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Imagine a world without plastics. Well, that was the world before the mass production of plastics in the middle of the 20th century, just several decades ago. Yet it seems to be a very distant past; an ungraspable reality for us. Every day, we encounter and use plastics, often getting them brand-new and discarding them just mere hours later. Thus, the unavoidable consequence—the ever-growing pile of plastic waste.

In this paper, we show step-by-step the assumptions needed to simplify matters, construct the model on the cycle of plastics, and the justification behind it. For the construction, we use a compartment method with 6 compartments (production, new plastics, single-use waste, disposable waste, recycled plastics, and mitigated plastics) which is widely used in model building and yet is quite powerful. Then, we present the model and how we can control the amount of disposable and single-use plastic waste so that it will not grow without bound to an environmentally unsafe level (in other words, the conditions needed such that the amount is stable or decreasing). After that, we estimate the parameters needed in the model using real-world data from 2015. By using those parameters, we simulate the model for 10 years forward to several regions based on their income (lower/LI, lower-middle/LMI, upper-middle/UMI, high/HI) and observe what happens to the amount of both types of plastic waste. Based on that simulation, we suggest several options on what should be done.

In the end, we conclude that

- Single-use and disposable plastic waste may accumulate uncontrollably if its production rate exceeds its recycling and mitigation rates.
- High-income countries tend to accumulate high single-use and disposable plastic waste and the amount tends to grow without bound.
- The global maximum value that can be safely mitigated annually is $3.582693886 \times 10^{10}$ tons for disposable plastic waste and $5.560963988 \times 10^{10}$ tons for single-use plastic waste.

We also suggest that

- LI countries should lower their plastic production rate by 8.45%
- LMI countries should keep their plastic production, recycling, and mitigation rate at their current level.
- UMI countries should lower their plastics production by 5.06% in 5 years and increase their recycling rate by 35.51% in 10 years.
- HI countries should boost their recycling rate 3-fold and mitigation rate 6-fold in 10 years and reduce their plastic production by half in 10 years.

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Plastic Waste Management :
A Regional Income Approach

1. Abstract

In 2050, the total of plastic production will be approximately 34,000 Mt, while 9,000 Mt waste being recycled, 12,000 Mt being incinerated, and 12,000 Mt being discarded (Gayer, 2017). Obviously, the contrast that being made by those number is quite concerning. Nowadays, numerous efforts have been made to mitigate plastic waste, yet some of these efforts are unsuccessful. Ogawa (2008) stated that several solid waste management projects have been carried out in developing countries in collaboration with external support agencies. However, many projects could not support themselves or expand further when the external agencies discontinued their support.

This paper will focus on how we may address the matter of single-use and disposable plastic waste mitigation. The basic design of our model is based on compartment model and the idea is to predict the maximum amount of single-use and disposable waste. We will use region-based approach based on gross national income of each country. The value then will be the standards for our recommendation to treat the problem related to waste management.

Keywords : plastics, waste management, single-use, disposable, mitigation, gross national income, GNI

2. Introduction

Plastic has become an unavoidable item in our daily lives, yet its existence has been the source of environmental controversies over the last few years. In the early days of plastics, it had been promoted as an economically and environmentally friendly material to replace traditionally used materials such as paper and wood which required more capital and resources to produce. But as the number of plastic wastes accumulated, we began to realize its negative impact to the earth and the organisms.

Geyer, Jambeck, and Law (2017) estimated that 60% percent of all plastics ever produced were discarded and accumulating in landfills or the natural environment. Geyer et al. (2017) further estimated that out of cumulative plastic waste generation between 1950-2015, 12% has been incinerated and 9% has been recycled, 10% of which has been recycled more than once.

There are numerous studies which documented the various effects of microplastics in ocean and land. It suggested that the mortality rate of European sea bass larvae increased significantly with the ingestion of polyethylene (the most commonly used plastic material) microbeads (D. Mazurais, 2015). For land mammals, polystyrene microplastics exposure altered the structure of mice gut microbiota (Yuanxiang Jin, 2019). Furthermore, Pivokonsky et al. (2018) found microplastics in all raw and treated water samples from three water treatment plants, and while the amount of microplastics was significantly lower in the treated water, it was still not negligible.

Thus, it is of the utmost importance to address the issue of mitigating plastic waste in the most environmentally healthy way as possible. In this paper, we will develop a model of plastic journey from its creation to recycling and mitigation and use that model to estimate the maximum possible amount of single-use and disposable plastics that can be mitigated in an environmentally safe way. We will also use that model to set a target to reduce plastic waste by varying several parameters in different regions that depend on several factors such as the market demand on plastics, the lifestyles of the region's inhabitants and their readiness to use minimum amount of plastics, technological capabilities of said region, and the availability of alternative material to plastics.

3. Model Construction

3.1. Hypothesis

We hypothesized that:

a. Single use and disposable plastic waste may accumulate uncontrollably if its production rate exceeds its recycling and mitigation rates.
b. High-income countries tend to accumulate higher single use and disposable plastic waste than other level of income countries despite their capital and technological resource in recycling and mitigating those waste.

3.2. Assumptions

a) Single internal source and mitigation (including recycling)

To simplify model, there is no plastic waste exchange between regions. It is justified because several countries have tightened the regulation on the waste exchange, thus the amount of plastic waste from outside source is considered to be negligible compared to internal source.

b) Simulated during short period of time

c) Constant new plastic production rate

During simulation, we assumed the rate production of new plastic product to be a constant during that t period because the model will be simulated for a short period of time. Furthermore, plastic production rate per country is determined by the total population of the country.

d) Equal probability of mitigation

All plastic waste (single-use and disposable) have the same probability to be mitigated.

e) Constant mitigation capability

Again, because the model is only simulated for a short period of time, there is presumably no change of policy or advancement on the mitigation or recycling capability of a region.

f) Constant usability period of single-use and disposable plastics

There is no significant variation on how long single-use and disposable plastics are being used. Hence, the rate is considered constant worldwide.

