Transitional probabilities for plastic waste management and implication on sustainability

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**ABSTRACT**

The global economy seems to be sinking in the ocean of plastic wastes. Plastic circular economy has been prescribed the key panacea with recycling as its key strategy. The issue of sustainable plastic circular economy has so far been the challenge amid the production of virgin plastics. The aim of this study is to assess the sustainability of plastic circular economy with complete dependence on plastic wastes. Sustainability assessment criterion was based on plastic waste generation and recycling transitional probabilities. A closed system is assumed to ensure that no new virgin plastic is produced. Data were obtained from eight research publications on plastic waste management. Sustainability was then assessed under four scenarios; joint force of plastic waste incineration and discarding, plastic waste discarding without incineration, plastic waste incineration without discarding; and complete riddance of plastic waste incineration and discarding. It was revealed that the already cumulated volume of global annual plastic waste generated can sustain plastic circular economy in a closed system only if plastic waste incineration and discarding are completely prohibited. The paper therefore has critical policy implications for waste management, resource conservation and sustainability, industrial ecology, and climatic change.

**KEYWORDS**

Circular economy; sustainability; transitional probabilities; closed system; plastic waste management; recycling

1 Introduction

The significant values of plastics have been long tested, its usefulness cannot be visible only in its physical or direct application to diverse product development, but also in its economic value and myriad roles it plays in the life of humankind. With a quick reflection, it is possible to outline the significance, \textit{inter-alia}, in such areas as employment, revenue generation, capital investment, contribution to the global industrial fabric, industrial value added, recycling waste, plastic products manufacturing to serve domestic and industrial purposes, and security and safety. The above and other usefulness have been described in detail (Jambeck et al., 2015; Liu et al., 2017; Meng et al., 2018; Zhao et al., 2018).

In spite of the above usefulness, the issue of plastic wastes and its management continue to represent threats to the health, security and safety of humans, lands and other natural habitats. This is the outcome of the rapid growth of plastic production and the associated high volume of wastes generated over the past six decades. In addition, as a result of poor infrastructure and low rate of recycling alternatives, plastic waste are frequently mismanaged, so end-of-life plastics accumulate across all major terrestrial and aquatic ecosystems, thereby causing an uncontrollable pollution (Alabi et al., 2019). Over the past decade, studies have far advanced on the environmental effects of plastic on the environment, humans, animals and resources of other ecosystems. Recent examples can be found in the studies conducted in (Alabi et al., 2019) and (Lebreton et al., 2017). These challenges will persist without cutting-edge management strategies for end-of-life plastics, and the issue of sustainability will remain a challenge to plastic waste management. Mounting up strategies to solve the global plastic problem was the outcome of the quest to enjoy the indispensable values of plastics devoid of the above devastating environmental and health consequences. Various strategic solutions emphasize a complete transition from the wasteful linear model—produce, use and discard (PUD)—to embrace circular economy model of plastic management, which objective is to minimize the extent of material loss to reduce pressure on primary resources (Ellen MacArthur Foundation (EMF), 2013, Global Environment
Recycling plastic wastes has remained the drive to achieve circular economy. Through plastic recycling, secondary plastic products are produced out of plastic waste. This reduces wastes as well as substitutes virgin resources, thereby promoting eco-efficiency (Grigore, 2017; Hopewell et al., 2009). However, it is still believed that circular economy alone cannot completely eliminate the global plastic problem in the face of increased rate of virgin plastic production. There are proposals to slow the material loop via demand reduction and production of only crucial plastic products, discouraging the production and consumption of plastic products that are not essential and promoting the use of renewable and recyclable alternatives to plastics. Other suggestions include, discouraging the production of packaging application and encouraging recycling, reuse of plastic packaging waste (Global Environment Community (GEF), 2018), as well as the production of bioplastics or non-fossil fuel-based plastics (Kaur et al., 2018). The question as regard the constitution of essential and non-essential plastics, cannot be substantiated, it could be relative to individual’s value judgment, line of business, geographical location, economic activities, among others.

In the literature, a lot of studies have uncovered the degree to which the huge volume of plastic wastes ever generated have flooded the global environment, and projections about the possibility of the world to sink in the ocean of plastic wastes by 2050. However, various suggestions to sustain circular economy in the face of galloping growth rate of plastic production have not considered how sustainability can be achieved via total dependence on recycling of plastic waste. Filling this gap constitutes the major accomplishment of this current study. The study therefore seeks to find answers to the following questions: Is there a system of plastic waste management that can support sustainability of plastic circular economy? Under what policy condition(s) can plastic circular economy be sustained if such a system exists?

To sustain plastic wastes management through circular economy, a simultaneous treatment of both forward and backward transitional phases of plastic wastes management will be considered. Therefore, a cyclical dynamic model will be formulated from which transitional probabilities can be derived. These probabilities include the plastic product/recycling transitional probability and the plastic waste transitional probability. Inherent in these probabilities are uncensored events determined by the level of short-lived plastic products and waste as well as the level of mismanaged plastic waste. The aim of this study therefore, is to assess the sustainability of plastic circular economy, using recycling and waste generation transitional probabilities under a closed system of plastic waste management. The closed system ensures that sustainability is evaluated in the event of no virgin plastic production. To achieve this aim, the paper specifically seeks to: develop a two-dimensional cyclical dynamic model, derive and solve the models for the transitional probabilities, and perform numerical computations and simulations. The motivation behind the study was driven by the uncontrollable level of environmental pollution as a result of mismanaged plastics and the quest to achieve sustainable circular economy in the event of zero production of virgin plastics.

