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Integrating Circular Economies: Enhancing Border Regions Environment and Public Health

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Abstract

The circular economy represents a groundbreaking economic model that transforming waste into valuable products, potentially benefiting regional and national economies. This research explores the correlation between household waste management and its impact on environmental degradation and public health. Employing the System Dynamics method, the study delves into the intricacies of real-world system behavior, examining causal links and interrelationships within a system of interconnected sub-systems. Utilizing mental data, including scientific publications, mass media news, and expert opinions, alongside quantitative time series, the research focuses on the limitations of household waste management in addressing air and water pollution, posing potential health risks. Findings indicate a connection between population growth and increased waste generation, predominantly from residential sources. Unmanaged waste creation threatens air and water quality, emphasizing the importance of waste management in minimizing pollutants for improved public health. Aligning with the circular economy's 3R concept, effective waste management not only mitigates environmental impact but also holds the potential to enhance income generation. The circular economy's recycling and green entrepreneurship promotion can stimulate investments, fostering job creation. Collaborative efforts between governments and business owners can further support distribution and marketing channels, encouraging local self-sufficiency.

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INTRODUCTION

Waste is a global issue affecting virtually every region. In 2018, global waste production reached 2.01 billion tons. Population growth and increasing urbanization are expected to drive global waste generation to 3.4 billion tons by 2050, as projected by the World Bank (Metadata for Radioactive Waste Management, 2019; OECD, 2017). Waste represents a significant and potentially profitable component of the recycling and waste management industry in developed nations. However, it remains a major challenge in developing countries (Rosa *et al.*, 2020). Inefficient manufacturing processes and inadequate product recycling initiatives exacerbate this dilemma (Wilson *et al.*, 2015). Implementing effective waste management strategies, including comprehensive regulations and policies, could help mitigate these challenges (Kristianto, Suratman, and Yani, 2023).

The circular economy is an emerging economic concept aimed at reducing and eliminating waste by regenerating waste materials into valuable new products (Andrews, 2015). This approach seeks to construct a sustainable economic system that integrates economic, social, and environmental factors (Millar et al., 2019). Governments establish laws targeting industrial waste management by utilizing the Life Cycle Analysis (LCA) approach to evaluate the efficiency of manufacturing processes at various recycling stages (Plastinina *et al.*, 2019). In Japan, this economic model is implemented through community-based rules and policies rooted in the 3R (Reduce, Reuse, Recycle) paradigm, supported by a reward-and-punishment system.

The circular economy principle serves as a key feature in policy formulation across industrialized nations. Its implementation involves providing facilities, education, and access to promote behavioral changes (Salmela, 2016). However, waste generation remains a persistent issue in China, particularly in Beijing, where the circular economy system functions suboptimally. Public awareness is low, emissions from pollution continue to rise, and pollutants from waste degrade public health (Barreiro-Gen and Lozano, 2020; Yang et al., 2021). In developing nations, population growth correlates with increased toxicity and pollution resulting from mismanaged waste (Ndanguza, Nyirahabinshuti, and Sibosiko, 2020). Population expansion increases public consumption, leading to greater waste tonnage annually. Improper waste management further degrades environmental quality (Al-khatib, Eleyan, and Garfield, 2015).

Indonesia faces significant challenges in waste management as it progresses toward developed nation status. Between 2015 and 2017, the country generated approximately 65.2 million tons of waste annually, incurring costs of up to 28.1 trillion rupiah. Improper management imposes substantial impacts on regional and national economies (Nelen and Bakas, 2021). Waste management remains a shared concern among stakeholders. The 2020 Global SDG Index ranked Indonesia 101st out of 166 nations (Indonesian Ministry of Development Planning, 2020). Addressing these issues requires collaborative efforts involving the Penta Helix—government, academia, businesses, media, and non-governmental organizations—to mitigate the externalities of waste production (Maalla and Adipah, 2020). The Indonesian government must implement initiatives in partnership with stakeholders to shift community perceptions of waste as a resource with economic value through a people-based circular economy model (Kristianto, Siahaan, and Vuspitasari, 2022).

As an archipelagic nation, Indonesia includes border regions requiring special attention. Bengkayang City Regency in West Kalimantan Province, which borders Malaysia, serves as the economic hub of Bengkayang District. The regency includes 17 districts and had a population of 34,723 in 2019, reflecting a 3.57% increase from 2015 (Bappeda, 2020). Population growth drives higher consumption and increased waste production, linked to rising regional income (GRDP).