3.3. Variables and Parameters

Variables

N_P : New plastics product (tons)

Su: Single-use plastic waste (tons)

D : Disposable plastic waste (tons)

M : Mitigated (excluding recycled) plastic waste (tons)

R : Recycled plastic waste (tons)

Parameters

P : Plastic waste production per time unit t (tons/year)

r_D : Rate of disposable plastic product to be discarded (1/year)

r_{Su}: Rate of single-use plastic product to be discarded (1/year)

r_R : Recycling rate (tons/year)

r_M : Mitigation rate (tons/year)

3.4. Model Description

We will adopt compartment method to construct the model. It has been assumed that the rate of plastic production to be a constant. Thus, the number of plastics in use grows with a rate

$$\frac{d\left(N_p + R\right)^+}{dt} = P$$

It is logical to state that the number of plastics in use shrinks proportionally to itself, because more plastics in use means more of it will be utilized.

$$\frac{d\left(N_p + R\right)^-}{dt} = -r_{Su}(N_P + R) - r_D(N_P + R)$$

Combined,

$$\frac{d(N_P + R)}{dt} = P - r_{Su}(N_P + R) - r_D(N_P + R)$$

The number of single-use plastics waste is proportional to the number of plastics in use, assuming that its proportion to the number of plastics in use is constant, so the growth will be

$$\frac{dS_U{}^+}{dt} = r_{Su}(N_P + R)$$

Because it has been assumed that the mitigation and recycling capability are constants, the number of single-use plastics will shrink with a rate

$$\frac{dS_U{}^-}{dt} = -r_R - r_M$$

Combined,

$$\frac{dS_U}{dt} = r_{Su}(N_P + R) - r_R - r_M$$

With the same approach, it is easy to follow that

$$\frac{dD}{dt} = r_D(N_P + R) - r_M$$

$$\frac{dR}{dt} = r_R$$

$$\frac{dM}{dt} = r_M$$

Below is the diagram we constructed to illustrate the plastic waste model:

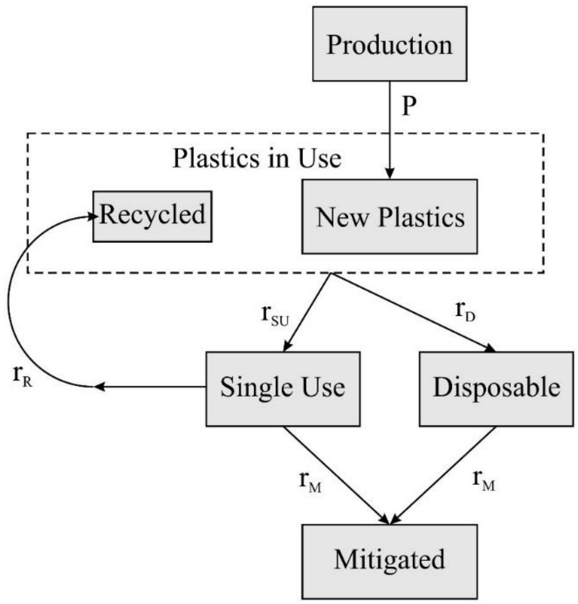


Figure 1 : Diagram of Plastic Waste Model

Based on the diagram, we use the concept of system of differential equation to make a model for our cycle.

$$\frac{d(N_P + R)}{dt} = P - r_{Su}(N_P + R) - r_D(N_P + R)$$

$$\frac{dS_U}{dt} = r_{Su}(N_P + R) - r_R - r_M$$

$$\frac{dD}{dt} = r_D(N_P + R) - r_M$$

$$\frac{dR}{dt} = r_R$$

$$\frac{dM}{dt} = r_M$$

Solving the last two equations,

$R(t) = tr_R + C_4$ .... **(3.4.1)**

$M(t) = tr_M + C_5$ .... **(3.4.2)**

Thus, for the first three equations, we have a first-order differential equation system

$$\begin{pmatrix} N_P \\ S_U \\ D \end{pmatrix}' = \begin{pmatrix} 0 & -(r_{Su} + r_D) & 0 \\ r_{Su} & 0 & 0 \\ r_D & 0 & 0 \end{pmatrix} \begin{pmatrix} N_P \\ S_U \\ D \end{pmatrix} + \begin{pmatrix} P - (r_{Su} + r_D)(tr_R + C_4) \\ r_{Su}(tr_R + C_4) - r_R - r_M \\ r_D(tr_R + C_4) - r_M \end{pmatrix}$$

Using some *MAPLE*, the solution is

$Np(t) = \frac{C_3 r_D e^{-(r_D + r_{Su})t} + C_3 r_{Su} e^{-(r_D + r_{Su})t} - (r_D r_R + r_R r_{Su})t - C_4(r_D + r_{Su}) + P}{r_D + r_{su}}$ .... **(3.4.3)**

$Su(t) = -\frac{C_3 r_{Su} e^{-(r_D + r_{Su})t} + (-r_{Su}P + r_D r_r + r_D r_M + r_M r_{Su} + r_R r_{Su})t + C_1(r_D + r_{Su})}{r_D + r_{Su}}$ .... **(3.4.4)**

$D(t) = -\frac{C_3 r_D e^{-(r_D + r_{Su})t} + (r_D r_M + r_M r_{Su} - r_D P)t + C_2(r_D + r_{Su})}{r_D + r_{Su}}$ .... **(3.4.5)**

with C_1, C_2, C_3, C_4 and C_5 are some constants

3.5. Maximum Level of Plastics Waste

The necessity to develop further plan to reduce the production of single-use and disposable plastic products requires definition of environmentally safe level. This definition acts as standards in the discovery of maximum levels of single-use and disposable plastic product that can be safely mitigated. First, we inspect the characteristics of our model solution as written above, particularly the solution involving mass of disposable **(3.4.5)** and single-use plastic waste **(3.4.4)**. Based on equation **(3.4.4)**, we found three terms of the equation that characterize the solution itself. These terms are the exponential, linear, and constant term as stated below respectively

$$-C_3 r_{Su} e^{-(r_D + r_{Su})t}, \ -(-r_{Su}P + r_D r_r + r_D r_M + r_M r_{Su} + r_R r_{Su})t, \ -C_1(r_D + r_{Su})$$