The paper contributes to literature by proposing an alternative method of assessing sustainability of plastic waste management via emphasizing absolute dependence on the huge volume of mismanaged plastic wastes, the proposed option is completely devoid of virgin plastic production, which has received little or no attention in the literature. For instance, the proposed closed system under which the model operates inherently applies the concept of industrial ecology, thereby making it possible to evaluate sustainability of plastic circular economy in the complete absence of virgin plastic production. In addition, the concept of transitional probabilities which was employed as the main tool of sustainability assessment, has also not been covered in the literature. This is a novelty which will serve as an alternative tool for sustainability assessment of plastic circular economy different from the widely studied conversional techniques. The paper therefore contains critical policy implications for waste management, resource conservation and sustainability, industrial ecology, and climatic change.

### 2 Materials and methods

#### 2.1 Model development

The major focus in this section is to propose a model from which the transitional probabilistic models can be derived. Consequently, a simple cyclical dynamic closed (CDC) model developed in (Addor et al., 2022a), which has been improved in (Addor et al., 2022b), has been adopted. It consists of two compartments: the house hold (where plastic waste generation occurs) and the production unit (where plastic wastes are recycled). The underlying assumptions as proposed (Addor et al., 2022a; Addor et al., 2022b, 2022) are:

- The plastic wastes management is considered within the framework of a closed system, where no new virgin plastics are produced. The motive is
to ensure that plastic production occurs only through recycling, this will help to ascertain if plastic wastes management can be sustained only through recycling.

- The plastic recycling and waste generation rates obey a Poisson process. This is to help to ascribe randomness to the plastic recycling and plastic wastes generation processes so transitional probabilities can be defined.
- Technology is fixed at a value 1 (Cobb-Douglas production Function)
- There is no policy intervention, so that the true behaviour of the system can be assessed within the context of a closed system.
- The share of plastic production and plastic waste generation according to industrial use sector are the same for all years.

Denote by: $x(t)$, the volume of plastic waste produced by the production unit over a specified time ($t$); $y(t)$, the volume of plastic waste generated by the household at over a specified period of time ($t$); $\mu$, plastic waste generation rate; $\psi$, plastic recycling rate and; $w$ the combined rate of plastic waste incineration rate ($w_i$) and discard ($w_d$), where $w = w_i + w_d$.

The system can be represented as depicted in Figure 1. It is significant to mention that the presentations in this paper including the methodology and results have been deposited in a preprint server (Addor et al., 2022).

Plastic products $x(t)$ reduces by the rate of plastic waste generation $\mu$ so that at any specified time period, $x(t)$ decreases by $\mu x(t)$ volume of plastic waste generated. Also, $x(t)$ will increase as plastic recycling increases at a rate $\psi$, this means that at any specified time period, $x(t)$ will increase by $\psi y(t)$ volume of recycled plastics. Similarly, the volume of generated plastic waste $y(t)$ faces a decrement by the volume of recycled plastics $\psi y(t)$ at any given time period; however, it experiences an increment from $x(t)$ at a rate $\mu$ of waste generation so that it increases by the volume $\mu x(t)$ of waste generated at any given time period. Further, $y(t)$ decreases as the combined rate of incineration and discarding ($w$) of plastic waste increases. Hence, at any given time period, $y(t)$ decreases by $wy(t)$ volume of discard and incineration.

The CDC model developed in (Addor et al., 2022a) is given by the system of first order linear differential equations as follows:

$$\begin{align*}
\frac{dx(t)}{dt} &= \psi y(t) - \mu x(t) \\
\frac{dy(t)}{dt} &= \mu x(t) - w y(t)
\end{align*}$$

where $w = w_i + w_d$

The cyclicity of plastic waste management can be modelled within a discrete time space $t \in \{1, 2, \ldots n\}$. There is therefore the tendency for uncensored events to arise as regards both forward and backward (reverse) logistic activities involved in plastic waste management. This may lead to the definition of uncensored events in both plastic waste generation and recycling. These include, respectively, short-lived (uncensored) plastic waste and short-lived (uncensored) recycled or plastic products. For the purpose of this paper, the terms uncensored plastic waste generation (UPWG) and uncensored recycled plastic (URP) will be applied. By assuming that waste generation and product recovery begin at the period $t$, and last for a time period of $\tau$, then both plastic product recovery and its wastes generation will last at period $t + \tau$. Denote by $y(t + \tau)$, the volume of plastic wastes generated at time $t + \tau$, and by $x(t + \tau)$, the volume of plastics recovered out of plastic wastes at time $t + \tau$. UWG is then defined, in this work, as the volume of plastic wastes at the period $t + \tau$, but

Figure 1. The two-dimensional cyclical model for plastic waste management (Addor et al., 2022a).
which hitherto was not waste somewhere within the period \([t, t + \tau]\). Similarly, URP refers to plastic products produced at the period \(t + \tau\), but which previously was not a product at some point in time within the period \([t, t + \tau]\). These definitions in respect of plastic waste management, uncensored events, may play significant roles in deriving transitional probabilities for both plastic waste generation and recycling. The transitional probability from plastic wastes into plastic product (in other words known as the recycling probability) refers to the likelihood associated with the amount (volume) of plastic products that can be recovered from a given quantity of plastic wastes. Similarly, the transitional probability from plastic products into plastic wastes (plastic wastes generation probability) refers to the likelihood associated with the volume of plastic wastes that can be generated from a given volume of plastic products. To present the proposed model for the transitional probabilities, the following variables are defined:

\(p_{yx}\) probability for the transition from plastic wastes into plastic products; \(p_{xy}\) probability for the transition from plastic products into plastic wastes; \(y_x(\tau)\) uncensored plastic wastes and;

\(x_y(\tau)\) uncensored plastic products.

