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# MODELAGEM EM DINÂMICA DE SISTEMAS PARA AVALIAR IMPACTOS E OPORTUNIDADES NA RECICLAGEM DE PLÁSTICOS

# SYSTEM DYNAMICS MODELING TO EVALUATE IMPACTS AND OPPORTUNITIES IN PLASTIC RECYCLING

# MODELADO DE DINÁMICA DE SISTEMAS PARA EVALUAR IMPACTOS Y OPORTUNIDADES EN EL RECICLAJE DE PLÁSTICOS

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**Resumo:** A gestão inadequada de Resíduos Sólidos Urbanos (RSU), em especial os plásticos, representa um desafio ambiental e econômico significativo. Este estudo utiliza a metodologia de Dinâmica de Sistemas para modelar e comparar cenários de reciclagem de plásticos, avaliando seus impactos ambientais, financeiros e suas oportunidades dentro de uma economia circular. Três cenários foram simulados, variando taxas de descarte e reciclagem, demonstrando que o aumento da reciclagem reduz emissões de $CO_2$, amplia os ganhos financeiros e contribui para a sustentabilidade. Os resultados indicam que estratégias mais robustas de gestão de resíduos são essenciais para minimizar impactos ambientais e gerar benefícios socioeconômicos. Como trabalhos futuros, sugere-se expandir a análise para outros tipos de resíduos sólidos urbanos.

**Palavras-chave:** Dinâmica de Sistemas; Reciclagem de Plástico; Resíduos Sólidos Urbanos; Sustentabilidade; Economia Circular.

**Abstract:** The improper management of Municipal Solid Waste (MSW), especially plastics, poses a significant environmental and economic challenge. This study employs the System Dynamics methodology to model and compare plastic recycling scenarios, evaluating their environmental and financial impacts as well as opportunities within a circular economy. Three scenarios were simulated, varying disposal and recycling rates, demonstrating that increased recycling reduces $CO_2$ emissions, enhances financial gains, and contributes to sustainability. The results indicate that more robust waste management strategies are essential to minimize environmental impacts and generate socioeconomic benefits. Future studies are recommended to expand the analysis to other types of municipal solid waste.

**Key words:** System Dynamics; Plastic Recycling; Municipal Solid Waste; Sustainability; Circular Economy.

**Resumen:** Los Residuos Sólidos Urbanos (RSU) son un problema tanto en Brasil como en otras partes del mundo, lo que exige que se consideren alternativas sobre cómo mitigar sus impactos negativos. Así, el objetivo de este estudio es comparar escenarios de reciclaje de residuos plásticos, analizando los beneficios e impactos. El método utilizado fue Dinámica de sistemas y planificación de escenarios. Los resultados confirman la necesidad de una mejor gestión de los residuos sólidos. Como trabajo futuro se espera analizar más residuos sólidos y sus impactos.

**Palabras clave:** Dinámica de sistemas; Reciclaje de plástico; Residuos sólidos urbanos; Sostenibilidad; Economía circular.

## 1. INTRODUTION

Environmental degradation and pollution are closely linked to the current consumption patterns of the global population, which drive the extraction and processing of raw materials, exacerbating environmental impacts (IBGE, 2020). Among these challenges, the improper disposal of solid waste stands out as a critical issue. High rates of waste production and inadequate final disposal methods remain persistent concerns for governments and society (FROTA, 2015).

The environmental impact of waste management has sparked global debates, with governments, companies, and civil society seeking innovative ways to mitigate environmental damage (SANTOS; ROVARIS, 2017). According to data from the United Nations (UN BRAZIL, 2016), half of the world's population resides in cities, a figure projected to rise to 60% by 2030. Li et al. (2017) estimate that by 2050, the global population will reach 9.6 billion, requiring resources equivalent to three Earths to sustain current consumption levels. Population growth, coupled with increased purchasing power and widespread consumption of disposable packaging materials like paper, plastic, glass, and metal, has accelerated landfill depletion and heightened environmental impacts, particularly in urban areas (ROCHA, 2012).

In response, Brazil implemented the National Solid Waste Policy (PNRS) in 2010, compelling municipalities to reform urban cleaning and waste management practices (MERSONI; REICHERT, 2017). These legal requirements have driven the search for effective alternatives for urban solid waste (USW) treatment and disposal. According to the National Sanitation Information System (SNIS), domestic and public waste collection in Brazilian communities reached 6.9 million tons in 2020, equating to approximately 176,000 tons per day (BRASIL, 2016).

The circular economy offers a promising framework for USW management, promoting a shift from linear consumption models to sustainable practices. By implementing circular economy principles, governments can foster environmental preservation while enhancing waste management systems.

Effective waste management prioritizes waste prevention, followed by reduction, reuse, recycling, treatment, and environmentally appropriate disposal. Addressing this challenge requires collaborative efforts between governments and societies worldwide, as the environmental impacts of poor waste management are global in scope.

This study seeks to address key questions: What are the impacts of improper plastic disposal? How might increased recycling alter these outcomes? To answer these questions, this research aims to develop a system dynamics model to analyze plastic recycling scenarios.

## 2. THEORETICAL REFERENCE

The circular economy proposes replacing linear production systems—in which resources are extracted, used to manufacture products, and generate waste throughout their lifecycle—with systems that prioritize resource reuse, recycling, and energy efficiency. This approach aims to decouple production activities from the consumption of finite and non-renewable resources, maintaining materials in regenerative cycles (IBEAS, 2022).

