Sustainable Development in the Plastic Industry: A Promising Future or Just a Hoax? Past, Present, and Future Perspectives from a Global Viewpoint

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ABSTRACT

The issue of fossil-based plastics presents a paradox, with conflicting solutions proposed. While an idealistic vision promotes biodegradable plastics as the ultimate solution, the reality is that fossil-based plastics dominate production, constituting approximately 99%. Despite the conceptual appeal of biodegradable plastics, their practical implementation remains limited with minimal production. Consequently, the current plastic waste management system faces challenges, with only about 25% of total plastic waste being recycled in 2023. A significant portion, around 31.2%, is incinerated, and 43.8% ends up in landfills or is improperly disposed of, reflecting a non-sustainable approach. Projections suggest a potential increase in recycling rates to nearly 44% by 2050, but incineration remains alarmingly high at close to 50%. To achieve sustainable growth and create a carbon and toxic-free environment, there is a need for a renewed commitment to accelerate the reuse and recycling of plastic waste. Failure to do so risks perpetuating the

condemnation of fossil-based plastics, despite their significant historical contributions to society and the environment.

Keywords: Sustainable Development, Global Plastic Waste, Waste Management

HISTORICAL DEVELOPMENT and PRODUCTION OF PLASTICS

From the Stone Age through the Bronze Age and the Iron Age, societal evolution has brought us into the contemporary era, characterized by the transformative impact of plastics on our way of life[1]. Commencing with early innovations involving bioplastics, and rubber such as natural rubber, vulcanized natural rubber, cellulose, cellulose nitrate, gutta-percha, viscose silk, and shellac from the 1820s to 1900, the subsequent decades witnessed a shift towards fossilplastics dominating the industry in the 1930s. The 1940s marked a surge in plastic inventions, largely driven by the needs of World War I and World War II. Since then, there has been a significant uptick in the utilization of plastics across various sectors[1-4]. Beyond advancements in plastics, the period since the early 1960s has seen the introduction of pigments and various additives, facilitating the application of color and properties to plastic materials[5-7]. Thereafter, the 1980s and 1990s marked the emergence of high-performance plastics manufacturing. Over time, these high-performance plastics have undergone enhancements through the integration of nanotechnology and composites. As of 2024, a diverse range of multi-type plastics and their advanced iterations find applications in various sectors, including health, mobility, communications, energy, food and water, shelter, clothing, protection, sports, and beyond[8-13]. In simple terms, plastic has transformed our everyday existence, making life unimaginable without it. To celebrate this impact, in 1980, the music producer ‘The Buggles’ released an album titled "The Age of Plastic"[14].

Table 1 below presents notable inventions in bio-based and fossilplastics for various years. Before delving into the details, it is essential to clarify the terms "bio-based" and "fossil-based." Bio-based plastics typically derive their chemical molecules or monomers from biomass, while fossil-based plastics are produced using chemical molecules or monomers derived from petroleum. Secondly, bioplastics can exhibit both biodegradable and non-biodegradable characteristics, while nearly all categories of fossilplastics are inherently non-biodegradable[15, 16].

Table 1: Various plastics inventions and their timeline by year[3, 4, 17].

Year	Polymers Name
1820s	Natural Rubber, Vulcanized natural rubber, and Gutta Percha (bio-based)
1862	Parkesine, and Cellulose nitrate (bio-based)
1892	Viscose silk or Rayon) (bio-based)
1898	Shellac (bio-based)
1907	Phenol formaldehyde (PF) or Bakelite
1912	Polyvinyl chloride (PVC)*
1918	Urea formaldehyde (UF)
1919	Cellulose acetate (CA) (bio-based)
1922	Long chain molecules plastics theory
1933-35	Polyethylene (PE), Polymethyl methacrylate (PMMA), and Nylon
1937	Polystyrene (PS)
1939-40	Polyamide, Polytetrafluoroethylene (PTFE), Low-density polyethylene (LDPE)
1940	Polyvinyl chloride (PVC)
1941	Polyethylene terephthalate (PET)
1944-60	High-impact polystyrene (HIPS), Acrylonitrile butadiene styrene (ABS), Polypropylene (PP), High-density polyethylene (HDPE), and Polycarbonate (PC)
1962	Polyimide (PI)
1969	Polybutylene terephthalate (PBT)
1977	Polyetherether ketone (PEEK)
1980s	Linear low-density polyethylene (LLDPE), Polyphenyene sulphide (PPS), Polyether sulphone (PES), and Kevlar fibers
1987	Polyacetylene (PA)

1989	Light-emitting polymers (poly-ethyne)
1990	Biopol (bio-based)
2000-2010	Nano-Technology applied to polymer and composite applications
2010 +	Plastics as the future

Bio-based plastics are labeled as (bio-based), while others are referred to as fossil-based plastics. * Represent first polymerization of vinyl chloride but processing of PVC was not possible.