Similarly, equation **(3.4.5)** also have the terms above, but with different coefficients, as stated below respectively

$$-C_3 r_D e^{-(r_D+r_{Su})t},\ -(r_D r_M + r_M r_{Su} - r_D P)t,\ C_2(r_D + r_{Su})$$

The exponential terms of both equations have zero limit value as $t \to \infty$, and the constant terms of both equations have constant limit value as $t \to \infty$. However, the linear terms of both models have ∞ (or $-\infty$) limit value as $t \to \infty$. If we add all the three terms on each equation, the function value of

$$-C_3 r_{Su} e^{-(r_D+r_{Su})t} - (-r_{Su}P + r_D r_r + r_D r_M + r_M r_{Su} + r_R r_{Su})t - C_1(r_D + r_{Su})$$

and,

$$-C_3 r_D e^{-(r_D+r_{Su})t} - (r_D r_M + r_M r_{Su} - r_D P)t - C_2(r_D + r_{Su})$$

will grow without bound. With this information in hand, we define the environmentally safe level as condition(s) that ensure the boundedness of **(3.4.4)** and **(3.4.5)**. Further inspection on those two functions reveals that each equation must fulfill the conditions in which the effect of each linear terms vanish, that is, for equation **(3.4.4)**

$$-r_{Su}P + r_D r_r + r_D r_M + r_M r_{Su} + r_R r_{Su} \geq 0$$

or equally,

$$(r_D + r_{Su})(r_R + r_M) \geq r_{Su}P \quad \textbf{(3.5.1)}$$

and for equation **(3.4.5)**

$$r_D r_M + r_M r_{Su} - r_D P \geq 0$$

or equally,

$$r_M(r_D + r_{Su}) \geq r_D P \quad \textbf{(3.5.2)}$$

Note that if the value of right-hand side of the inequalities is larger than the value left-hand side, we get decrement effect from each of the linear terms. This effect become larger as t increase. In fact, at some time t, the mass of single-use and disposable plastic waste will be negative. However, this is not concerning as we stated in the assumption that we only simulate this during short period of time.

Combined, **(3.5.1)** and **(3.5.2)** determine the conditions that each parameter must fulfill if we want **(3.4.4)** and **(3.4.5)** to be upper-bounded. These conditions are what we defined as environmentally safe level. Now that the standard has been defined, we can readily determine the value of maximum levels of single-use and disposable plastic product that can be safely mitigated. We define this **maximum value** as the value of mass of single-use and disposal plastic waste (in tons) tend to achieve after some period assuming the value always increasing. Otherwise, if the value is decreasing, we define the maximum value as the highest value of mass of single-use and disposal plastic waste can achieve.

4. Further Analysis

4.1. Regional Analysis

4.1.1. Region Clustering

According to our model, to reduce the plastic waste quantity to an environmentally safe level, we can just set the mitigation and recycling rate high and set the production constant low. Nevertheless, setting the mitigation and recycling rate high requires a great amount of resource and if we set the production constant low, it may be damaging towards the economy activity. So, we must find the upper bound or lower bound of the parameters. Because every country has their own unique ways to manage plastic waste and different resources, the upper bound or lower bound must be different for each country. However, it is not feasible for us to calculate each parameter for each country. Therefore, we decided to cluster countries into four groups. Based on its GNI per capita, Geyer, Jambeck, and Law (2015) classified countries into four different groups, Lower Income (LI), Lower-Middle Income (LMI), Upper-Middle Income (UMI), and High Income (HI). Adopting this criteria, 19 countries belong in the lower income group, 34 in lower-middle income group, 44 in upper-middle income group, and 54 in high income group. List of all countries within these categories are provided in the appendix.

Based on this grouping, we assumed that every country in the same group have the same effectivity and resource on waste management problems. So, when we simulate our model to observe the cycle of plastic waste, countries in the same group have the same parameter limitations. With this, it can be seen to what extent plastic waste can be reduced to reach an environmentally safe level according to the economic clustering.

4.1.2. Parameter Estimation

Extending prior section, we will determine some parameter value for each region, which will be used in further simulation. We extracted the data based on a paper authored by Geyer, Jambeck, and Law (2015) and Geyer, Jambeck, and Law (2017).

- **r_{Su} and r_D**

We assumed the r_{Su} and r_{D}, of each region is the same with the r_{Su} and r_D of the entire world. Geyer, Jambeck, and Law (2015) said approximately 70% of total plastics ever produced already become plastic waste. We used that fact to help us set the global r_{Su} and r_{D}. From Geyer, Jambeck, and Law (2017), we have the quantity of various types of plastic and after separating them into recyclable (single-use) and disposable category, we obtain 357,000,000 tons of single-use (S_U), 230,000,000 tons of disposable (D) and the total of them (T) 587,000,000 tons. Then, we use the ratio of each S_U and D relative to T and use 0.7 as the multipliers and obtain the lower-bound.

$$r_{Su} = 0.7\frac{Su}{T} = 0.42572402$$

$$r_D = 0.7\frac{D}{T} = 0.27427598$$

- **r_M and r_R**

Using the data from Geyer, Jambeck, and Law (2015), it can be seen that the proportion of world discarded plastic waste (r_{R+M}) (about 0.6), the amount of mitigated plastic waste ($R + M$), and the total of plastic waste (T) for each clusters. With that, we can calculate the r_{R+M} for each region using equality

$$\frac{\text{global } r_{R+M}}{\text{regional } r_{R+M}} = \frac{\frac{\text{global } (R+M)}{\text{global } T}}{\frac{\text{regional } (R+M)}{\text{regional } T}} \times \text{Plastic littered}$$

Thus,

$$\text{regional } r_{R+M} = \frac{\text{global } r_{R+M} \times \text{regional } (R+M) \times \text{global } T}{\text{regional } T \times \text{global } (R+M)} \times \text{plastic littered}$$

With the formula above, the estimated r_{R+M} for each region is 18,714,015.82 for LI, 63,556,160.95 for LMI, 89,267,807.59 for UMI, and 6,848,367.572 for HI.