In essence, the circular economy is a regenerative system that seeks to minimize resource use, waste generation, emissions, and energy losses through reduction, closing, and narrowing material and energy loops. These objectives are achieved through sustainable design, maintenance, repair, reuse, remanufacturing, refurbishment, and recycling of products (UNIFACS, 2023).

In Brazil, the National Solid Waste Policy (PNRS), established by Law No. 12,305/2010, sets guidelines for solid waste management, promoting the integration of circular economy principles. The PNRS encourages waste reduction, reuse, and recycling, aiming to engage society and production sectors in more sustainable practices (IBER, 2024).

The circular economy also focuses on developing products that can be easily disassembled and reused later, extending their lifecycle and reducing the demand for new resources (UNIFACS, 2023).

In recent years, Brazil has advanced in implementing circular economy practices, with various initiatives and public policies supporting this transition. Reverse logistics, for instance, is a key tool for the circular economy in the country, referring to the process of returning products and packaging to the production cycle after their use (IBER, 2024).

The circular economy provides an efficient alternative for solid waste management by reintegrating materials into production chains and increasing the added value and lifespan of by-products. This approach is essential for minimizing waste and ensuring the reuse of materials that can be reincorporated into production processes (IBEAS, 2022).

### 2.1 Urban Solid Waste

As urban centers grow, so does the amount of waste, and these are mainly the ones that take the longest to degrade in the environment by detrimental agents. Therefore, a large part of this material is deposited in inappropriate places such as rivers and soils, which affects biodiversity (VIANNA, 2015). Even though there are typologies of the word pollution, the concept ends up focusing, in general, on the factors that cause environmental degradation (MARQUES et al., 2014). Valle (2004) describes that environmental pollution can be defined as any human act or emission that causes a harmful imbalance to the environment in the short or long term through the release of substances or energy that act in water, soil, air.

It is noteworthy that the debate on solid waste is evident in modern society, a fact observed by the recent implementation of the European directive, and in Brazil, with the creation of the national solid waste policy (DEUS et al. 2015). In this context, the National Solid Waste Policy (PNRS) through Law no. 12,305 / 2010 establishes the principles, objectives and tools, as well as the guidelines related to the management and integral management of solid waste. However, there is a certain delay on the part of Brazilian municipalities in complying with this law, both due to lack of economic resources and lack of knowledge of its benefits (GOMES et al., 2014). In addition, the structuring of a PNRS met one of the great challenges facing governments and society, the dimension of the problem of solid waste generation.

Regarding the amount of waste generated between 2010 and 2019, the generation of USW in Brazil registered a considerable increase, from 67 million to 79 million tons per year. In turn, the per capita generation increased from 348 kg/year1 to 379 kg/year. Figure 1 shows the difference between total generation and generation per person.

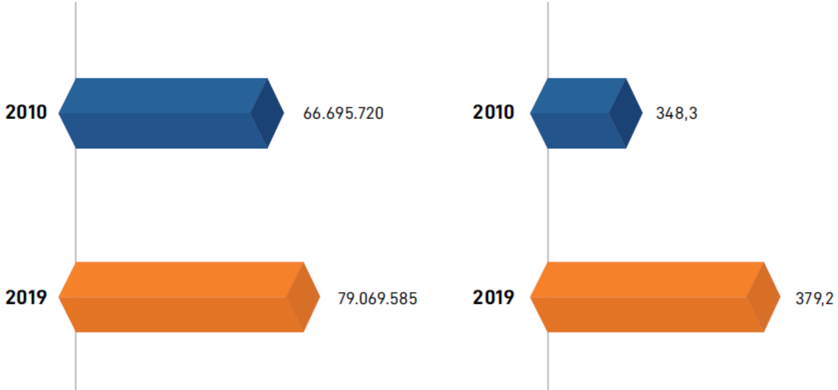

**Figure 1 -** USW generation in Brazil
Source: ABRELPE (2020).

The collection of solid urban waste grew in all regions of the country, from around 59 million tons in 2010 to 72.7 million tons and, in the same period, the collection coverage went from 88% to 92%. Figure 2 shows the projection of this collection.

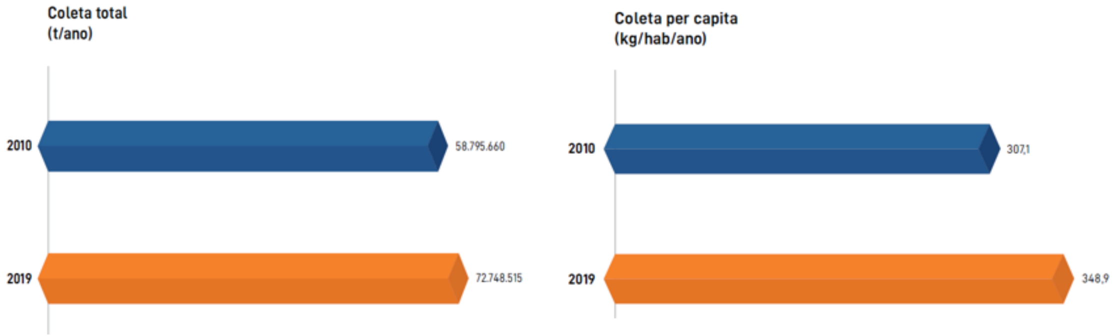

**Figure 2 -** USW collection in Brazil
Source: ABRELPE (2020).

Final disposal is one of the environmentally suitable alternatives for the final disposal provided for by the National Solid Waste Policy (PNRS), provided that specific operating standards are observed to avoid damage or risks to public health and safety and minimize negative environmental impacts (PNRS, 2020). In Brazil, most of the collected MSW goes to landfills, having registered an increase of 10 million tons in a decade, going from 33 million tons per year to 3 million tons. On the other hand, the amount of waste that goes to inadequate units (landfills and controlled landfills) also increased, from 25 million tons per year to just over 29 million tons per year (ABRELPE, 2020). Figure 3 shows that the correct disposal of waste has increased in the last ten years.