Waste management in Bengkayang City Regency remains inadequate. Waste at the landfill (Final Processing Site) is left unmanaged, with no government employees overseeing operations. Waste remains mixed, with no separation of organic and inorganic materials, and data on waste generation is unavailable. Access to the landfill is restricted, the waste processing industry is absent, and infrastructure and facilities are insufficient. Addressing these challenges requires fostering cultural awareness about waste management and providing long-term support to promote a paradigm shift toward viewing waste as a valuable resource, mitigating its negative impacts (Kristianto and Nadapdap, 2021). A visual representation of the waste situation in Bengkayang is presented in Figure 1 below.

Figure 1. Landfill locations and several landfill site locations
Source: Field observation, 2024

The increasing levels of waste generation, coupled with ineffective management, have significantly impacted environmental quality and public health (Yuliana, Paradise, and Mudawil Qulub, 2024). Local governments must implement preventative measures such as providing education, assistance, and socialization on the principles of reducing, reusing, and recycling (Agyemang *et al.*, 2019).

Public health consequences of inadequate waste management can be assessed through indicators such as the public health development index (Kemenkes, 2018). Waste management practices at the household level must improve. Educational and awareness programs emphasizing the importance of proper waste disposal and recycling play a key role in achieving this. Encouraging households to segregate waste and recycle materials such as paper, plastic, and glass significantly reduces the volume of waste sent to landfills (Guzzo et al., 2022).

Adopting a circular economy model contributes to national economic growth by increasing GDP in sectors such as water supply, waste management, and recycling (Grdic, Nizic, and Rudan, 2020). Waste management is a shared responsibility between the government and the community. Collaboration between these stakeholders is essential for reducing national waste and improving public health outcomes (Nwogwugwu & Ishola, 2019).

This study examines the interconnections between circular economy practices and waste management, focusing on their impact on air quality, water quality, and public health in the Bengkayang Border area of West Kalimantan. The primary objective is to develop a circular economy model that enhances air and water quality while improving public health in this region. Current waste management practices and their effects on air and water quality and public health in Bengkayang are analyzed. This analysis aims to propose a circular economy model that minimizes waste generation, promotes resource efficiency, and enhances environmental and health conditions.

The research explores explicitly how current waste management practices influence air and water quality and public health in Bengkayang. By analyzing these effects, the study aims to propose a circular economy model that minimizes waste generation, promotes resource efficiency, and improves the area's environmental and health conditions.

The findings of this research provide valuable insights into the benefits of implementing a circular economy model in waste management, particularly concerning air and water quality and public health. Environmental and public health outcomes in the Bengkayang Border area can improve through a tailored model addressing these challenges. The model includes sub-models for population dynamics, circular economy practices in waste management, air and water pollution, and public health. A community-based waste management policy is proposed, transforming waste into economically and practically valuable products.

RESEARCH METHODS

The concept of System Dynamics was applied in this research. This methodology integrates both quantitative and qualitative elements, emphasizing the cause-and-effect interactions and relationships among various subsystems. These subsystems collectively form a system where components influence one another in a circular manner (Tasrif, 2015). The approach seeks to explain complex behaviors and structures observed in real-world scenarios, particularly in learning processes, decision-making, and policy formulation (Sterman, 2009).

System Dynamics employs tools designed for problem resolution and prevention, such as the Causal Loop Diagram (CLD) and Stock Flow Diagram (SFD). The research utilized primary and secondary data sources, including mental models, textual information, and quantitative databases. The Mean Absolute Percentage Error (MAPE) approach was applied to evaluate the accuracy of the data by comparing actual and predicted values based on predefined criteria (Kolodiichuk, 2019).

Table 1. Criteria for Judging Mean Absolute Precent Error (MAPE)

MAPE Value	Criteria
< 10%	Excellent
10-20%	Good
20-50%	Enough
>50%	Bad

Source: Kolodiichuk, (2019).