To calculate r_R and r_M for each region, we use the global recycle rate (global r_R) from Geyer, Jambeck, and Law (2015). Then we may define r_R for each region as

$$\text{region } r_R = \frac{\text{global } r_R \times \text{regional } r_{r+M}}{\text{global } r_{r+M}}$$

Thus, we have the upper-bound of r_R for each region, which is 2,807,102.373 for LI, 9,533,424.143 for LMI, 13,390,171.14 for UMI, and 1,027,255.136 for HI.

Considering lack of data, we assumed that r_{R+M} is the total of r_R and r_M. So, to calculate r_M we used this simple relationship

$$\text{regional } r_M = \text{regional } r_{r+M} - \text{regional } r_r$$

Hence, we get the r_M for each region: 15,906,913.45 for LI, 54,022,736.81 for LMI, 75,877,636.45 for UMI, and 5,821,112.436 for HI.

- **Initial conditions (R_0, M_0, Su_0, D_0, Np_0)**

To estimate R_0, we use the ratio between r_R and r_{R+M}, and use the amount of mitigated plastic waste $(R + M)$ as the multiplier.

$$R_0 = \frac{\text{regional } r_R \times \text{regional } (R + M)}{\text{regional } r_{r+M}}$$

Thus, we get the R_0 for each region: 413,715,707.6 for LI, 1,405,045,282 for LMI, 1,973,464,819 for UMI, and 151,319,243.6 for HI.

To estimate M_0, we use the ratio between r_M and r_{R+M}, and use the total for regional $(R + M)$ as the multiplier.

$$M_0 = \frac{\text{regional } r_m \times \text{regional } (R + M)}{\text{regional } r_{R+M}}$$

Hence, we get the M_0 for each region: 413,715,707.6 for LI, 7,961,923,265 for LMI, 11,182,967,307 for UMI, and 151,319,243.6 for HI.

To estimate Su_0, we use the ratio between r_{Su} and r_{Su+D}, and use the total waste $(Su + D)$ for each region as the multiplier.

$$Su_0 = \frac{\text{regional } r_{Su} \times \text{regional } (Su + D)}{\text{regional } r_{Su+D}}$$

Thus, we get the Su_0 for each region: 2,493,471,057 for LI, 9,683,166,697 for LMI, 21,846,281,891 for UMI, and 19,136,224,929 for HI.

At last, for Du_0, we use the ratio between r_D and r_{Su+D}, and use the total waste $(Su + D)$ for each region as the multiplier

$$D_0 = \frac{\text{regional } r_D \times \text{regional } (Su + D)}{\text{regional } r_{su+D}}$$

Thus, we obtain the Su_0 for each region: 1,606,437,936 for LI 6,238,454,735 for LMI, 14,074,635,392 for UMI, and 12,328,660,318 for HI.

- **Production rate (P)**

To determine the production rate, we use the fact from Geyer, Jambeck, and Law (2015) which states 407 million tons new plastic is produced in 2015 and assume the production rate is proportional to the population on that region.

$$P = \frac{\text{Total regional population} \times 407 \cdot 10^6}{\text{Total population}}$$

Hence, we obtain P for each region: 33,612,595.58 for LI, 96,872,655.91 for LMI, 154,597,643.1 for UMI, and 121,917,105.4 for HI.

4.1.3. Model Simulation

We will focus in evaluating each region mass of disposable and single-use plastic waste and determine how it can be reduced into an environmentally safe level, as discussed in **3.5.**

- Lower Income Category

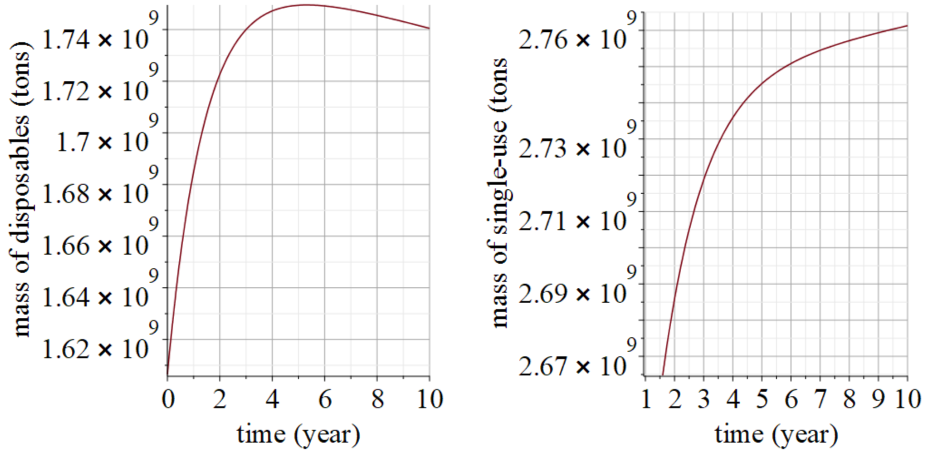


Figure 2. Disposable & single-use waste mass vs time for LI countries

From the graphs of single-use and disposable waste above (simulated for ten years), it can be seen that only single-use grows indefinitely. Thus, without intervention, the mass of single-use plastic waste will accumulate to an environmentally unsafe level.