The systems of linear ODEs that models a pair of regular and uncensored events for both recycled plastic products and plastic waste generation, derived from (Eq. 1), are, respectively, represented below.

\[
\frac{dy(t + \tau)}{dt} = \mu x_y(t + \tau) - (\psi + w)y_x(t + \tau) \quad (2)
\]

\[
\frac{dx_y(t + \tau)}{dt} = \psi y_x(t + \tau) - \mu x_y(t + \tau) \quad (3)
\]

It is imperative to note from (Eq. 2) that uncensored plastic waste \(y_x(t)\) increases as plastic waste generation increases at a rate \(\mu\), but decreases at a rate \(\psi + w\) proportional to itself. Thus, the volume of uncensored plastic waste decreases as more uncensored plastic waste is recycled at a rate \(\psi\), and as more uncensored plastic waste is discarded or incinerated at a rate \(w\). From (Eq. 3) also, uncensored plastic products \(x_y(t)\) increases as more plastic waste are recycled at a rate \(\psi\); but decreases proportional to itself at the waste generation rate \(\mu\).

The term \(\mu x_y(t + \tau)\) is eliminated from (Eq. 2) as demonstrated below.

\[
\frac{dy(t + \tau)}{dt} = \frac{dy_y(t, \tau)}{dt} = (\psi + w)y_x(t, \tau) - (\psi + w)y(t + \tau) \quad (4)
\]

Applying Laplace transform (LT) to (Eq. 4), yields as follows:

\[
sY(s + \tau) - y(0 + \tau) - [sY_x(s, \tau) - y_x(0, \tau)] = (\psi + w)Y_x(s, \tau) - (\psi + w)Y(s + \tau) \quad (5)
\]

For \(\tau \in [0, 1]\), \(y_x(0, \tau) = y_0(\tau) = 0\) (conventionally by definition), applying the initial condition for \(y(0) = y_0\) to (Eq. 5) results in

\[
sY(s + 1) - y(t) - sY_x(s, 1) = (\psi + w)Y_x(s, 1) - (\psi + w)Y(s + 1) \quad (6)
\]

Without loss of generality, define \(y(t, \tau) = y(t + 1)\). Then, applying inverse of LT to (Eq. 6) gives

\[
y(t + 1) = y_x(t + 1) + y(t)\exp[-(\psi + w)t] \quad (7)
\]

The underpinning assumption is that, \(\psi + w\) follows a Poisson Process with arrival time \(\psi t\) given by

\[
\psi t = -\ln(1 - p_{yx}) \Rightarrow \exp(-\psi)t = 1 - p_{yx} \quad (8)
\]

Substituting (Eq. 8) into (Eq. 7) yields

\[
y(t + 1) = y_x(t + 1) + y(t)(1 - p_{yx}) \Rightarrow p_{yx} = 1 - \frac{y(t + 1) - y_x(t + 1)}{y(t)\exp[-(\psi)t]} \quad (9)
\]

Similarly, \(\psi y(t + \tau)\) is eliminated from both equations in (Eq. 3) as follows:

\[
\frac{dx(t + \tau)}{dt} - \frac{dx_y(t, \tau)}{dt} = \mu x_y(t, \tau) - \mu x(t + \tau) \quad (10)
\]

Applying LT to (Eq. 10) and simplifying with the initial values will yield

\[
sX(s + \tau) - x(t) - sX_x(s, \tau) = \mu(1 - \beta)X_x(s, \tau) - \mu(1 - \beta)X(s + \tau), \Rightarrow X(s + 1) = X_x(s, 1) + \frac{x(t)}{s + \mu} \quad (11)
\]

The inverse LT is applied to (Eq. 11) to give

\[
x(t + 1) = x_y(t + 1) + x(t)\exp(-\mu t) \quad (12)
\]
The rate of transition from waste plastics to plastic products $\mu$ obeys a Poisson process that occurs at an arrival time $\mu t$, and is defined by

$$
\mu t = -\ln(1 - p_{xy}),
$$

$$
\Rightarrow \exp(-\mu t) = 1 - p_{xy}
$$

(13)

Substitute (Eq. 13) into (Eq. 12) and simplify to obtain

$$
p_{xy} = 1 - \frac{x(t + 1) - x_r(t + 1)}{x(t)}.
$$

(14)

2.2 Decision rule

Equations 5 and 7 will be used to compute the transitional probabilities of plastic recycling (or production) and that of plastic waste generation in the assumed closed system of plastic waste management. Obviously, both $p_{xy}$ and $p_{yx}$ are defined within the closed interval $[0, 1]$, which can also be expressed as $0 \leq (p_{xy}, p_{yx}) \leq 1$.