In the plastic industry, irrespective of the specific properties and types of plastics, they undergo transformation for their intended purposes through processes like injection molding, extrusion, blow molding, spinning, and casting[3, 18]. During the processing of plastics, a range of additives, including low molecular weight compounds such as antioxidants, UV stabilizers, processing aids, plasticizers, colorants, flame retardants, hardeners, accelerators, and blend compatibilizers, as well as fillers and fibers for matrix reinforcement, are incorporated. These additives enhance processability and contribute to attaining the desired physical or chemical properties in the end products[3, 6]. In this context, a prime illustration is PVC resin, which, owing to its heat sensitivity and considerable brittleness, was initially (in 1912, Table 1) impractical for direct processing. Consequently, the processing of PVC resin involved the introduction of plasticizers (specifically phthalates), heat stabilizers, and other additives to address these challenges[3, 19]. The fossil-based plastics highlighted in Table 1 compete effectively with alternative material classes like glasses and metals. Moreover, contemporary fossil-based plastics exhibit strong competitiveness by simultaneously lowering costs, enhancing performance, and promoting sustainability. These plastics possess distinctive attributes, the capability to be molded effortlessly into diverse shapes suitable for various applications, and a broad range of available raw materials. Furthermore, their molecular structure determines whether they exhibit rubbery or glassy characteristics, function as conductors or insulators of electrical and thermal charge, possess permeable or impermeable properties, are transparent or opaque, soluble or insoluble, adhere or do not adhere, emit or absorb light, exist in a solid or liquid state, repel or absorb substances, and are durable or degradable[3, 20-22]. Consequently, fossil-based plastics facilitate the development of new technologies by virtue of their lightweight nature. For instances, they found applications in fuel-efficient aircraft like the Boeing 787, space exploration vehicles and flights, automobiles, bulletproof clothing, energy-efficient buildings, solar panels, and high-speed lightweight vehicles [23, 24]. There are numerous other applications of fossil-based plastics based upon their properties and capabilities, including use in cables, pipes, packaging, and plastic coatings to protect metals from corrosion, among others[25]. As well as in medical fields, fossilplastics are employed as contact lenses, disposable syringes and tubes, 3D printed implants and more[26, 27]. Furthermore, fossilplastics have wide-range of applications in agricultural such as greenhouses, mulch, silage stretch films, and drip irrigation pipes and many more[28].

Despite the great achievements of fossil-plastics, bioplastics are still emerging as they are supposed to be biodegradable in nature. Thus, most of the bioplastics were uses in drug-release systems, packaging (e.g., bags and bottles), straws, and 3D printed medical implants[29, 30]. In the current, not only the development of bio-based plastic but also bio-based additives such as plasticizers, stabilizers, reinforcing agents, other type are gaining a huge attention[31]. The prominent example is celluloid foams, which was plasticized with non-phthalate camphor while processing[32]. In recent, camphor is polymerized with terpenoid to produce a fully bio-based polyester, in a greater interest of environmentally friendly plastic[33].

Most bioplastics have struggled to compete with the versatile and easily processed fossil-based plastics, which currently constitute approximately 99% of the world's plastic consumption (refer to Figure 1). In 2023, the global production has surged to 390 million tonnes due to heightened demand, with fossil-based plastics accounting for around 90.5%, followed by fossil-based recycled plastics at 8.4%, and bioplastics at 1.1% (as illustrated in Figure 1). Projections indicate a total plastic production nearing 564 million tonnes in 2050, with fossil-based plastics expected to maintain a share exceeding 90%. Similarly, bioplastics may represent around 5% of total plastic production. Considering these estimations, Figure 2 illustrates the distribution of all types of plastics by percentage, where PE holds the largest share at approximately 26.9%, followed by PP (19.3%), PVC (12.9%), PET (6.2%), PU (5.5%), and PS (5.3%). The share of all types of bio-based plastic is only about 1.1%. More specifically, Figure 3 details the distribution of bio-based/bio-attributed plastics, with biodegradable bioplastics like polylactic acid (PLA) holding the maximum share at 18.7%, followed by starch blends (18.7%), polybutylene adipate terephthalate (PBAT, 13.5%), polybutylene succinate (PBS, 4.1%), polyhydroxyalkanoates (PHA, 1.7%), and other biodegradable options (e.g., cellulose blends at 1.4%). Despite the presence of biodegradable bioplastics, non-biodegradable bioplastics such as bio-polyethylene (bio-PE), bio-polyethylene terephthalate (bio-PET), bio-polyamide (bio-PA), bio-polypropylene (bio-PP), bio- polytrimethylene terephthalate (bio-PTT), accounting for about 41% of all bio-plastic production, these materials are derived from biomass monomers and are thus classified as bioplastics [34]. Furthermore, plastics employed in packaging constitute the majority, comprising nearly 44%, with building and construction following at 18%, automotive at 8%, electrical and electronics at 7%, and household, leisure, and sport at 7%. Agriculture, farming, and gardening make up 4%, while the remaining 12% falls into the other category, as depicted in Figure 4.