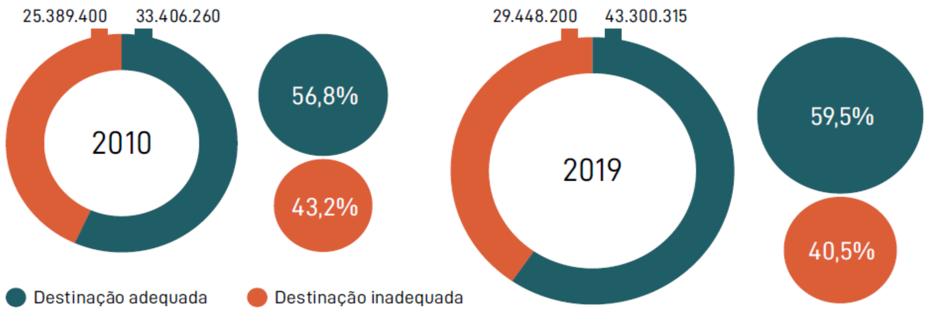

**Figure 3 -** Adequate vs inadequate final disposal of MSW in Brazil (t/year)
Source: ABRELPE (2020).

The best-known forms of final waste disposal are the Sanitary Landfill, Controlled Landfill and open-air dump. The dump is an inadequate form of final disposal of waste, which is characterized by the simple disposal of garbage on the ground, without measures to protect the environment or public health (IPT, 2020). Even though it is an inadequate form, according to data from the Brazilian Association of Public Cleaning and Special Waste Companies (ABRELPE, 2020), Brazil still has about three thousand dumps. The lack of financial resources on the part of the municipalities has prevented more accelerated advances in this area.

Knowledge of the composition of solid waste allows for adequate planning of the sector through strategies, public policies and specific processes that ensure the environmentally adequate disposal recommended by the PNRS, taking into account the best available and applicable alternatives, according to the types and quantities of existing waste. Figure 4 shows the percentage of types of waste discarded.

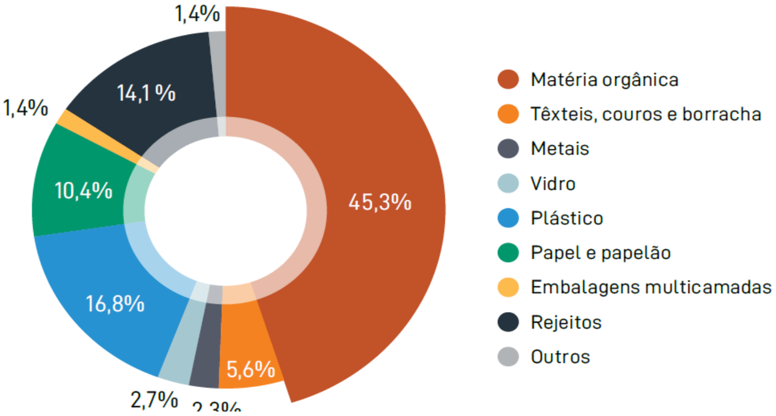

**Figure 4 -** Types of waste
Source: ABRELPE (2020).

For this study, plastic will be used in Brazil 16.8¨ of the total discarded waste is plastic. It causes a great impact on the environment and its recycling, in addition to generating extra income, can reduce the impacts on nature. The next section will address this issue.

## 2.2 Damage From Plastic Disposal

For Pimentel (2020), the production and consumption of plastic packaging has increased worldwide and the curve has been growing exponentially since the 50s. Due to its short shelf life, plastic packaging generates large amounts of solid waste (BERTRAM et al., 2017). The effective management of plastic packaging and its waste is part of the global challenges for sustainability (BESEN; FRACALANZA, 2016).

Plastic products are important and ubiquitous today, as they have multiple functions (EUROPEAN COMMISSION, 2018). Its production and use in scale began in the 1950s and grew exponentially, and it is estimated that 8.3 billion tons of plastics have already been acquired worldwide (GEYER et al., 2017).

The generation of plastic waste followed the exponential growth in the use of plastic products. It is estimated that in high and middle-income countries the mass fraction of licensees in municipal waste increased from less than 1% in 1960 to more than 10% in 2005

(JAMBECK et al., 2015). The global increase in the generation of waste from plastic materials is due to the growth of the plastic packaging market and the global change in the use of reusable packaging for one-way packaging (GEYER et al., 2017).

The generation of plastic material waste followed the exponential growth in the use of plastic material products. In high- and middle-income countries, it is estimated that the mass share of plastic materials in municipal solid waste increased from less than 1% in 1960 to more than 10% in 2005 (JAMBECK et al., 2015). The worldwide increase in the generation of waste from plastic materials was due to the growth of the plastic packaging market and the global change in the use of reusable to disposable containers (GEYER et al., 2017).