Any value of the transitional probabilities outside this range is undefined. The higher the values of $p_{yx}$, the higher the tendency (or likelihood) for plastic waste to be recycled into products and more products will be produced out of recovered waste; similarly, the higher the values of $p_{xy}$, the higher the likelihood for generating plastic waste out of plastic products. On the other hand, lower values of $p_{xy}$ implies a less likelihood to recover products from plastic waste, the same meaning applies to lower values of $p_{yx}$, which seem to be desirable for a system with higher values of plastic waste incineration and discarding.

In this study, sustainability is defined to imply the ability of a plastic waste management system to remain closed to ensure continuation of the cycle of both forward and reverse flow of products and waste respectively. The forward flow of products leads to waste generation, while the reverse or backward flow of waste leads to product creation. Thus, there is a closed loop where the cycle of material (plastic products and waste) flows unabated. This closed loop plays important role in the determination of the sustainability of the system more especially under the closed system where no new virgin plastics are produced. Negative values of both $p_{yx}$ and $p_{xy}$ represent an interruption to the system, that is, the loop will open at one side and the cyclical flow is discontinued. For instance, if $p_{yx}$ is negative, it means that the loop is opened at its reverse end, and no more products will be produced/recycled given the closed system. In the opposite view, negative values of $p_{xy}$ implies a cut loop at the forward wing, indicating discontinuity of waste generation. This obviously sounds very impossible, but possible under a closed system where no product means no waste and vice versa. The system will be more than sustainable if both probabilities are greater than unity, a situation which cannot be attained. It is important to note that sustainability of the system therefore depends on the uncensored plastic waste and product, which according to their definitions connotes how quickly a non-waste plastic material will assume the status of waste; and how quickly a non-product plastic item will assume the status of products. If the values of these uncensored plastic waste and products approach respectively the values of plastic waste and product, the transitional probabilities, $p_{yx}$ and $p_{xy}$ approach unity and the more sustainable the plastic waste management system becomes.

2.3 Data and computation of parameters

All computations were based on global annual plastic data, which cover the volume of global annual plastic: production, waste generation, recycling, discarding and incineration measured in metric tonnes (Mt). The global annual plastic production data were obtained from several publications of Plastic Europe, Plastic Europe Market Research Group (PEMRG) in conjunction with Conversio Markets and Strategy GmbH, which were published on annual basis, for example, as in (PlasticsEurope, Plastics—the Facts, 2020) and (PlasticsEurope, Plastics—the Facts 2021, 2021). The global annual waste data was obtained from (Geyer et al., 2017) and plastic wastes statistics of the World Bank Group as published in (Geyer et al., 2017).

As cited in (Geyer et al., 2017), aspects of the data were gathered from Plastics-the facts (PlasticEurope, Plastics—the Facts 2021, 2021; PlasticsEurope, Plastics—the Facts, 2020). Data on plastic resin production which spans the period 1950–2015 was obtained from the publications of PEMRG. Also, the global annual fiber production from 1970 to 2015 were obtained from the publication of the Fiber Year and Tencnor OrbiChem. The data was grouped into four regions as follows: Asia, NAFTA, EU28 + 2, and the rest of the world (Middle East, Africa, Latin America and CIS). In general, the data were truncated to start from 1988 to 2021. This decision was informed as a result of lack of data on recycling from 1950 to 1987. The first 33 observations (1988–2020) of the plastic production and waste generation were historical values, while the last (2021) were extrapolated based on an estimate of 8.5% growth (PlasticEurope, Plastics—the Facts 2021, 2021). On the other hand, in respect of the data on recycling, discarding, and incineration; the first 27 observations (1988–
2.4 Estimation of uncensored global annual plastic production and waste generation

Our definition of UPWG ($y_s$) and URP ($x_s$) relate to short-lived plastic waste and short-lived plastic products, it is important to define $y_s$ as plastic waste generated out of global annual plastic packaging. Similarly, $x_s$ was defined to embrace all plastics products that can be obtained by recycling or re-using plastic packaging waste. These definitions are adequate in the sense that packaging accounts for the largest share in both global annual plastic: production and waste generation (Geyer et al., 2017; Hopewell et al., 2009; Jambeck et al., 2015). The justification is based on the fact that the analysis of product mean lifetime distributions (Cooper et al., 2014; Davis et al., 2007; Geyer et al., 2017; Jambeck et al., 2015; Kuczenski & Geyer, 2010; Murakami et al., 2010; Mutha et al., 2006) indicates that the packaging application in the plastic market has the shortest end-of-life among every other application, they are easily discarded within 1 year of their use. The shorter the mean lifetime distribution of the products, the larger their contribution to global waste generation. Information about their easily reuse nature, which was displaced by an accelerated growth in their single-use is also available (Geyer et al., 2017; Jambeck et al., 2015). The percentage contribution of the plastic packaging application (42%) in the global annual plastic production in 2015 (Geyer et al., 2017) was applied to generate the volume of global annual plastic packaging from 1988 to 2021; subsequently, the global annual values $y_s$ were estimated using the percentage of global plastic packaging (54%) that degenerated into waste in 2015 (Geyer et al., 2017).