Models that satisfy the validation test after being determined to fulfill the requirements are simulated to determine the scenario in projecting the model's future. Models that pass the validation test and meet the necessary requirements are then simulated to project future scenarios. These simulations include optimistic, moderate, and pessimistic scenarios. Figure 1 illustrates the modeling process using the System Dynamics technique (Deaton and Winebrake, 2020):

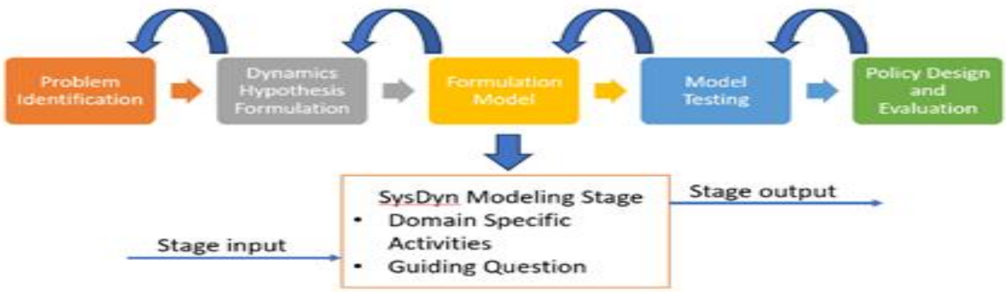

Figure 2. Stages of the method System Dynamics
Source: Deaton and Winebrake, (2020)

RESULTS AND DISCUSSION

The Causal Loop Diagram (CLD) approach is utilized to construct the conceptual framework for this research. This framework outlines the indicators to be measured and defines the boundaries of the model applied in the study. It is organized into three interconnected subsystems: the population subsystem in relation to waste, the waste management subsystem, and the environmental pollution and public health subsystem. The structure is illustrated in the image below.

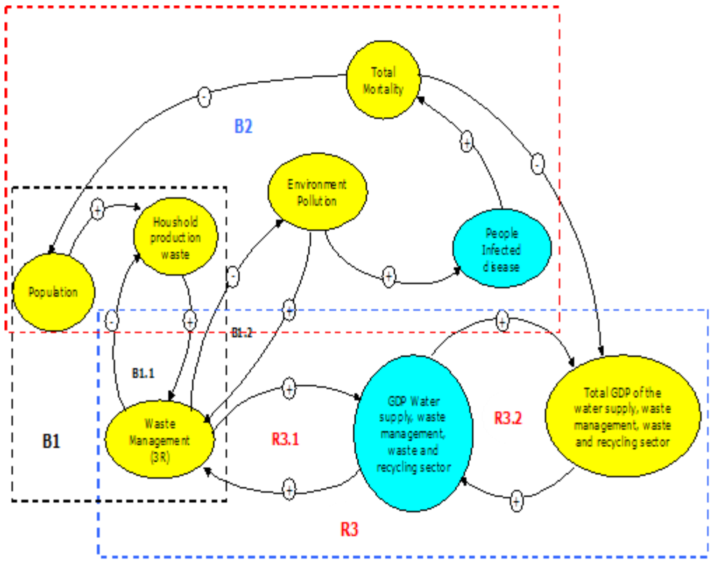

Figure 3. CLD Research Framework
Source: Data Processed, 2024

This study explores three sub-systems within the research framework, with time being a significant constraint, particularly concerning its influence on model parameters. The population sub-system highlights the relationship between population growth and the potential increase in waste generation in Bengkayang Regency, based on demographic trends. The system dynamics model focuses on key variables directly influencing population demographics, such as birth and death rates. Parameters such as birth rates and life expectancy are employed to capture decision-making behaviors and structural dynamics impacting population growth.

The waste management sub-system explores factors contributing to waste accumulation, particularly household waste, which forms a significant proportion of total waste. Household waste management is influenced educational initiatives, infrastructure development, recycling technologies, waste banks, the informal waste sector, and regulatory frameworks (Sukholthaman and Sharp, 2016). Community involvement is vital, starting with waste segregation at the source, followed by collection, transportation, processing, and final disposal. Key parameters include household waste generation and management practices, such as burning and landfilling, alongside the application of the 3R (reduce, reuse, recycle) principles, which generalize household waste management behavior.

Environmental pollution and public health issues arising from unmanaged waste are central to the third sub-system. Air pollution results from the combustion of organic and inorganic waste, which emits hazardous gases such as methane, sulfur dioxide, and carbon monoxide. These gases degrade air quality, causing respiratory illnesses and irritating the eyes, nose, and throat. Water pollution, on the other hand, occurs when untreated household waste is discharged into rivers, contaminating water sources and harming aquatic life. Improper waste management can obstruct water flow, leading to flooding and further environmental degradation. Preventative measures, such as reducing waste generation, sorting waste, and proper disposal, are essential for mitigating these issues. Governments can enhance these efforts through public education campaigns and the provision of adequate infrastructure.