To counteract this, we need to control the recycling (r_R) or plastic production parameter (P) in our model such that they satisfy **(3.5.1)** (note that **(3.5.2)** is already satisfied because disposable mass shrinks at certain point). Hence, the rate of plastic production should be lowered to 30,770,664.67 ton/year (about 8.45% less than their current plastic production at 33,612,595.58 ton/year) or their recycling rate should be improved at least to 4,535,499.879 ton/year (about 62% larger than their current recycling rate at 2,807,102.373 ton/year). Because lower-income countries generally have lower resources to recycle waste in general, they should prioritize lowering their plastic production.

In this scenario, the amount of single-use and disposable plastic waste that can be mitigated in an environmentally safe level are 2,744,244,653 tons/year and 1,768,000,757 tons/year respectively.

- Lower-Middle Income Category

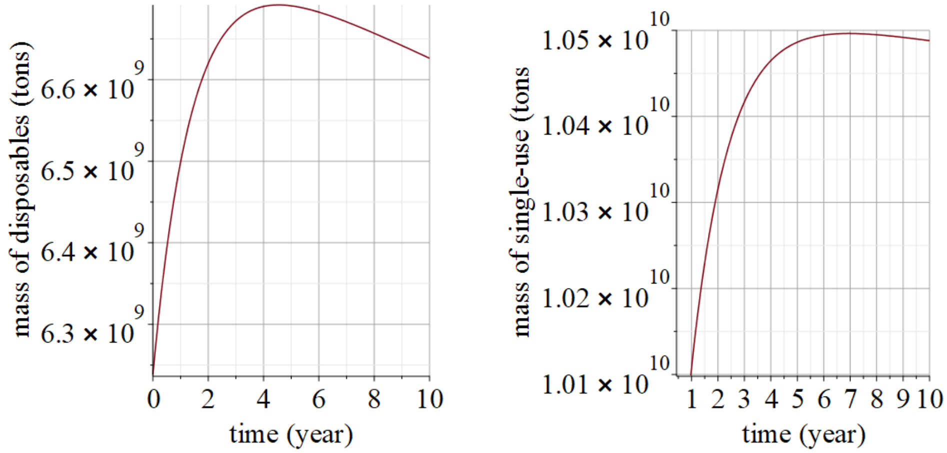


Figure 3. Disposable & single-use waste mass vs time for LMI countries

From the graphs above, it can be seen that lower-middle income countries generally have an environmentally safe level of disposable and single-use plastic waste, if they stay producing, recycling, and mitigating their wastes at their current rates.

In this scenario, the amount of single-use and disposable plastic waste that can be mitigated in an environmentally safe level are 10,535,265,560 tons/year and 6,787,425,993 tons/year respectively.

- Upper-Middle Income Category

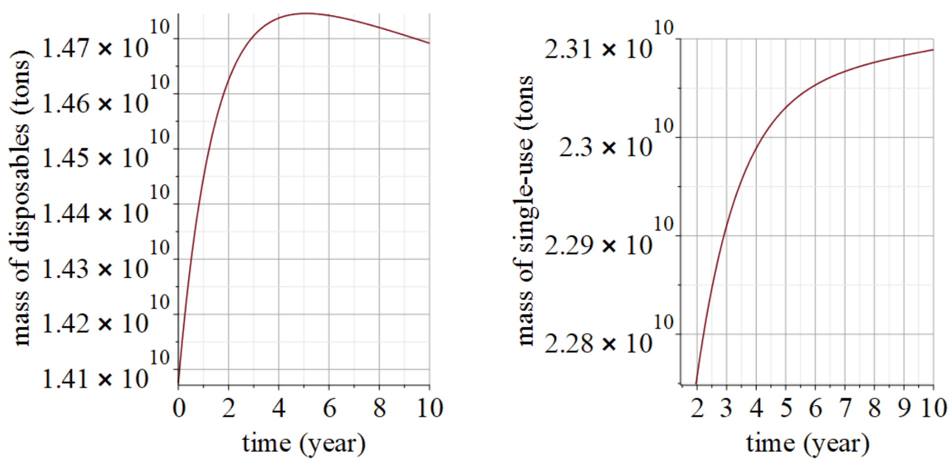


Figure 4. Disposable & single-use waste mass vs time for UMI countries

For this category, the simulation produces the same trend as in the LI category. Thus, they should reduce their production rate to 146,779,280.3 ton/year (about 5.06% less than the current rate of 154,597,643.1 ton/year) or improve their recycling rate at least to

18,145,120.94 ton/year (about 35.51% larger than the current rate of 13,390,171.14 ton/year). Because UMI countries generally have the resources to recycle, they should increase their recycling rate in addition to slightly reduce their plastic production rate.

In this scenario, the amount of single-use and disposable plastic waste that can be mitigated in an environmentally safe level is 23,042,639,930 tons/year and 14,845,398,270 tons/year respectively.

- High Income Category

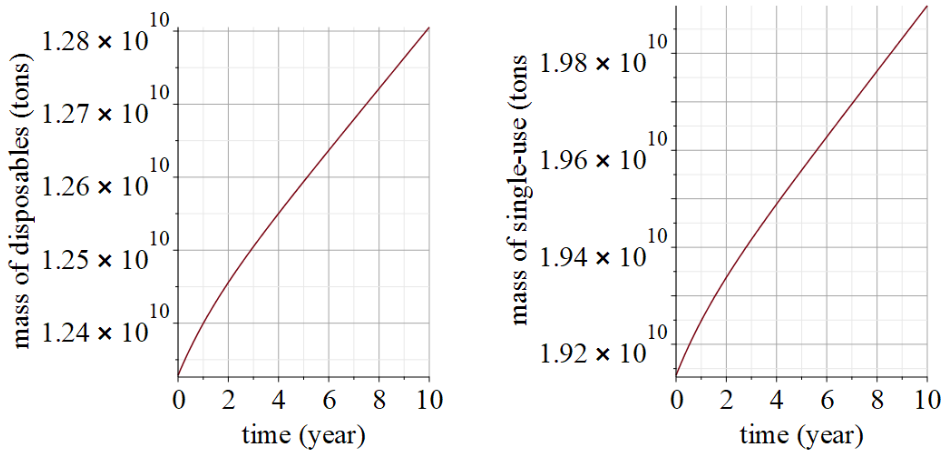


Figure 5. Disposable & single-use waste mass vs time for HI countries

For this category, both types of plastic waste will accumulate without bound. Thus, these countries should control their recycling (r_R), mitigation (r_M), and plastic production parameter (P) in our model such that they satisfy **(3.5.1)** and **(3.5.2)**. Assume that the production rate can only be reduced to 50% of the current rate, then these countries should boost their mitigation rate 6 times its current rate and their recycling rate 3 times its current rate. If there is no reduction in production, these countries should boost their mitigation rate 12-fold and their recycling rate 6-fold.