Plastics can be produced from fossil or biological raw materials and may or may not be biodegradable (PLASTICS EUROPE, 2018). Plant materials were initially used as raw material for the production of plastics (PIRINGER; BANER, 2008). However, currently, the most used raw materials are those of fossil origin (PIRINGER; BANER, 2008), such as fossil hydrocarbons that give rise to ethylene and propylene (GEYER et al., 2017).

The use of renewable raw materials for the production of plastics has increased in recent years, but their market share remains very low (GEUEKE et al., 2018). The current global production capacity of bioplastics (from renewable sources) and biodegradable plastic materials is only millions of tons (GEYER et al., 2017).

Plastic products present a number of potential risks to the environment and public health throughout their lifecycle, especially towards the end of their life. Regarding the production of plastic products, numerous studies have evaluated the environmental impacts of plastic packaging made with non-renewable raw materials (BARROS et al., 2018). Knowledge of the chemicals used for the conversion and processing of polymers into plastic products is also necessary in the production of plastic products, as measurable residual quantities can remain in the finished product (PIRINGER; BANER, 2008). This knowledge is essential for the toxicological evaluation of plastics (PIRINGER; BANER, 2008) during their use and subsequent disposal of waste, since these compounds can be transported in the packaged product or in the environment (GROH et al., 2019).

Improper disposal of plastic waste presents a series of risks to the environment and public health. It is estimated that 80 plastic pollution originates in the terrestrial environment (WALKER; XANTHOS, 2018). If they enter the environment, they will be exposed to the elements and become debris. Cozar et al. (2014) examined the distribution of plastic debris on the ocean surface and found debris accumulation mainly in the convergence zones of each of the five subtropical eddies.

Due to the hydrophobic characteristic of plastic waste, biofilms are formed on its surface (KOELMANS et al., 2017). Due to the adsorption power present in these plastic wastes, they can become vectors of other pollutants in the environment (CHEN et al., 2019). This biofilm formed on its surface can be contaminated with chemicals such as persistent organic pollutants (POPs), pesticides and heavy metals (KOELMANS et al., 2017). The adsorption, absorption and emission of chemical components from plastic waste depend on the environmental conditions of the environment and, therefore, the ecological risks of plastic differ in time and space throughout its lifetime (KOELMANS et al., 2017).

Plastics are mainly materials of fossil origin; the main raw material for the production of plastic is oil. However, only from the world production of oil and gas are used as raw materials for the manufacture of plastics. 3 to % are added to the energy requirement during processing, which is an average of 7.5% (HOPEWELL; DVORAK; KOSIOR, 2009; THOMPSON et al., 2009). It is considered a profitable raw material, lighter, more hygienic, more resistant, durable and inert. Unlike metals, it does not corrode. Its versatility allows the development of a wide variety of products with a wide range of applications (SINGLE, 2018).

Therefore, researchers such as Amélia et al. (2012); Silva, Santos and Silva (2013); Daltoé et al. (2016) understand that plastic debris is present in all terrestrial environments: in forests, rivers, oceans and urban spaces. Even in different formats, the most commonly found were plastic bags/bags/bags.

When discarded in nature, thanks to its impermeability, plastic can store rainwater and, therefore, help in the proliferation of Aedes aegypti (mosquito that transmits dengue, Zika virus and chikungunya). In nature, animals mistake them for food, and when they ingest them, they end up suffocating. Sea turtles can be cited as an example, as they often confuse the bags with jellyfish and die if ingested (ALVES; RIBEIRO; RICCI, 2011). Thus, plastic becomes a great aggressor of nature and life (RODRIGUES et al., 2011).

According to Derraik (2002), plastic reaches the ocean through actions such as the neglect of bathers who leave garbage on the beach; of ships and boats; of the rivers that carry it; from municipal sewers and, accidentally or not, from factories. Furthermore, according to the author, plastic packaging is the most common in the oceans. The plastic decomposition time in nature is estimated between 100 and 50 years (ALVES; RIBEIRO; RICCI, 2011; RODRIGUES et al., 2011; AMÉLIA et al., 2012), which varies according to the polymer used in its manufacture. Thus, the same bag can kill several animals during the time it remains in nature (ALVES; RIBEIRO; RICC, 2011).

It is estimated that disposable plastic originated in the 1920s and that is where the so-called "disposable fashion" emerged. In the end, it replaced all industrial segments around the world and was very successful, whether in civil construction or also in coffee. But even then, about 8.3 billion tons of plastic have already been produced, of which only 9% were recycled, it is not only harmful to the environment, but also harmful to health, contains various types of heavy metals and therefore, produces carbon. Each year, more than 100 million tons of disposable items are produced worldwide, with the main manufacturers concentrated in Asia (TOLEDO et al., 2017).

Brazil is one of the top five countries where disposable items are used. Regarding the use of disposable items, Brazil stands out for the use of more than 700 million glasses a day. Brazil's problem with this excessive use of glass, straws and inadequate disposal, which ends up affecting sanitation and the connection of rivers and beaches, can only be alleviated with the implementation of the 7Rs (Figure 3) for companies to start the rampant Reduce consumption (HILLIG et al., 2008).

## 3. RESEARCH METHOD

This study utilizes the system dynamics methodology to enhance the understanding of solid waste management processes. System dynamics supports decision-makers by enabling the simulation and evaluation of policy solutions within the modeled scenarios (THOMPSON; HOWICK; BELTON, 2016). Incorporating stakeholder knowledge into the model enriches its design and fosters a deeper understanding of system functionality and evolution (SCOTT; CAVANA; CAMERON, 2016).