Public health considerations within this framework include environmental health and individual behavior concerning environmental maintenance. Environmental health encompasses natural and artificial elements, such as waste, water, air, housing, and socio-economic factors. Poor environmental sanitation, including limited access to clean water, is a leading cause of diseases like diarrhea and respiratory illnesses. Social conditions also play a role; economic challenges hinder access to healthcare, while higher levels of education correlate with a better understanding of health and wellness. This sub-system evaluates disease potential due to air and water pollution caused by waste, assuming equal exposure to contaminants.

The validation test is performed to determine the level of forecasting accuracy by calculating MAPE (Mean Absolute Percentage Error), one of the evaluation metrics commonly used to assess forecasting accuracy in time series analysis, including the exponential smoothing method. MAPE calculates the average of the percentage errors between the actual value and the value predicted by the model. MAPE calculates the prediction error as a percentage of the actual value. The forecasting model becomes more accurate as the MAPE value decreases. Validation tests used to measure the accuracy level of forecasting by the exponential smoothing approach include data that is not utilized in building a model to test its performance. This is frequently done by separating the data into two parts: instructing the model and validating the model. The model's ability to predict previously unidentified test data is then evaluated using metrics like MAPE. The forecasting model performs better on test data with lower rates of MAPE value. The calculation results of the validation test of the preset model are as follows:

Table 2. MAPE-Based Validation of Test Results

MAPE value		**Population Sub Model**		**Sub Model of waste management to GDP of the Waste Management sector**		**Environmental Quality Sub Model**		**Public Health Sub-Model**	
Value	**Criterion**	**Value**	**Criterion**	**Value**	**Criterion**	**Value**	**Criterion**	**Value**	**Criterion**
< 10%	Excellent	3,75 %	Excellent	-	-	3,4%	Excellent	3,62%	Excellent
10%-20%	Good	-	-	l 1,47%	Good	-	-	-	-
20%-50%	Enough	-	-	-	-	-	-	-	-
>50%	Bad	-	-	-	-	-	-	-	-

Source: Data Processed, 2024

The sub-systems must be presented and examined to construct a main model using the System Dynamics methods. The basic model was built as a Stock Flow Diagram (SFD) and intended to be eased with the assistance of computer Powersim 10 programs. The structure of a system influences and determines the behavior of models inside it. In this scenario, the structure consists of several interconnected and connected components. The variations inherent in each component play a vital influence.

In basic terms, the meaning is establishing the structure of a model by creating a Causal Loop Diagram (CLD) that depicts the real system in real conditions in society, based on the structure of the model to be built, and studying the behavior of each parameter to be examined. Furthermore, the behavior of each variable is examined and created to simulate the conduct of the parameters that have been established concerning fluctuations in time. Lessons learned and comments are described based on the principal sub-systems and systems developed in entirety, which include:

In this population sub-model, two feedback loops are arranged that affect the population stock, as in Figure 3:

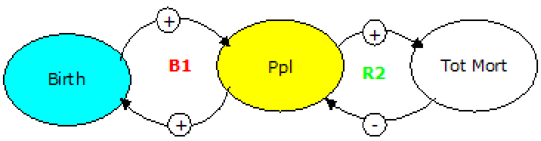

Figure 4. CLD of Population sub-system
Source: Data Processed, 2024

The feedback loop of population growth is expanding, which requires population size and tends to increase year after year. Birth and mortality create a feedback loop; population size is determined by the number of births in a region. As the population increases, per capita income escalates, potentially increasing trash creation. The quantity and velocity of birth will affect growing waste creation, which is connected to the quality of the environment. The consequence of waste production on environmental quality is the opposite, which means that the generation of uncontrolled waste will reduce the quality of the environment.

The decrease in environmental quality will result in abundant mortality and low levels of public health due to infections caused by environmental pollution. The population submodel designed has merely one level, which is the number of attendees, with growth supported by the birth rate as a component of growth and a decline in population due to the mortality rate.

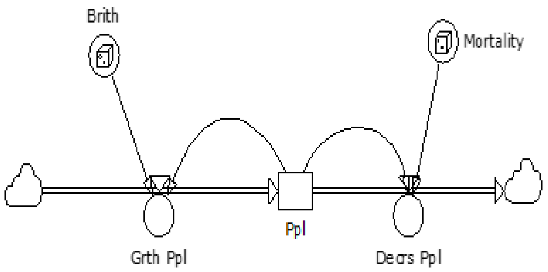

Figure 5. SFD of Population Sub-system

Source: Data processed with Powersim 10

An increase in population size leads to a steady rise in the number of people, which in turn causes changes in the dynamics of waste generation. This increase in waste production originates from various sources, including households, traditional markets, workplaces, enterprises, public buildings, and other regions. The volume of waste produced is influenced by the waste generation rate per capita, which is in direct relation to the overall population size. As the population grows, so does the amount of waste generated, creating a significant and proportional interaction between population size and waste production. The dynamics of both influence waste management managed and unmanaged waste, with implications for environmental quality and public health. Figure 5 shows the basic input framework for the waste management sub-model, while Figure 6 illustrates the stock-flow diagram structure of the waste management sub-system.

