CHEMICAL ENGINEERING TRANSACTIONS

VOL. 103, 2023

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Panos Seferlis, Yee Van Fan, Athanasios Papadopoulos

**ISBN** 979-12-81206-02-1; **ISSN** 2283-9216

DOI: 10.3303/CET23103001

# A Simulation Model to Analyze the Efficacy of Plastic Waste Management Policies

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Plastics play an integral part in industrial development. However, plastic wastes have likewise become one of the largest sources of pollution. Inadequate treatment and improper disposal of plastics continue to persist, causing health hazards and endangering marine life. This study adopts a System Dynamics approach to understand the propagation of plastic wastes from usage to eventual disposal. A model is developed to simulate the efficacy of different strategies and plastic wastes management policies currently adopted by government and private sectors. It quantifies the importance of proactive solutions versus reactive measures to mitigate plastic pollution. Scenario analysis in the form of parametric changes is used to understand the critical factors that significantly controls the behavior of the stakeholders in the system. The model's integrative view of the plastic waste problem improves its capability to develop policies that can effectively reverse the increasing trend of plastic wastes.

## 1. Introduction

Plastic is a cheap, lightweight, versatile, and resistant object that is useful for many functions in different industries (Ritchie and Roser, 2022). The viability of plastics has however led to it being a significant source of waste. Improper waste disposal further aggravates the problem it poses to the environment. According to Gibovic and Bikfalvi (2021), there are about five to thirteen million tons of plastics released into the ocean every year on a global scale, which is 1.5 to 4 % of the global plastics production.

Thushari and Senevirathna (2020) classified plastic waste management strategies into two: proactive versus reactive. Proactive solutions target the reduction of plastic usage by identifying alternative materials such as natural polymers, among others. Reactive solutions on the other hand involve treating pollution once plastics have entered the marine environment. The latter's accessibility and familiarity make them the more popular choice for organizations, including both private and public sectors. In addition, most firms opt for end-of-pipe techniques or short-term reactive strategies in their environmental management since proactive measures are perceived as non-value adding and financially straining in the shareholders' wealth at the point of time (Kaur, 2021). Although researchers, academics, and policy makers acknowledge that proactive environmental management is important, this is still not clearly captured in frameworks or models on environmental issues due to lack of proper guidelines on operationalizing it at the firm level (Potrich et al., 2019).

Worsening plastic pollution has driven the development of initiatives and proper practices of plastic use and waste management. The literature shows that research works have utilized life cycle assessment and plastic footprinting methods to guide companies in addressing plastic pollution (Boucher and Billard, 2019). Zong (2021) likewise used regression modelling to estimate the upward trend of plastic wastes in oceans, in which an exponential trend is foreseen for plastic pollution. This study presents an alternative perspective by developing a dynamic representation of the plastic waste environment. In this work, a simulation model based on the System Dynamic approach is developed to assess the effects of initiatives on plastic pollution and their corresponding degree of effectiveness. The study specifically aims to evaluate the effectiveness of different waste management practices in addressing the impacts of plastic waste on the marine environment.

Paper Received: 22 February 2023; Revised: 27 March 2023; Accepted: 25 May 2023
Please cite this article as: Tee M., Sy C., 2023, A Simulation Model to Analyze the Efficacy of Plastic Waste Management Policies, Chemical Engineering Transactions, 103, 1-6 DOI:10.3303/CET23103001

## 2. System definition

The causal loop diagram in Figure 1 provides a high-level description of the system under study. Variables are connected through arrows, which represent the causations. The (+) and (-) signs signify the direction of change among two variables. A (+) sign implies that the variables change in the same direction while a (-) sign signifies an opposite change. The succession of these relationships forms the feedback loops; such that a change in each variable travels around the loop and comes back to affect the same variable (Sy, 2017). The classifications of these loops according to the two mentioned types are determined by the number of negative causal links present. A balancing (B) feedback loop contains an odd number of negative causal links while a reinforcing (R) feedback loop may contain none or an even number of negative causal links.