System dynamics was selected for its ability to capture the nonlinear behavior of critical feedback loops. The method employs cause-and-effect diagrams to identify key variables and their causal relationships, facilitating a structured analysis of the system (SAHIN et al., 2019; LU et al., 2017). According to Navid, Ghaffarzadegan, and Rahmanda (2020), system dynamics serves as a tool for systemic thinking, offering insights into the investigation, analysis, and prediction of system behavior while addressing the complexities inherent in problem-solving and solution implementation.

This methodology allows decision-makers to model the intricate interconnections between internal system variables and external factors in detail. It emphasizes the development of both qualitative and quantitative models to analyze complex systems and study their dynamic behavior over time (JIAO et al., 2015). Sterman (2000) outlines five key stages in the application of system dynamics, which are detailed in the following section.

### 3.1 Stages of System Dynamics Modeling

The first step in system dynamics modeling is problem identification, which involves clearly defining the issue to be addressed and the model's objectives. This process requires mapping all variables involved, including their positive and negative feedback loops and time delays, which dictate interactions and control dynamics over short time intervals. The problem is structured using a cause-and-effect diagram, providing a foundational map that captures all components and their interactions. Based on this initial framework, an inventory and flow diagram was subsequently developed. According to Reddy et al. (2019), such diagrams are essential for analyzing a model's empirical validity through computer simulation. This research specifically addresses the following question: What is the impact of improper plastic disposal on pollutant emissions?

The second step is formulating the dynamic hypothesis, which aims to explain the causes underlying the identified problem. Lane, Munro, and Husemann (2016) emphasize the importance of testing the hypothesis to assess the model's adherence to real-world behaviors. In this study, the hypothesis was tested against the actual dynamics of municipal solid waste (MSW) management in the examined city. The resulting hypothesis is: "Recycling plastic is essential to reducing pollutant emissions."

The third step involves the formulation of a quantitative system dynamics model, or simulation model. This includes defining decision rules (mathematical equations), quantifying variables, constructing inventory and flow diagrams, and calibrating the model by assigning initial parameter values.

Model testing and verification constitute the fourth step, which ensures the model's reliability for scenario analysis and decision-making (STERMAN, 2000). Evaluation tasks include dimensional analysis, calibration, and verification. Dimensional analysis was performed using the unit verification function of the Vensim software. Model calibration, as described by Zare et al. (2019), involves comparing, adjusting, and evaluating simulation results to align them with observed or real-world data.

The fifth step focuses on linking potential strategy formulation with the evaluation of simulated results. This involves identifying scenarios—alternative strategies—and analyzing the simulated results over time (B'ERARD, 2010). The iterative process of scenario development and analysis, conducted collaboratively with experts and stakeholders, enhances the model's performance. The ultimate goal of the simulation model is to compare different "what-if" scenarios, forecast the system's future behavior, and provide actionable recommendations (STERMAN, 2000).

### 3.2 Scenario Planning

After completing the quantification and verification of the phase model, it is necessary to develop the scenarios to be evaluated and simulated. System dynamics is suitable for scenario analysis as this method allows for temporal exploration and insertion of different strategies in a simple model. For this, conditions were determined for each scenario. Scenario conditions require encompassing specific characteristics associated with variables. The scenarios were developed using a spectrum of assumptions outlining possible futures of the MSW generation system analyzed under different trajectories of changes that may exist. These assumptions were sensibly reflected throughout the scenario-based modeling procedure.

To develop these scenarios, different values were assigned to the variables used in the model, including some shadow-type variables. These variables have the function of inserting the temporal behavior of the model. The scenarios were simulated by assigning different values according to the need for each decision to be analyzed. In other words, variables are assigned different ranges of values based on the conditions of the selected scenario and associated configuration characteristics. The projected scenarios were based on data from Brazilian Association of Public Cleaning and Special Waste Companies (ABRELPE, 2021). According to data from ABRELPE (2021), optimistic estimates suggest that only 30% to 70% of waste produced in developing cities is collected to be thrown away, that is, it is not recycled. Table 1 presents the scenarios simulated in the study.

**Table 1 -** Projected Scenarios

| SCENARY | DISCARD | RECYCLING |
|---|---|---|
| CA [Current] | 92,00% | 8,00% |
| CB [Moderate] | 70,00% | 30,00% |
| CC [Optimistc] | 50,00% | 50,00% |

Source: Developed by the authors (2024).

### 3.3 Data Collection and Analysis

The data used in the study came from relevant articles in the modeled area, national and foreign government bases, in addition to the support of stakeholders in the area. The focus of the studies used is to improve the management of urban solid waste, environmental sustainability, system dynamics, in addition to environmental and financial guidelines for MSW management. The data reveal the composition of waste discarded in the country: 57.41% organic matter (food leftovers, spoiled food, bathroom trash), 16.49% plastic, 13.16% paper and cardboard, 2.34 % glass, 1.56% ferrous material, 0.51% aluminum, 0.46% inert material and 8.1% other material (IPEA, 2020). Plastic was chosen because it is the second largest discarded waste. The model was developed in the Vensim® environment in the version for academic use. Vensim® is a very didactic and functional program that allows the user to easily access all the details of the model's formulation.