In this scenario, the amount of single-use and disposable plastic waste that can be mitigated in an environmentally safe level is 19,225,211,210 tons/year and 12,385,990,420 tons/year respectively.

4.2. Global Analysis

In prior discussion, we evaluate each region separately. However, plastic waste problem is a global problem. Thus, we need to determine a global rate for each parameter. We will also consider the aftermath in achieving such rate. Note that the parameters listed below will be the global target in order to mitigate plastic waste without further environmental damage.

4.2.1. Global Parameter

We already assumed that r_{Su} and r_D are constant worldwide. Thus, we focused only on the remaining parameters. For r_R, r_M, and P, we could sum each region target parameter to estimate the values. This is justified because of our first assumption, which is single internal source and mitigation. Hence, we have $r_{Su} = 0.42572402$ (1/year), $r_D = 0.27427598$ (1/year), $r_R = 89{,}318{,}547.2$ (tons/year), $r_M = 180{,}733{,}961$(tons/year), $P = 335{,}381{,}154$ (tons)

To determine the initial value, it is also logical if we sum all the initial value from each region. Thus, we have $R_0 = 3{,}943{,}634{,}360$ (tons), $M_0 = 22{,}347{,}261{,}376$ (tons), $Su_0 = 53{,}159{,}144{,}574$ (tons), $D_0 = 34{,}248{,}188{,}381$ (tons), $Np_0 = 564{,}727{,}361.2$ (tons)

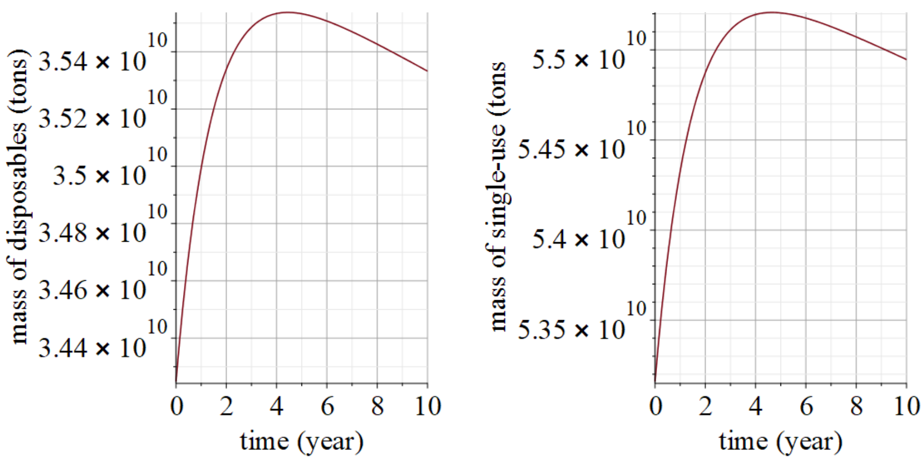


Figure 6 Disposable & single-use waste mass vs time worldwide

Using *MAPLE* we find $Su(t)$ and $D(t)$ as stated below

$$Su(t) = -2.450495306e^{\frac{-7t}{10}} \cdot 10^9 - 6.60813466\, t \cdot 10^7 + 5.560963988 \cdot 10^{10}$$

$$D(t) = -1.578750481\, e^{\frac{-7t}{10}} \cdot 10^9 - 4.932396859\, t \cdot 10^7 + 3.582693886 \cdot 10^{10}$$

Based on the definition of maximum value, we conclude that the global maximum value (or minimal achievable level) of disposable plastic waste that can be safely mitigated is $3.582693886 \times 10^{10}$ tons annually, and the maximum value of single-use waste that can be safely mitigated is $5.560963988 \times 10^{10}$ tons annually.

4.2.2. The Aftermath

In the developing countries, such as LI, LMI, and UMI categories, there will be several consequences if the global level of single-use and disposable plastic waste achieved. The most severe effect is the response from public. Because of the dependency with plastics, changing the habit to use plastic will we quite hard to achieve. Furthermore, because of the rapid growing in economy sector, reducing plastic production in this country will also face some difficulties.

In the high-income countries, it can be seen that in order to control the amount of single-use and disposable plastic waste to an environmentally safe level (that is, the amount will not accumulate without bound), the rate of plastic production, recycling, and mitigation should be changed quite drastically. Thus, other problems might arise from this.

As the rate of plastic production decreases by 50%, manufacturers are obliged to replace plastic material with other environmentally friendly materials that might not be quite as economical. Hence, the price of goods will likely skyrocket, and middle to lower income households might be the most affected group by this phenomenon. After all, this group is most dependent on inexpensive retail goods, which mostly rely on using plastics as its primary packaging material, unlike upper-middle and high income families which usually shops in high-end, organic shops.

5. Model Diagnostics and Result

5.1. Weaknesses

As the result of some of our assumptions in the model, it may not accurately describe all detailed conditions in the real world. It is possible that some variables that may have a significant impact in the calculation are not included in our model. Here is some of that factors.

1. **The model did not consider plastic waste in no man's land**

   According to Rice (2020) on *USA TODAY*, Great Pacific Garbage is a collection of plastic wastes originated from the Pacific Rim, including countries in Asia, North America, and South America. It covers 1.6 Mkm^2 of the ocean based on the cleanup projects researchers. Hence, there is a large amount of plastic waste in unclaimed territories which are not a part of any country.