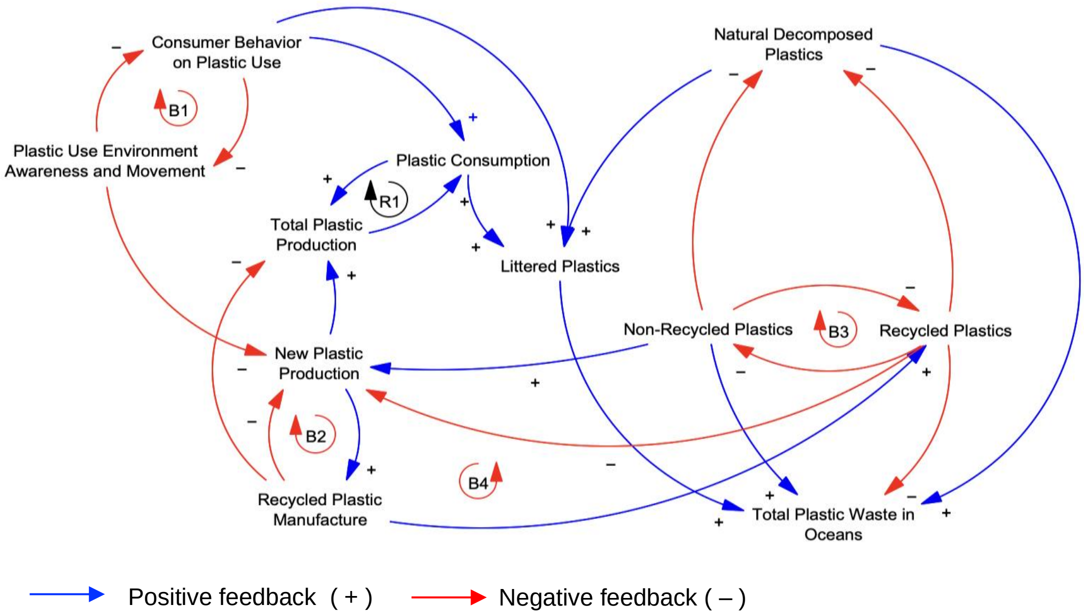


*Figure 1: Causal loop diagram for the global plastic system*

The balancing loop B1 refers to the interactions between consumer behavior and plastic use environment awareness and movement. The higher the environmental awareness a consumer has, the lower the consumer behavior towards plastic use. It was found that the level of awareness on plastic pollution influences an individual's plastic consumption (Thomas et al., 2019). The balancing loop B2 refers to the interactions between the production types of new plastic and recycled plastic. New plastic production refers to the plastics that are at their initial life, while recycled plastic manufacture refers to the plastics whose end-of-life status has restarted due to recycling processes. There is a relationship between these variables since more recycled plastics calls for less new plastics being produced. However, if more new plastics are produced, there is a higher tendency of recycling plastics. These relationships are based on the study of Khadke et al. (2021), where recycling is an increasing trend, which affects the current production methods.

The balancing loop B3 refers to the interactions between the main types of plastic waste management, which are the recycling and nonrecycling methods. They are inversely proportional to each other, as an increase in recycling activities will naturally lessen the rate of activities for the other waste management methods (Khadke et al., 2021). Meanwhile, the balancing loop B4 refers to the interaction between the recycling activities and production of new plastics. This is an extended loop for B2, where this loop integrates the quantity of recycled plastics into the loop. Finally, the only reinforcing loop in the system refers to the interaction between the total plastic production and plastic consumption. Demand for plastics increases its production rate. This relationship is based on the database of Our World in Data (Ritchie and Roser, 2022), where there exists an increasing trend for both production of plastics and consumption.

## 3. Stock flow diagram

The System Dynamics (SD) approach utilizes the stock flow diagram shown in Figure 2a to model and provide quantification for the identified relationships in the causal loop diagram. The diagram is translated into integral equations, usually facilitated using high-level simulation programs, such as Vensim PLE that is used in this study. System variables are generally classified according to two types: stocks and flows. Stock variables represent the accumulations in the system. These variables determine the state of the system and are dependent on past values. The following represents general forms of these equations:

$$Stock(t) = \int_{t_o}^{t} [Inflows(s) - Outflows(s)]ds + Stock(t_o) \quad (1)$$

where, *Inflows(s)* represents the value for the inflow at any time *s* between the initial time $t_o$ and the current time $t$. Equivalently, the net rate change of any stock, its derivative, is the inflow less the outflow, defining the differential equation,

$$\frac{d(Stock)}{dt} = Inflow(t) - Outflow(t) \quad (2)$$

Total plastic waste and plastic production are the two stock variables in this system. In contrast, flows are unable to accumulate through time. They simply alter the quantity of the stocks by being either an inflow or an outflow to it. Examples of the flows are the creation of new plastics and rate by which these are recycled. The quantity of flows is determined by summating the inflows less the outflows of a particular stock. The resulting base run from the Vensim model is shown in Figure 2b. This coincides with the data presented by Ritchie and Roser (2022), wherein total plastic wastes are shown to have exponentially increased through the years and will continue to do so in the foreseeable future.