To estimate the global annual values of $x_s$, first, the percentage share of plastic packaging in global annual plastic waste generation (46%) in 2018 (Statista, 2021) was applied to generate the volume of global packaging waste. Subsequently, a 25% recycling rate was used to

![Figure 2. Global annual plastic production, waste generation, recycling, discarded and incineration.](image)

Table 1. Values of parameters and their sources

| Parameter | Value   | Source                                      |
|-----------|---------|---------------------------------------------|
| $\psi$    | 0.14642 | (Addor et al., 2022a, Addor et al., 2022b) |
| $\mu$     | 0.81474 | (Addor et al., 2022a, Addor et al., 2022b) |
| $w_p$     | 0.20642 | (Addor et al., 2022a, Addor et al., 2022b) |
| $w_d$     | 0.64716 | (Addor et al., 2022a, Addor et al., 2022b) |
| $w$       | 0.85338 | (Addor et al., 2022a, Addor et al., 2022b) |

2015) were historical values, while the remaining 6 (2016–2021) were extrapolated based on the estimated guide in (Geyer et al., 2017). Figure 2 is a depiction of the global annual plastic data.

It is important to note that the values of the waste: recycling, incineration, and discarding were generated according to the estimates in (Geyer et al., 2017), which analyzed the distribution of global annual plastic waste by disposal method. The complete data from 1988 to 2021 can be found in (Addor et al., 2022a; Addor et al., 2022b).

The parameters $\psi$, $\mu$, and $w$ are adopted, where $w = w_p + w_d$. The values of the parameters and their sources are summarized in Table 1.
estimate the global values of $x_t$. The assumed 25% rate of recycling out of the estimated global annual plastic packaging was made for the purpose of simulation. The above procedures are summarized in Table 2.

The values in Table 2 will serve as the basis for assessing the impact of plastic packaging waste generation on the plastic recycling probability; and that of plastic packaging waste recycling, on the plastic waste generation probability.

| Global Annual Variable (Metric tonnes) | Global Annual Plastic Packaging | Uncensored Values (Metric tonnes) |
|---------------------------------------|---------------------------------|----------------------------------|
| $x$                                   | 42 (Geyer et al., 2017)         | 54 (Geyer et al., 2017)          |
| $y$                                   | 46 (Statista, 2021)            | 25 (Assumed)                     |
|                                       | $y_x$, $x_y$                   | $0.42 \times 0.54 \times x$, $0.46 \times 0.25 \times y$ |

The expression (Eq. 8) will be used to compute the transitional probabilities for plastic waste generation, which illustrate the tendency to generate waste out of a given volume of plastic products. Then, using (Eq. 8), (Eq. 15), (Eq. 16) and (Eq. 17) to compute the recycling probabilities under the given scenarios (C1, C2, C3, C4), it will be possible to determine the tendency to recycle plastic products out of the waste generated, subject to the scenarios under consideration. Simulations will be performed to evaluate the effects of variations in the values of the estimated uncensored global annual plastic waste generation ($y_x$) and production ($x_y$) on variations in the transitional probabilities for global annual plastic recycling ($p_{yx}$) and waste generation ($p_{xy}$) respectively.

### 3 Results and discussions

#### 3.1 Results

The result of the computed transitional probabilities under C1, C2 and C3 are presented (Figures 3 and 4). Specifically, the transitional probabilities for plastic waste generation are summarized in Figure 3.

As illustrated under all the three scenarios (a), (b) and (c) of Figure 3, the transitional probabilities for plastic waste generation are positive throughout the period, ranging from 0 to 0.14. This indicates that plastic waste generation is independent of the scenarios under consideration. Thus, once plastics are produced, their end-of-life is eventually inevitable.

On the other hand, Figure 4 presents the transitional probabilities for plastic waste recycling. Contrary to the equal trend of transitional probabilities observed for plastic waste generation under the different scenarios, it is very clear that the transitional probabilities for recycling depend on the scenarios considered. The transitional probability for recycling started from zero and attained negative values immediately thereafter. Under the full force of incineration and discarding (a), the probability values decline throughout the period, that is, from an undefined value of approximately $-0.85$ to $-1.3 \times 10^{12}$. 

**Table 2. A summary of computational technique for $y_x$ and $x_y$.**
The negative values are outrageously high right from the second year (1989). Once the values of the transitional probability for plastic recycling are negative, it indicates the impossibility to sustain plastic recycling, regardless of the magnitude, under the assumed closed system, where no new virgin plastics are produced. As a result, plastic waste generation will discontinue since there will be no more plastic products out of which plastic waste will be generated other than the volume of already generated plastic waste. It is therefore, very clear that plastic recycling cannot be sustained, and one end of the plastic waste-material cycle will remain opened under the closed system of plastic wastes management when a greater percentage of plastic waste are incinerated and discarded.

The transitional probabilities for plastic waste management under C2 are also summarised in Figure 4 (b). The plastic recycling probability values continue to fall; however, the rate of fall is low in comparison with that under C1. Right from a value of zero in 1988, the recycling probability attained an undefined value of \(-0.5\) approximately in 1989, then continued to fall until it reached \(-1.4 \times 10^8\) in the year 2021. Therefore, bringing into perspective the single force of discarding of plastic waste (without incineration), recycling probability values remain negative and undefined, indicating that with a higher rate of discard in the closed system, plastic waste recycling cannot be sustained. In the assumed closed system, plastic is recycled only when waste is generated; conversely, plastic waste is generated only when there are plastic products which are created through recycling. Therefore, the cycle will only remain closed if plastic recycling and waste generation are simultaneously in full force to perpetuate the mutual cyclical dependence. Now, given that plastic recycling cannot be sustained under the single force of discarding of plastic waste, the quest to achieve the transition to plastic circular economy cannot be sustained.