## 4. MODEL DEVELOPMENT

Solid waste management has become an increasingly complex issue around the world in the last decade, demanding greater attention from all involved. This fact can also be observed in Brazil, mainly due to the influence of the principles, guidelines and the innovative and daring system of the National Solid Waste Policy, sanctioned in August 2010 (PNRS, 2010). Therefore, knowledge of the sector, based on what is current and reliable, is of fundamental importance, allowing for the monitoring of progress made, guiding the necessary adjustments and indicating the paths to universalization and the desired growth to become viable. There is no development in any sector without continuous monitoring of progress (ABRELPE, 2020).

Solid waste is one of the main groups that cause environmental degradation, both because of the large amount generated and because of its inadequate treatment and disposal (SANTOS et al., 2015). Currently, the disposal of urban waste is a critical issue around the world, both in developed and developing countries, as it is a source of risks to the environment and human health (LI et al., 2016). Sustainable solid waste management means reducing environmental damage and reducing costs for the government (NEVES; MENDONÇA, 2016)

Melquiades (2015) emphasizes that the inappropriate disposal of plastic is a critical problem in many cities in Brazil. According to Souza and Guadagnin (2009), the collection and transport stages spend between 60% and 80% in terms of overall costs when it comes to waste management. In this research, the generation of MSW and the possibility of increasing plastic recycling in a city in the state of Rio Grande do Sul were simulated. The simulation time was ten years, the variation in the generation of MSW was generated from the variation in population according to data collected on the Brazilian Institute of Geography and Statistics (IBGE) online platform (IBGE, 2021). The model must react to different factors, such as: population growth and the average generation of solid urban waste per capita.

For the definition of the simulation model variables (Figure 5) academic and governmental works in the area of solid waste were used (ABRELPE, 2021; IBGE, 2021). The evaluation of these was carried out with the participation of environmental managers and professionals in the field of solid waste. The selected variables, as well as their interrelationships with other variables, which influence the total values of generation and final disposal of urban solid waste, are:

- The annual birth rate (Natal Rate), and the annual mortality rate (Mortality Rate), directly influence the population inflows and outflows (AddPopulation and DiminuioçãoPop), which determine the total population (Populacao Atual) of the municipality. The natural or vegetative growth rate (total births - total deaths) was used in the model, which corresponds to the only possible form of growth or reduction of the world population and, when analyzing the growth of specific areas, it should also be considered migrations.
- The average amount of waste (RSUgeração) generated by each inhabitant multiplied by the total population of the municipality results in the total amount of waste (GeracaPerCapita) in the municipality.
- The variable responsible for storing the amount of plastic generated is the auxiliary

variable "GeraçãoResíduoPlástico", which in turn receives its value from the multiplication of the average amount of waste (RSUgeration) by the population's plastic generation rate (Per Ger Plástico).

- To analyze how much plastic is discarded or recycled, the variables “Discarded Plastic” and “Recycled Plastic” were generated. It is in these two variables that the scenarios are generated, the change in the behavior of the scenarios is made possible by the variables “TxDescarta” and “TxReciclado”, such values can be changed according to the desired simulation.
- The environmental analysis is generated from the variables “CO2 Reduction” and “CO2 Emission”. The reduction receives its data from the plastic recycling, how much the emission is added to the plastic disposal.

The model developed (Figure 5) represents the logic for population generation and consequently the amount of waste generated annually. To define the variables of the submodel, academic and governmental works in the area of solid waste were used, more specifically, ABRELPE (2021), Ministry of the Environment (2021) and IBGE (2021). The natural or vegetative growth rate (total births – total deaths) was used in the model, which corresponds to the only possible form of growth or reduction of the world population.

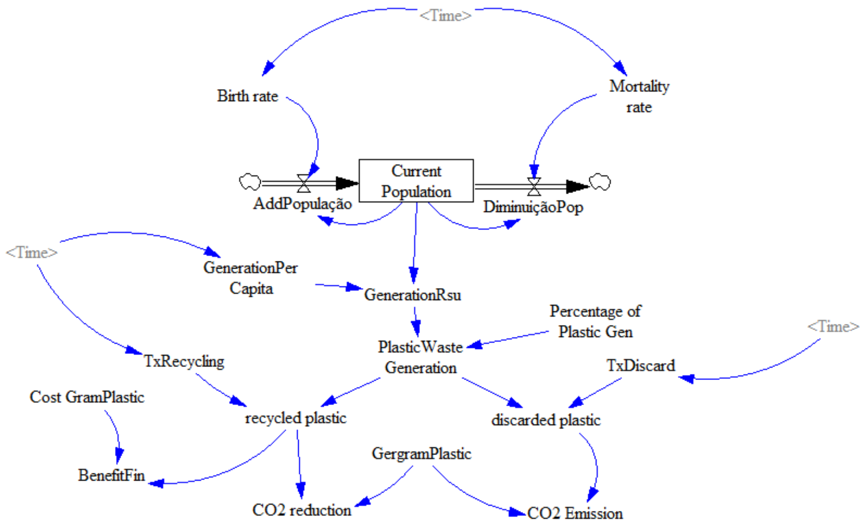

**Figure 5 -** Computational Model Developed
Source: Developed by the authors (2024).

To analyze the behavior of population growth in the region, it is necessary to understand the number of births and annual deaths. To support the data entered in these two rates, the IBGE projection platform was used. The projections of rates involving the size of the population of Brazil and the Federation Units are prepared based on information on the components of demographic dynamics from demographic censuses, sample household surveys and administrative records of births and deaths investigated by the IBGE. Given the transformations that have taken place in population dynamics, projections are continuously monitored and undergo periodic reviews, both for the incorporation of new information, when changes are detected in the hypotheses foreseen for the components, and for the updating of its calculation methodology improvements duly explained in the respective methodological reports. The projected values of the rates that influence the inhabitants are shown in Table 2.