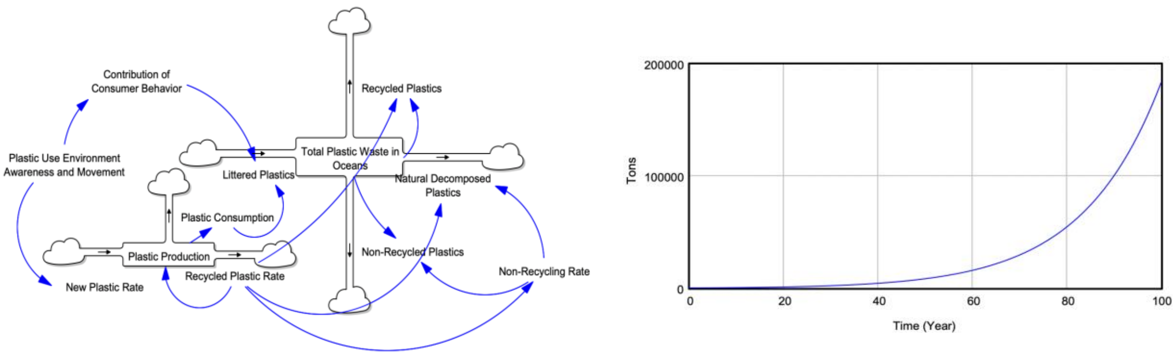


*Figure 2: (a) Stock flow diagram for the global plastic system and (b) base run for total plastic waste*

## 4. Computational experiments

The model is a generalized representation of plastic waste accumulation. Situation-specific scenarios can then be simulated by subjecting the base model to parametric changes. For instance, these changes can investigate the effects of a country investing more in plastic waste mitigation versus one that does not. Parametric changes were also done to the model to see whether these can alter the exponential trend seen in the base run. Figure 3a shows the results when the initial environmental awareness rating was changed in the system.

Lee at al. (2015) discovered a stark contrast in the level of environmental awareness between developed and developing countries. They found that 40 % of adults worldwide have never heard of environmental issues such as climate change. This number rises to 65 % in developing countries like Bangladesh and India. Environmental awareness is determined to be a vital factor in affecting consumer behavior since ignorance to the impact of plastic consumption contributes to more consumption and waste generation (Wongklaw, 2020). Personal beliefs have a high impact on the public response to such issues (Thomas et al., 2019). A change in trend was seen when the rating is adjusted from the current estimate of 2.8 % (taken from Soares et al., 2021), to 70 % awareness level. It is to be noted that it had to cross this percentage level of awareness before a significant change could be observed in the simulation. After the initialization (as seen from the spike), the trend decreases smoothly over time approaching to zero. This shows that higher environmental awareness significantly affects the problem variable positively as there is less plastic pollution in the oceans. Specifically, this is due to less littering occurring and less new plastics produced, which influences the recycling activities. The feedback loops of consumer behavior and plastic production are directly influenced, while the recycling activities are indirectly influenced by the parameter change.

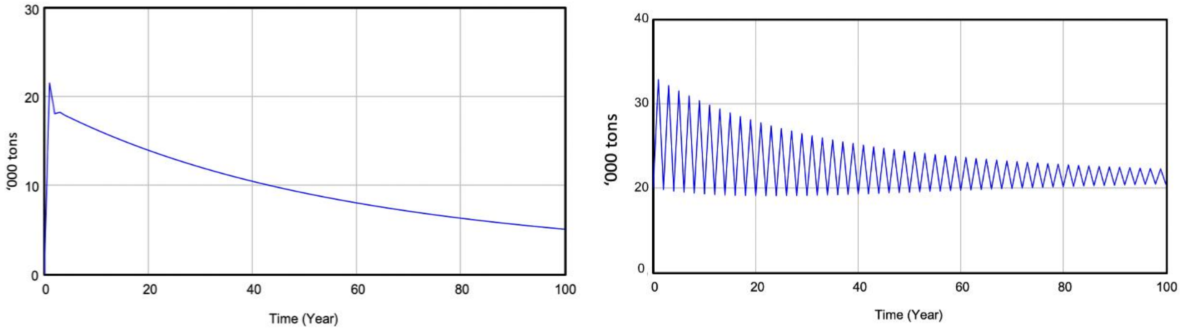


*Figure 3: (a) Total plastic waste under changes in environmental awareness rating and (b) total plastic waste under changes in level of recycling activities*

The Organisation for Economic Co-operation and Development (OECD)'s Global Plastic Outlook showed that only 9 % of plastic wastes are recycled (OECD, 2022). OECD countries are now setting their respective recycling targets and investing on improved recycling technologies to address this. As recycling activities are bound to increase through time (Khadke et al. 2021), the initial recycling rate is likewise adjusted until a significant change in the problem variable is observed. Figure 3b shows that the exponential trend will change when at least 24 % of plastic wastes are recycled such that an oscillating behavior is observed. This change in behavior is a product of a balancing loop between recycling versus nonrecycling activities. The oscillating behavior signifies that a sustained effort is required to constantly ensure that recycling targets are met. Otherwise, the behavior will revert to the original exponentially increasing trend.