2. **The model did not consider the exchange of plastic waste**

   It is common that some countries export or import their plastic waste. According to Nixon (2011), current international trade flows of waste follow a pattern of waste being produced in the Global North and being exported to and disposed of in the Global South. Nixon further stated that multiple factors affect which countries produce waste and at what magnitude, including geographic location, degree of industrialization, and level of integration into the global economy.

3. **Constant rate of plastic mitigation, recycling, and production**

   Our assumption regarding the constant rate of mitigation, recycle, and production may not be a realistic representation in the real world. The advancement of technology or change of policies on plastic waste management will make the mitigation and recycle rate dynamic and the change on market demands or product design will cause the production rate to fluctuate.

4. **Relevant only for 10-15 years timespan**

   Because of data shortage, our parameters and initial condition approximation will only be relevant for only 10-15 years timespan.

5.2. Conclusions

Based on our model and prior analysis, we conclude that:

- It is proved that single use and disposable plastic waste may accumulate uncontrollably if its production rate exceeds its recycling and mitigation rates.
- High-income countries accumulate high single-use and disposable plastic waste and tend to grow without bound.
- The global maximum value that can be safely mitigated is $3.582693886 \times 10^{10}$ tons annually for disposable plastic waste, and $5.560963988 \times 10^{10}$ tons annually for single-use plastic waste.

5.3. Suggestions

In consideration of distinct characteristics between countries, we decide to form our suggestion based on our clusterization with gross national income per capita. Here is our suggestion to all four economic clustering to reach global level

- Lower Income Country

  For lower income countries, in the short-term we suggest lowering plastic production by 8.45% for 2.5 years. For long term period we suggest increasing the recycling rate by 62% for 10 years (or about 12.8% for every 2.5 years, as $(100\% + 12.8\%)^4 \approx 100\% + 62\%$). It can be done by collaborating and doing projects with countries that possess the advanced technology for more efficient recycling process. Also, scavengers or informal waste pickers should be incorporated into the formal sector and be provided with sanitary working conditions; - and in the event that waste reduction and recycling activities are implemented, they should be promptly rewarded (Ogawa, 2008).
- Lower-Middle Income Country

  For lower-middle income countries, based on our model, the growth of plastic waste is already controlled by the current mitigation and recycling rate. We suggest these countries to be cautious of the increase in their production rate. If one day these countries become economically more prosperous which result in change of GNI category (such as LMI to UMI), it should be concerned that they will greatly increase their industrial plastic waste production. However, it will not be problematic if they also maintain the recycling and mitigation rate to compensate for the increase in plastic production. According to Ogawa, 2008, they should invite private sector in plastic waste management collection and disposal services to lower the financial need of the government.
- Upper-Middle Income Country

  For upper middle income countries, the short-term suggestion is to lower their plastics production by 5.06% in 5 years (or about 2.56% in each 2.5-year term, as $(100\% - 2.56\%)^2 \approx 100\% - 5.06\%$). For longer period, we suggest increasing their recycling rate by 35.51% in 10 years (or about 7.9 % in each 2.5-year term, as $(100\% + 7.9\%)^4 \approx 100\% + 35.51\%$). This can be done by funding more research on plastic waste management or by carrying out waste management collaboration with countries that possess the technology. According to Ogawa, 2008, it is essential to raise awareness of civilian and decision makers. It can lead to moving national socio-economic and industrial policies and government programs in favor of improving plastic waste management.

- High Income Country

  For high income countries, due to high industrial demands on plastic product, their relatively advanced technology, and abundant capital and human resources, without drastically reducing their plastic production, they should drastically increase their mitigation rate 12-fold (or by 86% in each 2.5-year term as $(100\% + 86\%)^4 = 1200\%$) and increase their recycle rate 6-fold in 10 years (or by 57% in each 2.5-year term as $(157\%)^4 = 600\%$). Because this is quite extreme, we suggest them to decrease their plastic production by half in 10 years (or about 15.9% in each 2.5-year term, as $(100\% - 15.9\%)^4 = 50\%$) , increase their mitigation rate 6-fold in 10 years (or by 57% in each 2.5-year term as $(100\% + 57\%)^4 = 600\%$), and increase their recycling rate 3-fold (or about 31.6% in each 2.5-year term as $(100\% + 31.6\%)^4 = 300\%$).

Memo

To : International Council of Plastic Waste Management

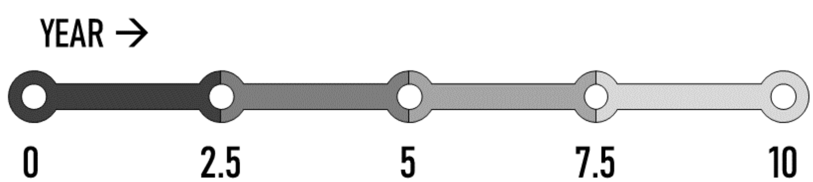
From : Team 202115

Subject : **Global Mitigation of Single-Use and Disposable Plastic Waste**

Responding to your request on February 13th, our team have investigated and evaluated the matter relating to the escalating environmental crisis. The investigation is resulting some target to achieve that hopefully may reduce the single-use and disposable plastic waste production.

The model we build encompasses the timespan of ten years ahead. Here, we focused on determining the limit of recycle rate, mitigation rate, and production rate. Our team has predicted that when the rate of recycle and mitigation are above $89{,}318{,}547.2\,(\text{tons/year})$ and $180{,}733{,}961(\text{tons/year})$ respectively, and the rate of production is below $335{,}381{,}154$ (tons/year), we can control the amount of these waste with an annual maximum amount at $3.582693886 \times 10^{10}$ tons for disposable plastic waste and $5.560963988 \times 10^{10}$ tons for single-use plastic waste. We also predicted that the amount of those two wastes are bounded above by the maximum amount at the end of the timespan of ten years.