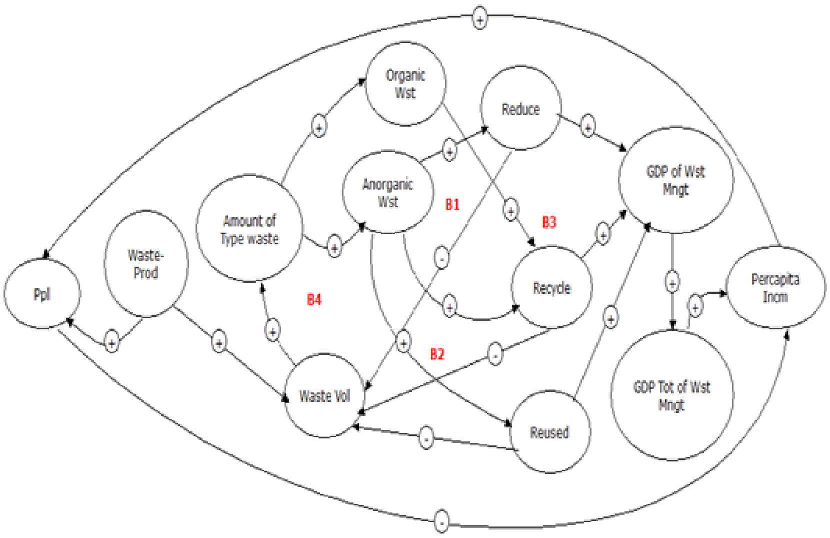

Figure 6. CLD of Waste Management sub-system
Source: Data Processed, 2024

The waste management system is concerned with the collection, transportation, processing, and final disposal of waste from Temporary Disposal Sites (TPS) to Landfill Sites (TPA). The system has a causal effect on both managed and unmanaged waste originating from the source. An increase in unmanaged waste results from practices such as burning waste, discarding it into waterways and rivers, and landfilling it. This situation can be controlled by managing waste at the source before it is transferred to the TPS. Key issues that can be addressed include waste selection and sorting at the source.

This category of waste includes both organic and inorganic materials. Waste segregation begins at the household level. Reducing waste at the source can lower the volume of waste transferred to the TPS, which in turn reduces operational mobility costs. However, if waste from the source is not properly managed, it will increase expenditures and may cause environmental harm, ultimately affecting public health.

Strengthening regulations with a reward-and-punishment system, alongside providing ongoing support and training, can help prevent improper waste management at the source. The government should also invest in infrastructure and facilities to support waste management programs.

Increasing the recycling component can create opportunities for new businesses and industries within the recycling sector. The expansion of the recycling industry has the potential to generate new jobs and boost regional income.

