can improve the quality of the environment and the health of the local community.

## CONCLUSIONS

The study showed that the systems dynamic models that integrate population, circular economy, and environmental sub-models are very effective in analysing the impact of SDG 12 policies. Population growth contributed to increased waste, which in turn can damage air and water quality and increase the risk of public health problems, such as acute respiratory infections (ARI) and diarrhoea. As a result, simulations conducted on the scenario of increasing 3R implementation by 20% from 2011 to 2030 showed several positive results. There was a potential for a significant decrease in the amount of waste managed, which is reduced by 6.38 million tons per year. In addition, the contribution of the waste sector to gross domestic product (GDP) had increased by 261.6%. Water pollution could also be minimised. Water and air pollution decreased by 38.86 Mg/L and 62.04 Mg/L. In addition, the number of cases of Acute Respiratory Infection (ARI) and diarrhoea decreased by 74.8%. Validation of the model using MAPE showed results of 3.75% for the population and between 2.39% and 4.41% for the environment. This confirms that the model can be relied upon as a tool in long-term policy formulation.

To optimize the circular economy, a comprehensive approach is needed that includes strengthening infrastructure (development of Waste Banks, MRF (Material Recovery Facility), technology-based TPS3R optimization, and logistics), integration of digital technologies for waste monitoring, government-private collaboration in recycling investments, holistic education and 3R campaigns with community incentives, progressive regulatory enforcement (restrictions on single-use waste, strict sanctions, integration of recycling indicators in SDG evaluations 12), as well as further research related to the ambitious 3R targets and the impact of climate change and global recycling markets. This multidimensional synergy is crucial to make the circular economy the foundation of sustainable production and consumption according to the SDGs targets.

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