### 4.1 Contribution of pollution reduction efforts

The observations from the parametric changes are then used to identify and compare plastic waste management policies that fall under reactive and proactive solutions. Pollution reduction efforts are determined to be one of the reactive solutions for plastic waste pollution. An example of which includes rehabilitation activities and clean up drives that both individuals and organizations mount to reduce the amount of plastic pollution in the marine environment. Figure 4a shows the new stock flow diagram with the addition of the clean-up variable, which is modeled to decrease the inflows attributed to littered plastics. Based on the results from Figure 4b, the behavior is like the base run, with evidence of a slowdown in the growth of the problem variable. There is an improvement through the slow growth but there are no signs of a trend reversal. The total amount of plastic will continue to increase and will not approach zero over time.

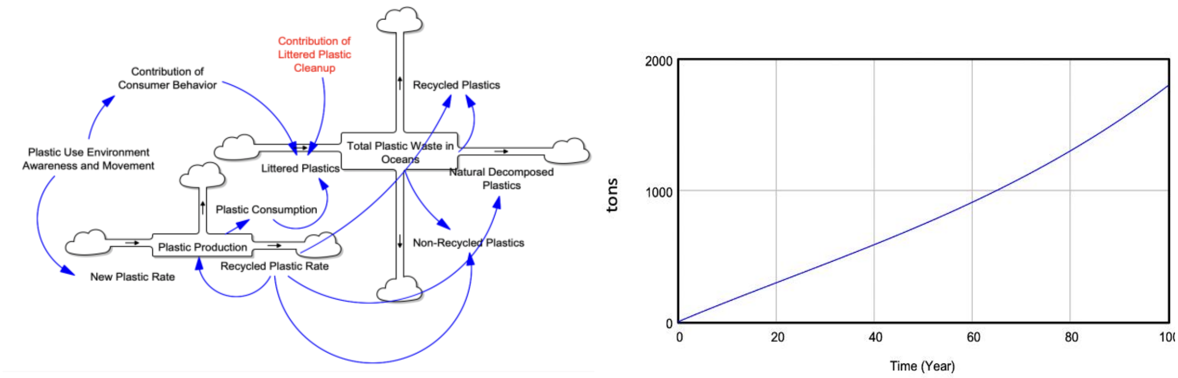


*Figure 4: (a) Stock flow diagram for the global plastic system under pollution reduction efforts and (b) total plastic waste under increased efforts to reduce plastic pollution*

### 4.2 Contribution of circular economy initiatives

Circular economy initiatives are determined to be one of the proactive solutions due to its continuous improvement and development on the production, consumption, and management of plastics. Examples of these initiatives include capacity-building performed by organizations advocating for a plastic-free environment with the goal of shifting mindsets and actions of people (Thushari and Senevirathna, 2020). Given this, the change is enacted to the system through the environmental awareness variable. In contrast to the previous waste management program, this policy affects the amount of plastic wastes indirectly. Figure 5a shows the new stock flow diagram showing how such advocacies target the awareness level of the public and consumers. The results in Figure 5b shows a change in the behavior of total plastic wastes. At the beginning of the period, there is still growth in total plastic wastes, which eventually decreases over time. The increase can be attributed to the delayed effect of the awareness campaign. The adoption of this concept would take some time to materialize and take effect with the generation of plastic wastes. The effect of this policy is more significant than pollution reduction efforts since such initiatives attempt to target the usage of plastics, rather than wastes generated from it.