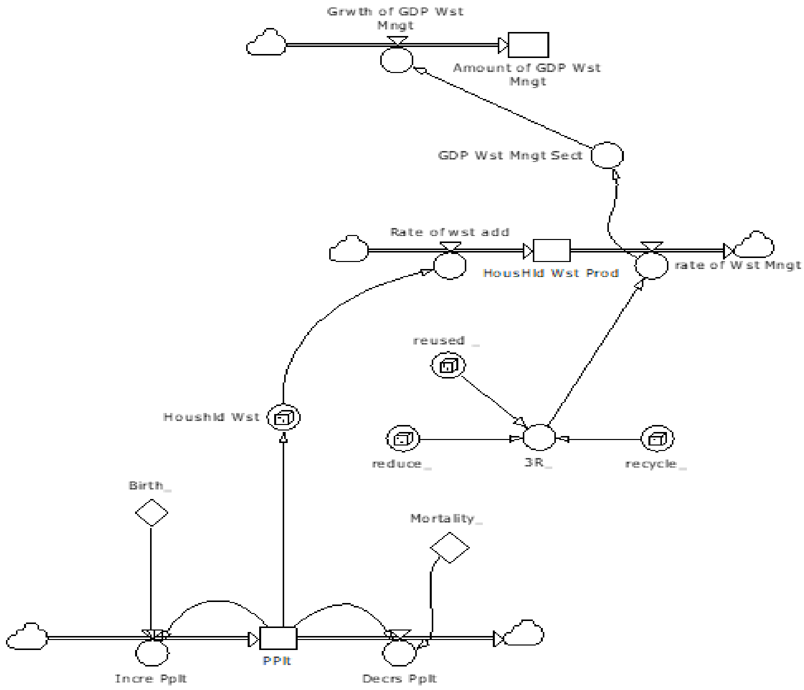

Figure 7. SFD of Waste Management Sub-system
Source: Data Processed, 2024

A lack of knowledge and local involvement in waste management can lead to declining environmental quality (Sethy et al., 2019). Inadequate waste management systems contribute to increased waste production, and the vast amounts of waste generated have the potential to cause environmental contamination. Excessive environmental pollution negatively impacts air and water quality, degrading overall environmental conditions. Addressing this issue requires raising public awareness and strengthening legislation on waste management at the source. These efforts are expected to reduce waste generation and mitigate pollution. The feedback structure of this system is illustrated in Figure 7, while the stock flow diagram for these processes is shown in Figure 8

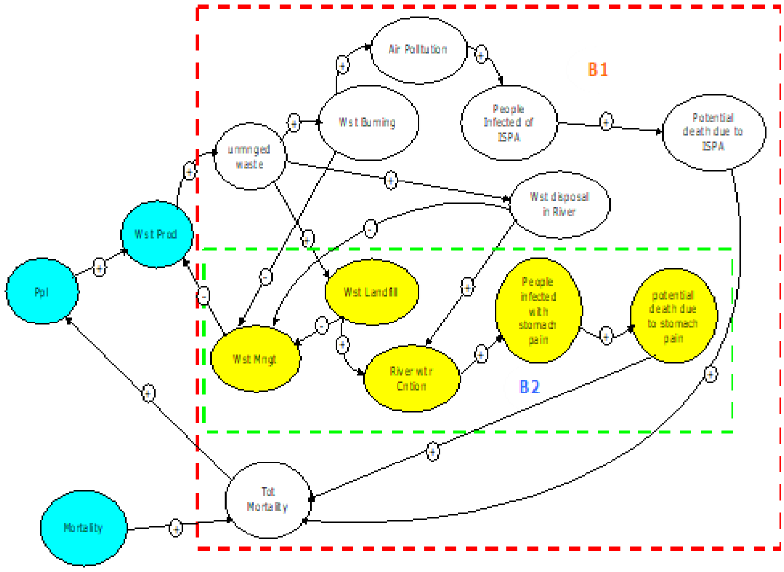

Figure 8. CLD of Environmental Quality and Public Health Sub-System
Source: Data Processed, 2024

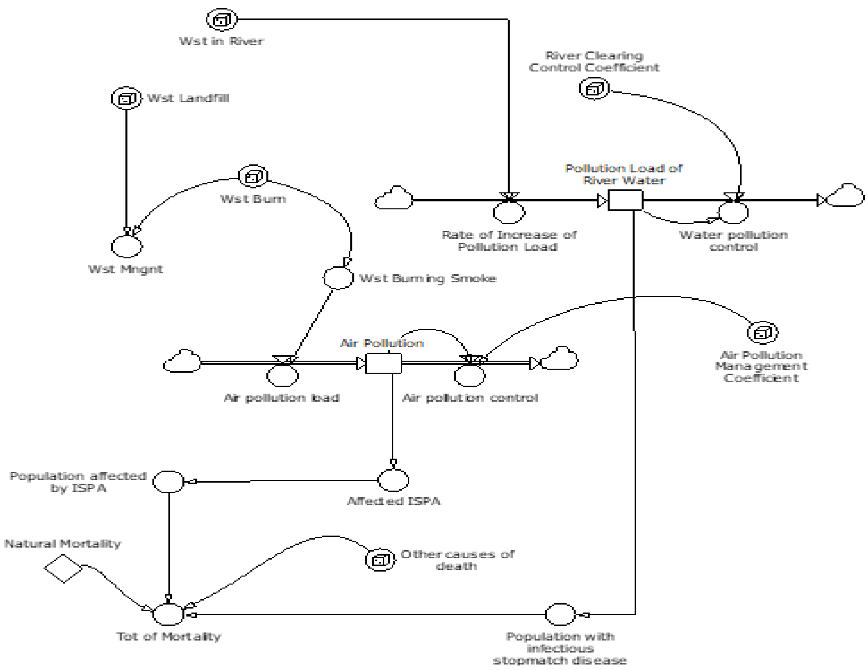

Figure 9. SFD of Environmental Quality and Public Health Sub-System
Source: Data Processed, 2024