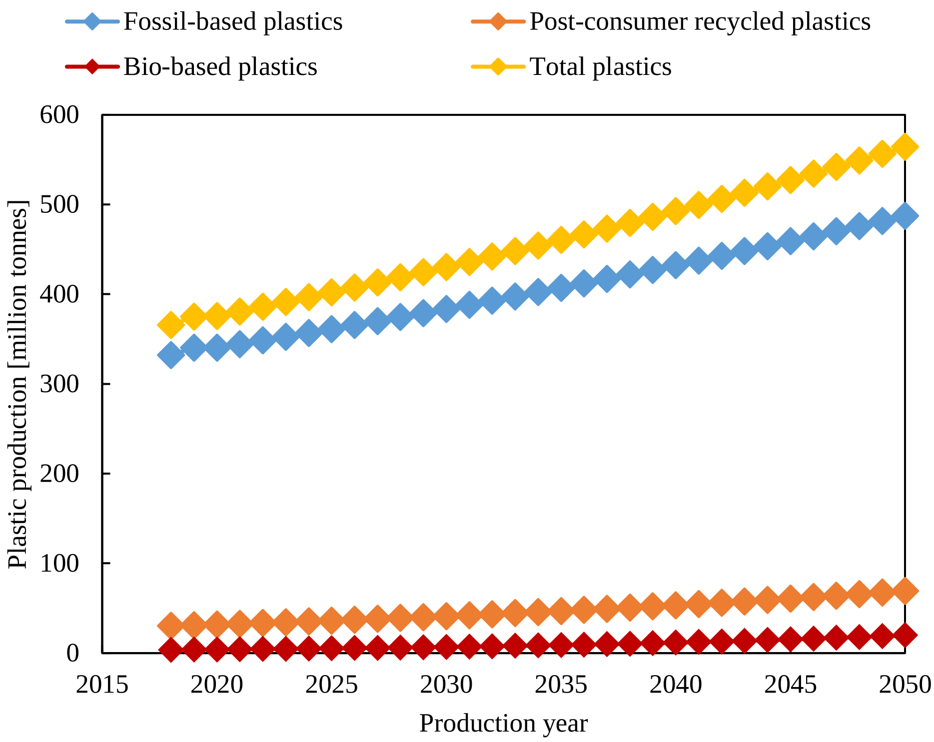

Figure 1. Global production of all plastics [million tonnes] in the respective year from 2018 to 2050 [35, 36]