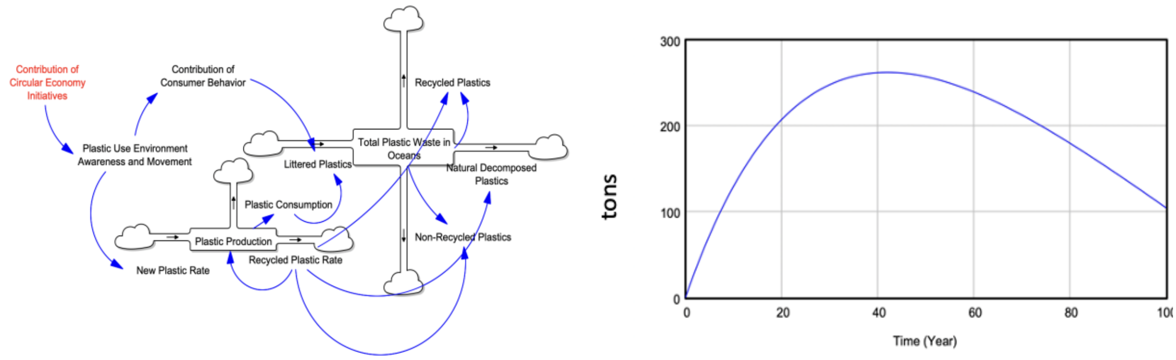


*Figure 5: (a) Stock flow diagram for the global plastic system under circular economy initiatives and (b) total plastic waste under circular economy initiatives*

### 4.3 Contribution of reformed plastic production

Process reformation on plastic production is determined to be one of the proactive solutions, where this affects how an industry processes plastic internally. Given this, the policy of reformation as a proactive solution is inputted in the system affecting the production variable. This differs from the previous waste management practices as it primarily targets the source and calls for a reduction of plastic usage in general. Figure 6a shows the new stock flow diagram with the variable, while Figure 6b shows the results of the model run.

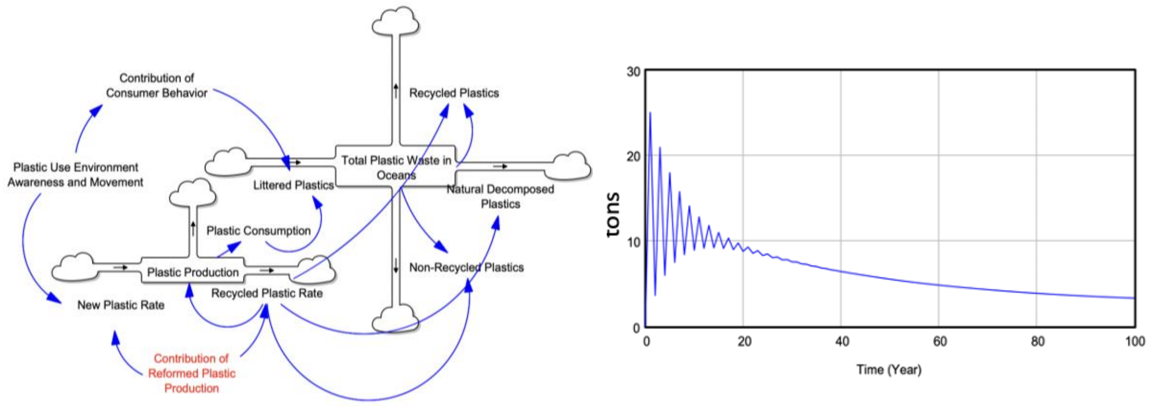


*Figure 6: (a) Stock flow diagram for the global plastic system under reformed plastic production and (b) total plastic waste under reformed plastic production*

The oscillations are attributed to the initialization phase of the system upon the introduction of the management policy. After which, the graph then shows a continued decrease in the number of plastic wastes. This reaffirms the observations from previous research works that the best course of action is to eliminate the source and find alternatives to plastics. While these types of solutions may be more expensive than reactive solutions (Topan and Van der Heijden, 2020), proactive solutions yield more desirable results due to its long -lasting effects to the system. Such programs will be more difficult to mount but they are designed for sustainability and longevity.

## 5. Conclusions

Plastic pollution is a persisting problem in society due to the lack of environmental awareness and initiatives to act upon it. The study developed a system dynamics model using the Vensim software to replicate the system of plastic pollution. The computational experiments showed that recycling activities and environmental awareness of the public are significant drivers for the success of plastic wastes management. These variables must be prioritized to help reduce plastic wastes in our environment. Through the findings of the model, it is recommended for industries and governments to continuously implement projects, initiatives, and regulations to improve environmental awareness and reduce the production of new plastics. In addition, it is found that proactive solutions (i.e., regulations and reformed processes) are more effective than reactive solutions in terms of sustainability, desirability, and speed. While it is impossible to eliminate the use of plastics, there should be conscious efforts to reduce the dependency to it. The costs associated to these programs prove to be barriers for the adoption of industries and governments. The challenge therefore is to enact waste management practices that can change such mindsets and for continued efforts to target the source of plastic waste. For further research, the concept of circular economy may be integrated into the modeling as the research focused on a linear supply chain for plastic wastes production, consumption, and waste management. A more detailed look at the interrelationships of variables could also be done, exploring how awareness and advocacies affect the choice of plastic as a raw material and how plastics propagate from production, usage and to disposal.

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