Further, the result of the transitional probability, as illustrated in Figure 4 (c), were examined under the full operation of incineration (without discarding). The recycling probability started from zero in 1988, to an
Figure 4. A time series plot of the transitional probabilities for plastic recycling under the: (a) full forces of incineration and discarding, (b) full force of discarding without incineration and (b) full operation of incineration without discarding.

An undefined value of \(-0.03\) in 1989, then finally reaching \(-710\) in 2021. The transitional probabilities for plastic waste recycling remain undefined as they are negatives and fall throughout, the force of incineration overpowers that of recycling; nevertheless, this is an improvement of the situation under C2. The implication is that circular economy in the event of a higher level of wasteful plastic waste incineration cannot be sustained under the assumed closed system.

Finally, the results of the transitional probabilities for plastic recycling and plastic waste generation under the best-case scenario, C4, are summarised (Figure 5). All the probabilities are positive, with the plastic recycling probabilities \((p_{xy})\) consistently higher than that of plastic waste generation. Observe that the plastic recycling probability is bounded within the closed interval \(0 \leq p_{xy} \leq 0.48\), while the plastics waste generation probability is bounded within \(0 \leq p_{xy} \leq 0.14\); indicating that plastic wastes can be recycled to the maximum of 44% approximately. Also, plastic waste can be generated to the maximum of 14% approximately. The results imply that plastic waste management is sustainable in a closed system where policy intervention prohibits the practices of incinerating and discarding of plastic waste. Thus, all plastic waste generated must be recycled since that remains the only source of input, by concept, for plastic production.

The foregoing analyses has demonstrated that under the C1, C2 and C3, there cannot be sustainable recycling to convert the volume of plastic waste generated into products. This eventually leads to unsustainable plastic circular economy. However, under C4, recycling is sustainable to convert the volume of plastic waste generated into plastic products, thus, leading to a sustainable plastic circular economy. Simulations were also performed for the assumed closed system under the best-case scenario, the results associated with variations in \(y_s\) are depicted in Figure 6. The simulated results demonstrate that as the volume of global annual uncensored plastic waste generation \((y_s)\) increases, the transitional
probability for plastic recycling $p_{yx}$ increases correspondingly and vice versa (Figure 6). The recycling probability $p_{yx}$ increases averagely by about 22% in response to a 10% increase (which was obtained by computing the mean absolute percentage increase (MAPI) corresponding to $p_{yx}$) in the volume of global annual plastic packaging waste generation.

On the other hand, as the volume of global plastic packaging waste generation decreases by 10%, $p_{yx}$ correspondingly decreases by a margin close to 22%
averagely. This was also obtained by taking the mean absolute percentage decrease (MAPD).

The results of the sensitivity analysis in respect of \( x_r \) are also summarized (Figure 7). On the average, a 10% increase in the global annual volume of \( x_r \) is associated with a more than proportionate increase in the plastic waste generation probability \( (p_{xy}) \) by approximately 175%. On the other hand, a 10% decrease in the global annual value of \( x_r \) also corresponds to an approximately 175% decrease in \( p_{xy} \).

**3.2 Discussions**

The paper sought to find answers to an interrogation about the existence of a system that supports sustainable circular economy. In addition, it was a quest in this paper to determine policy condition(s) under which circular economy can be sustained if such a system exists. To this end, a closed system was proposed and transitional probabilities for plastic recycling and waste generation were applied as the bases of assessment. Interesting results were obtained, which have proven the significant policy implications of the study.

In general, the assumed closed system was considered within the context of an endogenous model, that neglects the inflow of virgin plastic production. In this case, all stakeholders have no alternative to absolute dependence on plastic waste as the only plastic material input. This promotes the concept of industrial ecology or eco-

**Figure 7.** A time series representation of the transitional probabilities for plastic waste generation at 35% (a), 25% (b), 15% (c) and 55%(d) rate of recycling uncensored (packaging) plastic waste. 35% represents 10% increase from 25%; 15% represents 10% decrease from 25%; and 55% is the European Union’s (EU’s) target set.