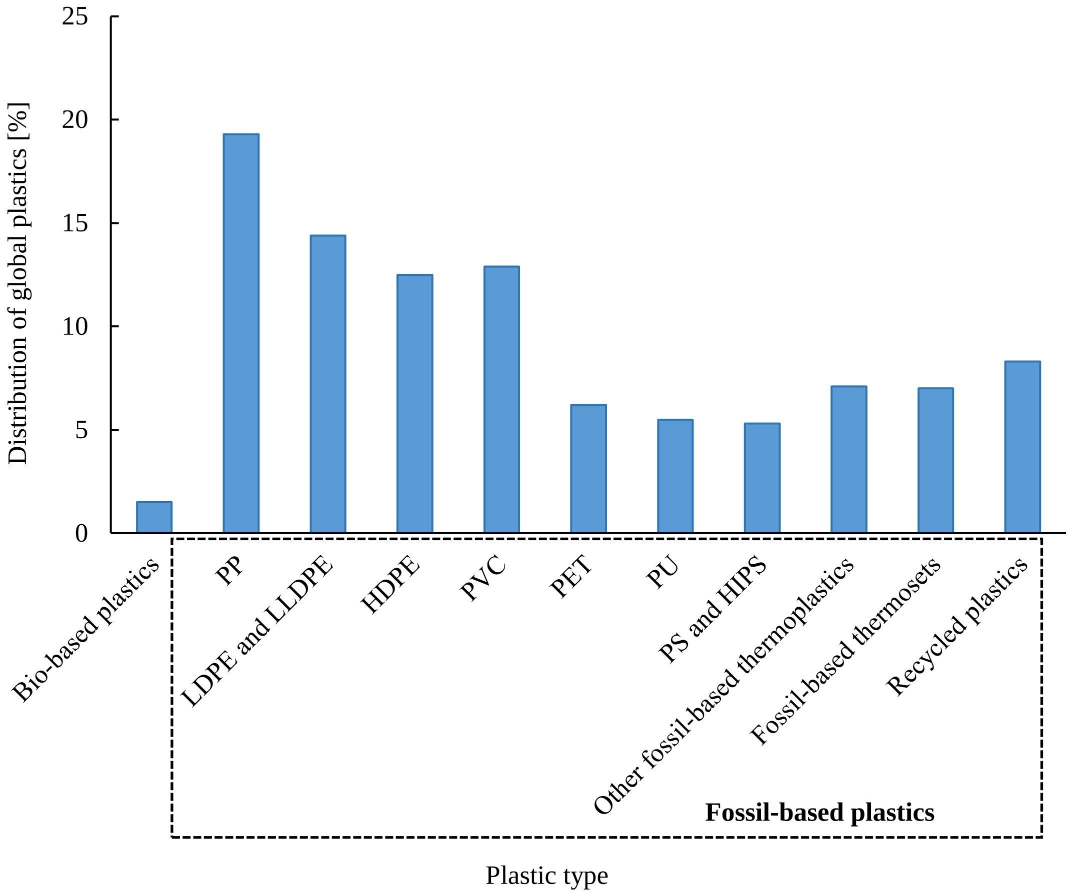

Figure 2. Distribution of global plastic production [%] by type[36].

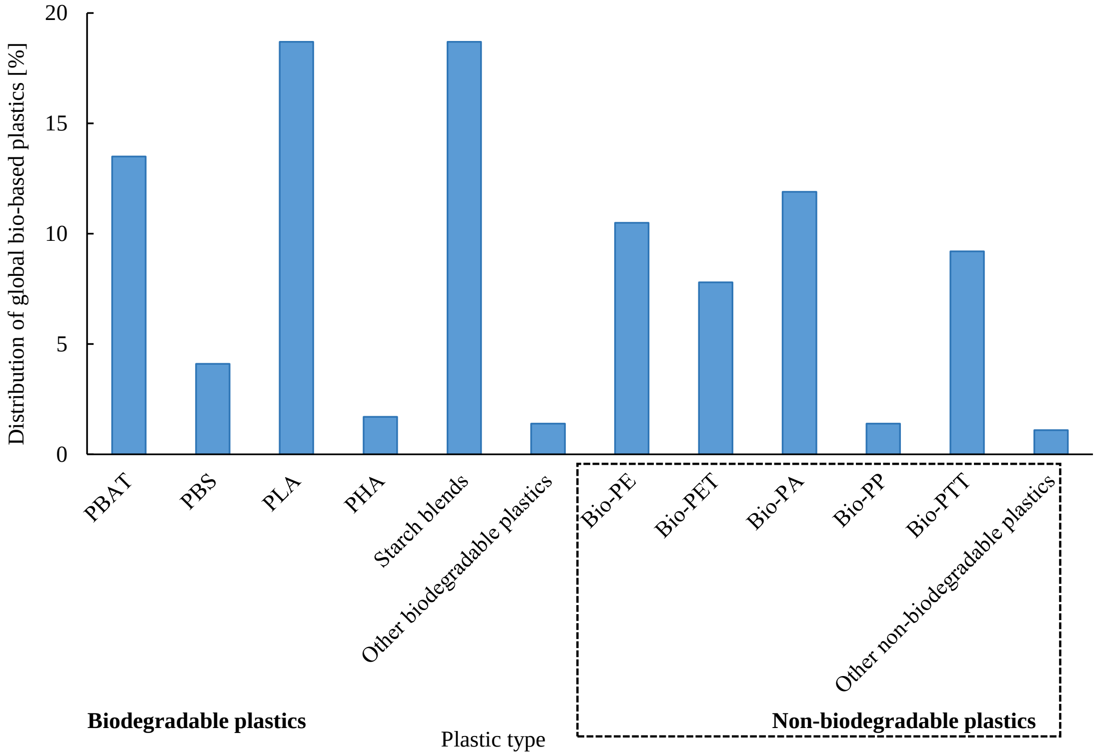

Figure 3. Distribution of global bio-based plastics production [%] of about 2.11 million tonnes by their type in 2020. [37]