Ineffective waste management leads to a decrease in environmental quality, which results in increased pollution in water and air due to waste burning, improper disposal, and the dumping of waste into streams and rivers. Air pollution caused by waste combustion can raise pollutant levels, including dust and harmful gases such as CO (carbon monoxide), NO2 (nitrogen dioxide), CH4 (methane), and SO2 (sulfur dioxide). The accumulation of these pollutants can contribute to the formation of acid rain and the emission of greenhouse gases, which in turn exacerbates global warming (Hosseinabad et al., 2017).

These investments primarily target waste-producing areas by providing infrastructure such as government-owned waste banks, organic and inorganic waste bins, and other facilities to meet community needs. Population growth can lead to increased waste generation, resulting in higher levels of unmanaged waste. This, in turn, is often exacerbated by a lack of public awareness regarding waste management. Inadequate environmental awareness can contribute to the spread of diseases, as improperly managed waste can lead to contamination.

Untreated waste undermines sustainability and increases the production of toxic substances. As a result, the number of people affected by waste-related illnesses rises, diminishing public health. However, improving environmental quality can have positive effects on public health outcomes.

Figure 8 illustrates the Stock-Flow Diagram (SFD) of the environmental quality and public health sub-systems, demonstrating how individuals can enhance public health by understanding and prioritizing environmental health and health behaviors in their daily lives. The speed at which the number of illness cases rises and falls directly impacts the overall quality of public health. Many people are affected by illnesses due to increasing air pollution and water contamination caused by inadequate waste management. However, the number of illness cases can be reduced if people improve their understanding of health knowledge, attitudes, behaviors, access to sanitation, and access to clean water. This requires the local community's awareness of the consequences of neglecting environmental health.

The level of education, both formal and informal, is strongly linked to awareness (Mamady, 2016). Lower levels of education are often associated with reduced knowledge about the detrimental impacts of environmental degradation on health. Knowledge, attitudes, and the implementation of health awareness can be promoted through a spiritual approach and education, supported by collaborations with government and educational institutions. These partnerships can help engage the local population and provide essential information about the negative effects of environmental degradation on public health (Mugabi et al., 2018).

The combined model incorporates policy interventions aimed at addressing household waste through the principles of reducing, reusing, and recycling (3R). These interventions are visually represented in the following figure.