efficiency. It has been established that plastic circular economy cannot be sustained under a closed system with the full influence of the combined rates of plastic waste incineration and discard, neither can it be sustained under the single force of either discarding or incineration of plastic wastes. As the simulation indicates, the transition to plastic circular economy can be sustained in a closed system only under a policy condition that completely bans both discarding and incineration of plastic waste. With the combined influence of discarding and incineration of plastic wastes, the plastic waste generation probability attained its highest value of approximately 14% in 2008, which has a good implication for future public and environmental health, albeit this cannot serve as feedstock to revive the downward trend of plastic recycling. As a panacea to the assertion that recycling alone cannot solve the problem of plastic waste management giving the higher rates of virgin plastic production (Global Environment Community (GEF), 2018), a closed system has been proposed for plastic waste management, which has an inherent mechanism to support sustainable plastic recycling vis-à-vis circular economy. It permits an automatic application of the concept of industrial ecology, which promotes recycling against incineration and discarding alternatives of plastic waste treatment. Several contentions have been advanced in favour of plastic recycling in respect of environmental resource conservation, lower rates of greenhouse footprint and global warming (Bernardo et al., 2016; HPRC, 2015; WRAP, 2010) relative to the discarding and incineration.
Among all the unsustainable scenarios, the results under the single force of plastic waste incineration outperformed the others. The case would have been better if fuel and energy were recovered during the process of incineration; however, up to date, incineration has been the most applied technique of thermal destruction of plastic, which involves no energy or fuel recovery (Geyer et al., 2017). This indicates that mechanical recycling remains the only source of plastic recovery whose transitional probabilities consistently imply unsustainable plastic recycling under the single force of incineration. Given a policy intervention that outrightly bans discarding and incineration of plastic wastes as plastic waste treatment methods, the closed system ensures that all plastic wastes are recycled. This produces a cycle of high rate of plastic recycling, which in the long run, will serve as seed for a continuous stream of plastic waste generation. Thus, in a plastic waste management system, where no virgin plastics are produced, plastic waste can serve as a feedstock (material input) for producing more secondary products through recycling, thereby displacing the huge volume of virgin plastic resources that would have been exploited in the case of an open system. This conforms to the view shared in some of the literature (Eriksen et al., 2018; Grigore, 2017) about substitutability of virgin plastic resources, or promotion of eco-efficiency. Discussing further, plastic waste generation will be kept low while recycling must be emphasized using already created waste in the place of virgin plastic resources. This is also in line with recommendations in (Global Environment Community (GEF), 2018) to reduce the demand and consumption of plastics, especially, in the packaging application; increase recycling; and encourage reuse of plastic packaging waste. In as much as this is a good recommendation, it is advisable that the process of plastics waste generation be guided and regulated to optimize generated volume of plastic waste, which could serve as a resource for recycling under the closed system. Under this best-case scenario, the concept of plastic industrial ecology is first promoted to engineer the transition to a sustainable plastic circular economy. It is a reverse of the view held in the literature that recycling promotes industrial ecology (Hopewell et al., 2009). Our endogenous model is engineered by a close system, which first emphasizes the concept of industrial ecology to ultimately promote recycling, thereby sustaining plastic circular economy.

In respect of the assessment of the variational effect of uncensored waste \(y_t\) on the plastic recycling probability \(p_{xy}\), it was established that \(y_t\) is a positive correlate of the plastic recycling probability. This underscores the point that every activity relating to the generation of plastic packaging waste creates an impetus for sustaining plastic recycling activities. In general, the more plastic wastes are generated the higher the likelihood that plastic wastes will be recycled under the assumed endogenous system of plastic waste management, where incineration and discarding alternatives of plastic waste management are completely banned. Following the above analysis, it necessary to consider redesigning plastic packaging in a way that can be reused to accelerate the rate of transition between product recovery and waste generation; and vice versa. The result is a closed-loop recycling, which is in line with the call to optimize cycling of plastic waste in the circular economy (Rouch, 2021).

A reference to the perturbation analysis of the effect of uncensored plastic products \(x_t\) on the plastic waste generation probability \(p_{xy}\) evinces a direct relationship between \(x_t\) and \(p_{xy}\). However, a 10% decrease cannot sustain plastic waste generation at certain years (1994, 1996, 1997, etc.). Since plastic waste constitutes the main plastic production input of the closed system, plastic recycling will cease in the long run. The plastic-material cycle will remain open given the mutual cyclical dependence between plastic waste generation and plastic recycling. Thus, any policy intervention of this closed economy under the scenario C4, must ensure that recycling of packaging waste should not fall below 10%. A closer observation reveals that the EU target of 55% recycling of packaging waste will ensure an increase in \(p_{xy}\) by approximately 524%, on average. It is therefore clear, that as more packaging wastes are recycled, the plastic waste generation probability increases indicating a high tendency for packaging waste to increase. This confirms most of the result in the literature where the rapid increase in the global annual plastic waste over the past six decades was ascribed to the large composition of packaging application as a component of the global annual plastic production (Geyer et al., 2017; Statista, 2022). Product reuse can serve as a means of recycling to best fit the description of uncensored plastic products. This confirms a proposal in view of plastic packaging redesign to revive the old culture of product reuse (Kamaruddin et al., 2017).

By extending the definition of uncensored plastic waste to cover all mismanaged plastics, increasing uncensored plastic waste can equally be defined as increasing recovery of mismanage plastics in open or uncontained landfills that pollute the land, fresh water bodies, the ocean and other natural habitats or ecosystems. Therefore, threats that associate with rampant plastic waste generation are minimized in the face of higher and sustainable rate of plastic recycling. This,
stems from the fact that the incidence of environmental pollution resulting from the uncontrollable volume of global mismanaged plastic wastes will be widely eliminated (Alabi et al., 2019; Grigore, 2017; Wei & Zimmermann, 2017; Zhao et al., 2018).

Significant it is, to emphasize the strength of the model which relies partly on the fact that it reflects the inherent time-dependent and cyclical dynamics of the plastic life-cycle. Moreover, the models are built based on a real-world practice of plastic waste management. A case in point is the scenario C3 emphasizing the complete riddance of plastic waste incineration, which is a common characteristic of the plastic waste management data of the EU. The introduction of partial ban on plastic waste import in 2010, and a complete ban in 2017 in China were means to eradicate plastic landfills in China (Chinese Ministry of Environmental Protection (CEMP), 2017, Brooks et al., 2018). Finally, the concept of a closed system neglects the production of virgin plastics and permits strict reliance on waste as a plastic production resource leading to the attainment of industrial ecology. Therefore, proposed model has critical policy implications for waste management, resource conservation and sustainability, the industrial ecology, and climatic change (OECD (Organization of Economic Co-operation and development), 2018).