In considering the diversity among countries, we consider region specific timeline to achieve, rather than a global timeline. However, the maximum amounts we stated before can only be achieved if we reach the target from each region. Here, we divide 151 countries by its gross national income and resulting in four categories, lower income/ LI, lower-middle income/ LMI, upper-middle income/ UMI, and high income/ HI. We present the timeline below:



LI	Decrease plastic production by 8.45%
	Increase recycling rate by 12.8% every 2.5 years
LMI	Keep plastic production, recycling, and mitigation rate around current rates
UMI	Decrease plastic production by 5.06% every 2.5 year
	Increase recycling rate by 7.9% every 2.5 years
HI	Increase recycling rate by 31.6% every 2.5 years
	Increase mitigation (other than recycling) rate by 57% every 2.5 years
	Decrease plastic production rate by 15.9% every 2.5 years

For lower income country, we suggest decreasing plastic production by 8.45% for short term target, while in the long term we suggest they increase recycling rate by 12,8% by 2.5 years. Lower income country tends to have low capability of recycling and low plastic waste mitigation budget. This will possibly slow down the improvement of the recycling rate. Hence, we set the recycling rate target as long term target.

Lower-middle countries perform the best mitigation and recycling rate. Our model predict that their single-use and disposable plastic waste are bounded above and can be handled safely without further environmental issue.

The characteristics of upper-middle income country related to recycling and mitigation of plastic waste are quite similar, as they only have problem in handling the single-use plastic waste. For upper-middle income country, decreasing plastic production may be harder than lower income country, hence we set the short-term target achievable by 5 years.

Apparently, high income countries have lots of problems involving single-use and disposable plastic waste mitigation. Because of their mass production and rapid development of their industry, it is very hard to reduce the production rate of plastics. To minimalize the reduction of plastic production, they need to increase the rate of mitigation and recycling by 57% per 2.5 years and 31.6% per 2.5 years respectively. Those number are quite huge, hence we set those targets as long term target.

Although each region face considerably huge difficulties, there are also some circumstances that will accelerate the achievement of the target such as projects in mitigation and recycling of plastic waste between developing and developed country, environmental-friendly policies related to waste management, and the change of public culture in each country.

This suggestion is based on the model and several consideration relating to data we got to analyze the problem. Hence further consideration should be made if you want to use this suggestion as reference.

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APPENDIX A: Regional Economy Clustering

High Income Countries:

- Antigua & Barbuda
- Aruba
- Australia
- Bahamas
- Bahrain
- Barbados
- Belgium
- Bermuda
- British Virgin Islands
- Brunei
- Canada
- Cayman Islands
- Channel Islands
- Croatia
- Curacao
- Cyprus
- Denmark
- Estonia
- Faroe Islands
- Finland
- France
- Germany
- Gibraltar
- Greece
- Greenland
- Guam
- Hong Kong
- Iceland
- Ireland
- Isle of Man
- Israel
- Italy
- Japan
- Kuwait
- Malta
- Netherlands
- New Caledonia
- New Zealand
- Northern Mariana Islands
- Norway
- Oman
- Portugal
- Puerto Rico
- Qatar
- Saudi Arabia
- Singapore
- Slovenia
- Spain
- Sweden
- Trinidad and Tobago
- Turks and Caicos Islands
- United Arab Emirates
- United Kingdom
- United States
- Uruguay

Upper-Middle Income Countries:

- Algeria
- Argentina
- Belize
- Bosnia and Herzegovina
- Brazil
- Bulgaria
- Chile
- China
- Colombia
- Costa Rica
- Cuba
- Dominica
- Dominican Republic
- Equatorial Guinea
- Fiji
- French Guiana
- Gabon
- Grenada
- Iran
- Jamaica
- Jordan
- Latvia
- Lebanon
- Libya

- Lithuania
- Malaysia
- Marshall Islands
- Mauritius
- Mexico
- Montenegro
- Namibia
- Nauru
- Palau
- Panama
- Peru
- Poland
- Romania
- Seychelles
- South Africa
- Suriname
- Thailand
- Tunisia
- Turkey
- Tuvalu

Lower-Middle Income Countries:

- Albania
- Angola
- Cameroon
- Congo Rep of
- Cote d'Ivoire
- Djibouti
- Ecuador
- El Salvador
- Georgia
- Ghana
- Guatemala
- Guyana
- Honduras
- India
- Indonesia
- Iraq
- Kiribati
- Maldives
- Morocco
- Nicaragua
- Nigeria
- Pakistan
- Papua New Guinea
- Philippines
- Samoa
- Sao Tome and Principe
- Senegal
- Solomon Islands
- Sri Lanka
- Tonga
- Ukraine
- Vanuatu

Lower Income Countries:

- Bangladesh
- Benin
- Carbo
- Cambodia
- Comoros
- Congo, Dem rep. of
- Eritrea
- Guinea
- Guinea-Bissau
- Haiti
- Kenya
- Liberia
- Madagascar
- Mauritania
- Myanmar
- Mozambique
- Sierra Leone
- Somalia
- Tanzania
- Togo

APPENDIX B: List of Parameters and Initial Conditions

ECONOMY STATUS	$r_R(>)$	$r_M(>)$	$r_{Su}(<)$	$r_P(<)$	P
LMI	0.17603807	0.997549065	0.42572402	0.27427598	96872655.91
UMI	0.109593688	0.621030899	0.42572402	0.27427598	154597643.1
HIC	0.009593379	0.054362478	0.42572402	0.27427598	121917105.4
LI	0.201294248	1.140667405	0.42572402	0.27427598	33612595.58

ECONOMY STATUS	R_0	M_0	Su_0	D_0	Np_0
LMI	1405045282	7961923265	9683166697	6238454735	134414347.3
UMI	1973464819	11182967307	21846281891	14074635392	214509874.8
HIC	151319243.6	857475713.5	19136224929	12328660318	169164435.4
LI	413715707.6	2344389010	2493471057	1606437936	46638703.7