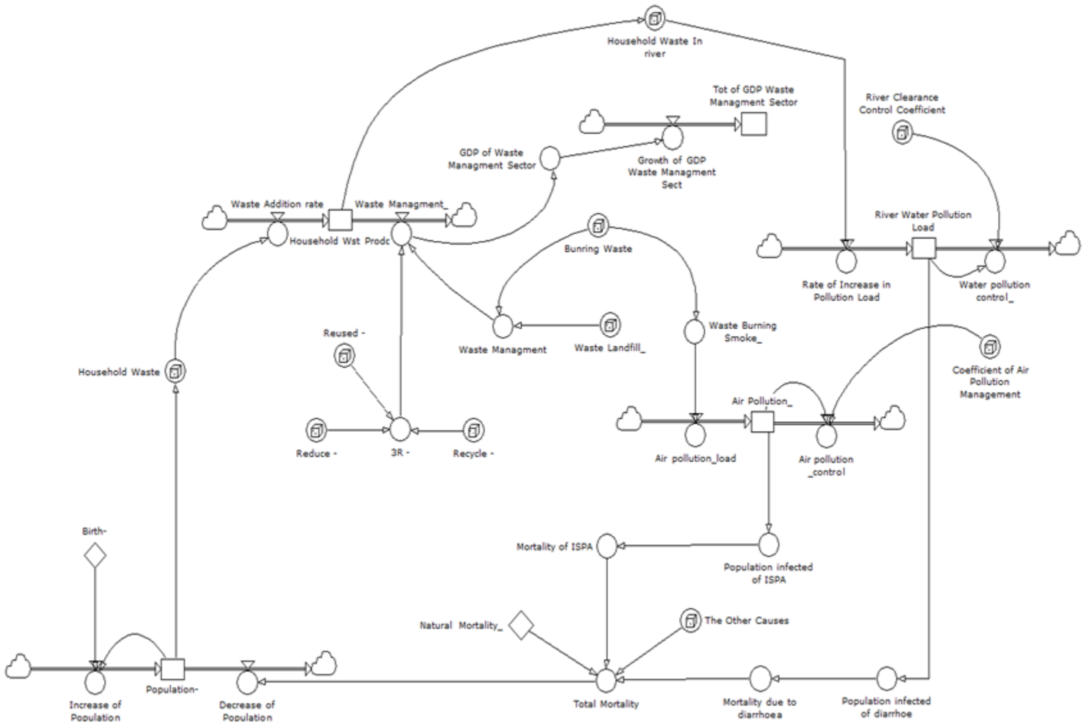

Figure 10. SFD of Circular Economy Main Model
Source: Data Processed, 2024

In the simulation model created using the PowerSim 10 program, dynamic 3R behaviors (reduce, reuse, and recycle) occur within the community. A mismatch between understanding, attitudes, and actual behaviors can influence these behaviors. It is crucial that all members of the community practice discipline, consistency, and sustainability. Collaboration among the community is essential, involving the Penta-Helix elements: the general public, academia, government, private/business sector, and media, to ensure waste management is approached in an integrated manner.

As the population grows, so does the amount of waste generated. As policymakers, the government's role extends beyond merely issuing laws; it is important for the government to act as a facilitator and support system for the community. Adopting the New Public Service (NPS) approach to public service delivery would provide more humanistic and inclusive services. The NPS approach is a concept that promotes a revolutionary way of delivering public services to better meet community needs, more effectively and productively.

Implementing the NPS concept in waste management can be achieved through various initiatives, including the establishment of waste bank programs, recycling and composting initiatives, and technological innovations. These innovations include the development of smart sensors and artificial intelligence for monitoring waste generation and segregation, as well as automatic waste collection systems using machine learning to detect waste types (Borchard, Zeiss and Recker, 2021). Additionally, android-based applications for reporting waste collection points (Gubernatorov, 2021), partnerships between local governments and the private sector to improve infrastructure, and innovative recycling facilities can also contribute to the solution. Further strategies include tipping fees, recycling incentives, and volume-based payment schemes for waste management services, as well as implementing green curriculum programs in schools and providing waste management training. Decentralizing waste management by empowering local communities to manage their own waste including developing community-based waste management systems and supporting local groups in recycling and composting initiatives can also play a critical role in improving waste management outcomes.

CONCLUSION

The circular economy model in waste management is closely linked to air quality, water quality, and public health.

Firstly, regarding air quality, circular economy practices—such as recycling, reducing, and reusing goods and materials—aim at minimizing waste generation and optimizing resource use. Reducing the amount of waste sent to landfills helps decrease greenhouse gas emissions and other pollutants that contribute to air pollution. Lowering air pollution directly benefits the quality of the air people breathe, reducing the risk of respiratory diseases and improving overall quality of life.

Secondly, the circular economy model positively impacts water quality. Waste reduction, recycling, and reuse practices reduce the amount of waste that pollutes water. Preventing waste from entering water bodies helps protect vital water resources and maintains the quality of water needed for domestic, agricultural, and industrial purposes. This can be achieved through proper waste treatment processes or by preventing waste from entering the water in the first place. Additionally, it reduces the risk of waterborne diseases and improves public health by safeguarding water quality.

Thirdly, from a public health perspective, population growth can potentially increase the amount of waste generated by the general population. If not managed effectively, this increase can have negative public health consequences. However, implementing a circular economy approach to waste management reduces waste generation and allows for more efficient and safer waste management. This approach helps prevent waste accumulation, which may cause disease transmission, such as infectious diseases, the spread of disease vectors, or environmental pollution that affects human health. Furthermore, a circular strategy promotes the adoption of safer, more environmentally friendly products, reducing the risk of exposure to harmful substances.

Effective implementation of the circular economy model in household waste management requires appropriate policies. These should include waste segregation into categories such as organic, inorganic, hazardous, and recyclable waste. Additionally, the 3R (Reduce, Reuse, Recycle) approach, recycling activities, composting, the establishment of waste banks, TPS3R (Temporary Disposal Site with 3R), recycling centers, and collaboration with the private sector—such as Public-Private Partnerships (PPP) with Material Recovery Facilities (MRF) and Extended Producer Responsibility (EPR) financing—are vital for realizing the circular economy concept. By implementing these policies, the circular economy model can contribute to economic growth through the creation of new business opportunities based on recycling and increased job creation.

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