The weakness of the models can be linked to the fact that sustainability of recycling was assessed without considering the effect of population growth; thus, it cannot be ascertained as to whether sustainable plastic waste management can be achieved in the context of rapid global population growth under the closed system in the event of complete riddance of waste incineration and discard. The concept of plastic waste separation together with other correlates of quality plastic material and recycling was not considered. That notwithstanding, the sustainability assessments under the different scenarios have been able to establish that higher rate of recycling is adequate to promote eco-efficiency. However, mass recycling is a necessary but not a sufficient attempt to achieve circular economy vis-à-vis closing the plastic material loop. Premium should therefore be attached to both quantity and quality of plastic wastes materials and products recycled.

It is recommended that any research effort in furtherance of this study should incorporate the roles of waste separation in the transitional probabilities; additionally, population and technology should be considered in a non-nonlinear context.

4 Conclusion

The aim of the study was to assess the sustainability of the plastic circular economy model in a closed system of plastic waste management. The paper therefore sought to find answers to the following questions: Is there a system of plastic waste management that can support sustainability of plastic circular economy? Under what policy condition(s) can plastic circular economy be sustained if such a system exists? Sustainability was evaluated using numerical computations and simulations under four different scenarios.

The outcome of the computations revealed that plastic circular economy cannot be sustained in the event of either plastic waste incineration or discard or both. It is sustainable only under a system devoid of plastic waste incineration and discarding. This system promotes the concept of industrial ecology. Thus, the plastic/waste material cycle is kept closed; and enough plastic wastes are recovered to substitute virgin plastic resources thereby promoting eco-efficiency. Therefore, the proposed closed system of plastic waste management supports the sustainability of plastic circular economy. This is possible with policy enactment to prohibit plastic waste incineration and discard. Further revealed from the simulations was the fact that uncensored plastic waste (global volume of plastic waste generated out of plastic packaging) is a positive determinant of the transitional probability of recycling. This indicates that as more packaging waste are generated, more secondary plastic products will be produced and vice versa. Similarly, the transitional probability of plastic waste generation correlates positively with the global volume of uncensored plastic products (volume of recycled plastic packaging). As more packaging wastes are recycled, the volume of global annual plastic wastes generation will increase, the reverse is also true. However, the recycling of packaging waste should not fall below 10%. It was therefore extended that more mismanaged waste in the environment could be recovered as uncensored plastic waste to increase the volume of global annual plastic recycling, this will reduce the rate of plastic pollution in the environment and its associated health consequences.

In line with all the other studies, it is recommended that plastic packaging application should be redesigned to promote reuse or to optimize cycling in the plastic waste-material loop. In addition, all countries should embrace the practice of circular economy under the proposed closed system with policy enactment to prohibit waste incineration and discarding. This will increase dependence on plastic wastes as the main resource under plastic industrial ecology. This should be practiced alongside other environmentally friendly non-fossil fuel or
biodegradable alternatives.

**Authors contributions**

All Authors discussed and conceived the research idea. Authors Eric N. Wiah (ENW) and Felix I. Alao (FIA) designed the framework for the study including the mathematical formulation of the first stage model. John A. Addor (JAA) conducted the literature search, collected the data, extended the model to its probability version, and derived the transitional probabilities. ENW and FIA modified the model and proposed scenarios for the sustainability assessment, while ENW and JAA performed the computations and simulations. JAA and FIA performed the analysis. Full editing was performed by ENW and FIA. JAA prepared the manuscript according to the format of the journal. All authors read through the work and agreed before submitting for publication.

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The main research focus of the authors is in the area of Applied Mathematics, with major emphasis on mathematical modelling and dynamical systems. Currently, the research focus of the authors is in the following areas: sustainable environment, plastic waste management, climate change, resource conservation and energy, social interaction dynamics and epidemiology. This paper falls within the context of plastic waste management, sustainable environment, resource conservation and energy, and climate change. Specifically, the paper forms an aspect of an underway research project titled “Mathematical Models for the Cyclical Dynamics of Plastic Waste Management”. John Awuah Addor is a senior Lecturer at the Department of Mathematics, Statistics and Actuarial Science, with four-teen years of teaching experience. He holds an MSc. Degree in Industrial Mathematics, and he is currently a PhD candidate at the Department of Mathematical Sciences of the Faculty of Engineering, University of Mines and Technology, Tarkwa, Ghana. His research interest is in applied mathematics in the areas of mathematical modelling, dynamical systems, epidemiology, environment and sustainability, optimal control theory, circular and green economy. He has several publications to his credit.

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**Public Interest Statement**

The paper uses transitional probabilities to assess the sustainability of plastic circular economy (PCE). The models were formulated within the context of a closed system of plastic waste management that ignores the production of plastics using virgin resources. This assumption of a closed economy inherently promotes the concept of industrial ecology. The main aim is to determine if total dependence on plastic waste can sustain PCE to meet the global plastic requirement. Sustainability of PCE was considered under four given scenarios: C1: full force of incineration and discard, C2: the force of discarding without incineration, C3: the force of incineration without discarding and C4: total riddance of incineration and discarding. The results revealed that PCE cannot be sustained under C1, C2 and C3, however, it can be sustained under C4. Thus, PCE can be sustained if incineration and discarding of plastic waste are completely avoided.

**Data availability**

Data will be made available upon request to the corresponding author. Also, data is available at: https://www.researchsquare.com/article/rs-1507266/v1.

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