**Table 2 -** Fees

| **Ano** | **Taxa** | |
|---|---|---|
| | **Nascimento** | **Mortalidade** |
| 2022 | 12,34 | 7,27 |
| 2023 | 12,2 | 7,36 |
| 2024 | 12,03 | 7,45 |
| 2025 | 11,85 | 7,54 |
| 2026 | 11,67 | 7,65 |
| 2027 | 11,5 | 7,76 |
| 2028 | 11,33 | 7,87 |
| 2029 | 11,16 | 7,99 |
| 2030 | 11 | 8,12 |
| 2031 | 10,84 | 8,26 |

Source: IBGE (2022).

## 5. EXPERIENCE OF COMPUTATIONAL MODELS

The first analysis to be developed based on the model refers to the population of the region examined, in year zero or in the first year of the simulation there were 80,729 people and in the following year (year 1) there was an increase of 3,326 people. In the ten years simulated there was an average oscillation around 3.8% and reached 108,781 inhabitants in the year 10. Knowing the possible population of the region and considering the average production of MSW per capita, it was possible to estimate the production of waste per capita for eleven years old. Thus, in year 0 (zero) approximately 30.6 tons of waste will be produced, reaching 130,293 thousand tons in year 10, with an average annual production of RSU of around 350,000 thousand tons.

Waste that is not collected is often deposited in open dumps, along streets or in riverbeds, and this practice induces environmental degradation and poses risks to public health (EZEAH et al. 2013). In this way, the importance of the discussion about procedures such as recycling and selective collection is highlighted. Figure 6 shows the projections of discarded and recycled plastic. It can be seen that one is the opposite of the other. The scenario that represents the current behavior (CA) is the one that discards the most and the one that recycles the least. The CC scenario is the one that recycles the most and the least discards.

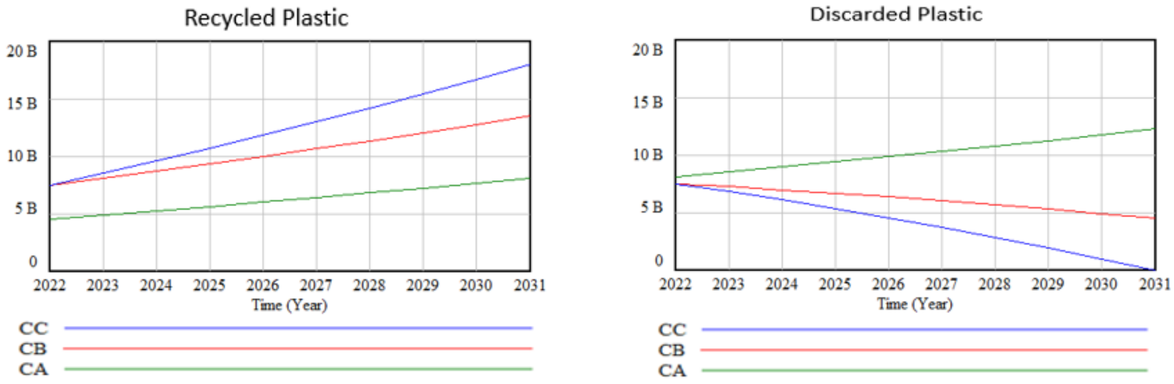

**Figure 6 -** Recycled Plastic x Discarded Plastic
Source: Simulation Result (2024).

The CC scenario, which represents an optimistic behavior, will be able to recycle around 18 thousand tons of plastic, while the current scenario (CA) will recycle a maximum of 6,500 tons. This difference will reflect in less CO2 emissions and will also be able to introduce new products to the market, supporting the circular economy and also adding income to low-income families. For Petit-Boix and Leipold (2018), the circular plastic economy will stimulate the new economic model in which nothing is discarded and all elements of the production chain are reused in the manufacture of new products, reducing the extraction of raw materials from nature.

Air pollution is one of the biggest environmental problems in the world, being a worrying factor both for the present and for the next generations (STATE ENVIRONMENT INSTITUTE, 2020). Therefore, the analysis of the model referring to the emission of carbon dioxide (CO2) resulting from the complete combustion of carbon is shown in Figure 7. In the simulation carried out, it can be seen that the CC Scenario has the highest reduction index of CO2, totaling, in the ten years simulated here, approximately 700 tons. This represents 4 tons more than the scenario with the highest emission rate (Current Scenario - CA), as in year 10 it will reduce up to 300 tons of CO2. The Modal Scenario also presents greater CO2 reduction when compared to the Current Scenario, it will emit approximately 550 tons, about 250 tons more than the Current Scenario. Regarding emissions, the current scenario will emit up to 5 thousand tons of $CO^2$, around 500 thousand tons per year.

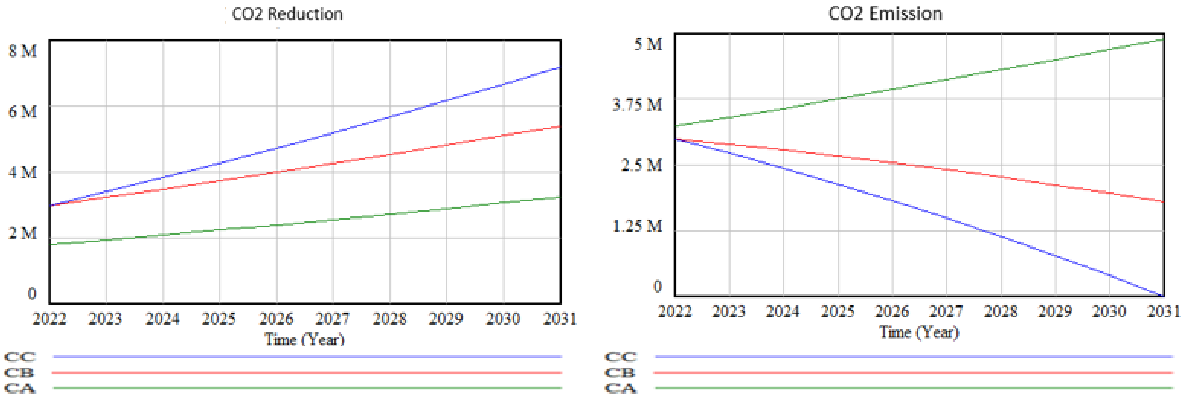

**Figure 7 -** CO2 generation
Source: Simulation Result (2024).

Finally, the financial gain from plastic recycling was analyzed. In this sense, the analysis of the system dynamics presented a model that will be able to know the amount of generated waste. With it, it is possible to identify, for example, the percentage of recyclable waste and estimate the potential economic gain from the sale and reuse of these materials. From the segregation and weighing of urban solid waste, it is possible to make a monthly estimate of the economic potential of these wastes based on prices provided by specialized companies (CANES et al., 2013).

Considering the quantities and types of plastics generated, the economic gain with the possible commercialization of these materials was estimated. Initially, the gain was calculated considering the sale of recyclable waste. Hypothetically, it was suggested to sell the materials through participation in a Selective Collection program. From Figure 8, it can be seen that the CC scenario may generate, with the sale of plastic recycling, approximately R$ 1,748,000.00, while the CB scenario, which is the moderate scenario, may add approximately R$ on a daily basis. 1,378,000.00, while the current scenario generates some value with recycling, but it is around one million less compared to the CC scenario and seven hundred thousand reais when compared to the CB scenario.

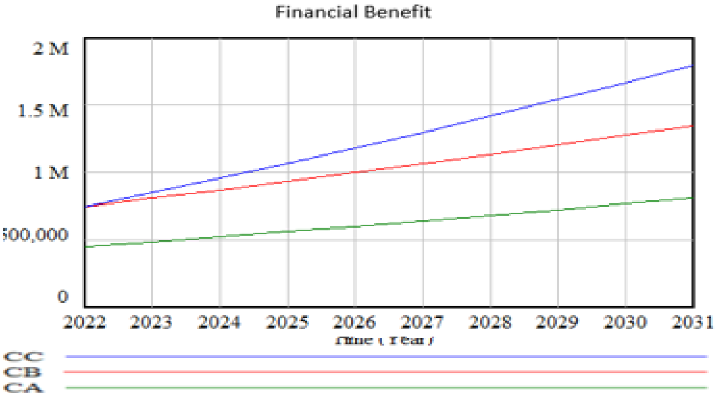

**Figure 8.** Financial Benefit
Source: Simulation Result (2024).

It is observed by the simulations generated in this work that there is a big difference in financial and environmental terms between the proposed scenarios. This demonstrates the importance of using knowledge to better manage Urban Solid Waste.

## 5. FINAL CONSIDERATIONS

The problems of MSW have become a problem both in Brazil and in other parts of the world and, in addition to the significant financial costs, the environmental damage caused by the harvest must be considered, since the collection trucks burn tons of fuel oil. Consequently, this requires the search for ways to alleviate these problems, seeking alternatives to reduce both the negative economic impacts and the environmental impacts derived from urban solid waste.

The proper disposal of solid waste is one of the major problems faced in Brazilian cities, being stimulated by the increasing production of waste (SOUZA et al., 2013). The current growth of the urban population is intrinsically linked to the increase in consumption rates, thus increasing the use of raw materials and consequently the generation of solid waste, reflecting our production and consumption patterns (CNMA, 2013). Solid waste is understood as materials or substances in solid or semi-solid state resulting from human activities, which are discarded and require proper final disposal, given nature and available technology (CARVALHO; PEREIRA, 2013).

Therefore, considering the proposal of this article and among the analyzes carried out, it was found in the ten simulated years that the number of inhabitants in the region considered for the purposes of the study reached a total of 108,781 at the end of the simulation period. From this it was possible to estimate the production of waste per capita in the period, where it was found that the average annual production of MSW will be around

350,000 tons. Considering the goals of the PNRS, aiming to gradually reduce the amount of material disposed of in landfills, three scenarios were proposed with different rates of recycling and disposal of plastic waste.

As for the simulated scenarios reached the proposed objective and also answered the generated dynamic hypothesis, the scenarios confirmed that recycling in a higher percentage will reduce environmental damage and will also provide more income for needy families. The optimistic scenario, called CC scenario, was the one with the highest performance, both financially and environmentally, the current scenario is the one with the worst performance, pointing to the negative impact of poor management of urban solid waste, especially plastic.

At the end of this study, it is expected that it has contributed to managers and government officials seeking new options in view of the problem faced with MSW and, at the same time, being able to find ways to take advantage of the advantages provided by plastic recycling. Aiming at the continuity of this study, as a recommendation for future research, an investigation with more urban solid waste is indicated, taking into account the benefits that could be achieved with recycling on a larger scale.

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