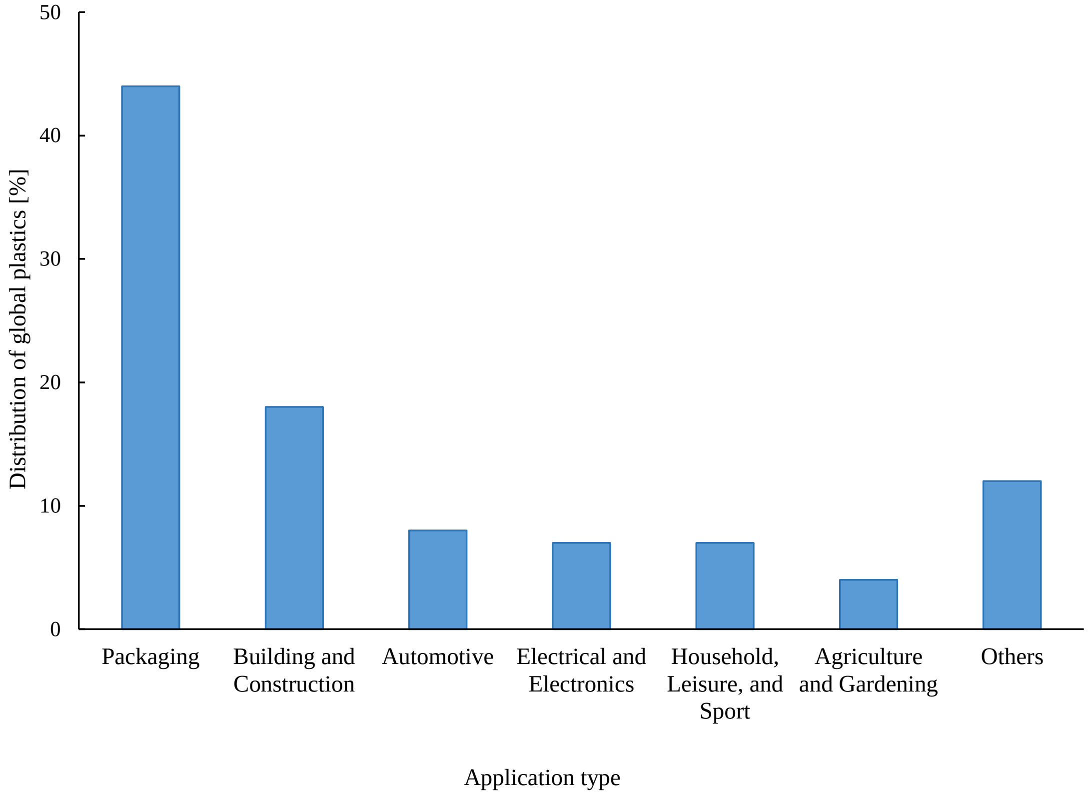

Figure 4. Distribution of global plastic production [%] by applications in 2021-2023[13, 36].

INTRODUCTION TO SUSTAINABLE DEVELOPMENTS

Similar to the observed plastic production trend discussed earlier, the current trajectory of resource utilization could potentially result in a global system collapse within the next century. Resource scarcity is a widely recognized issue with implications for both the environment and society, notably contributing to global climate change through factors such as carbon emissions. The vulnerable approach to carbon resources has already initiated this process. If these challenges persist, they could significantly impact economic development and overall quality of life. Therefore, there is a pressing need for the development of a balanced and cyclical system that integrates resources, carbon, and socioeconomics – commonly known as sustainable development (see Figure 5a)[38, 39]. Figure 5b [40] illustrates a life cycle example where the economy establishes infrastructure for processing and creating products to support the social structure, utilizing initial resources. Throughout the phases of product development—before, during, and after—environmental impact occurs through emissions such as carbon, toxins, and waste. Importantly, the generation of waste after product use and the methods employed for its disposal are critical factors that significantly affect the environment.

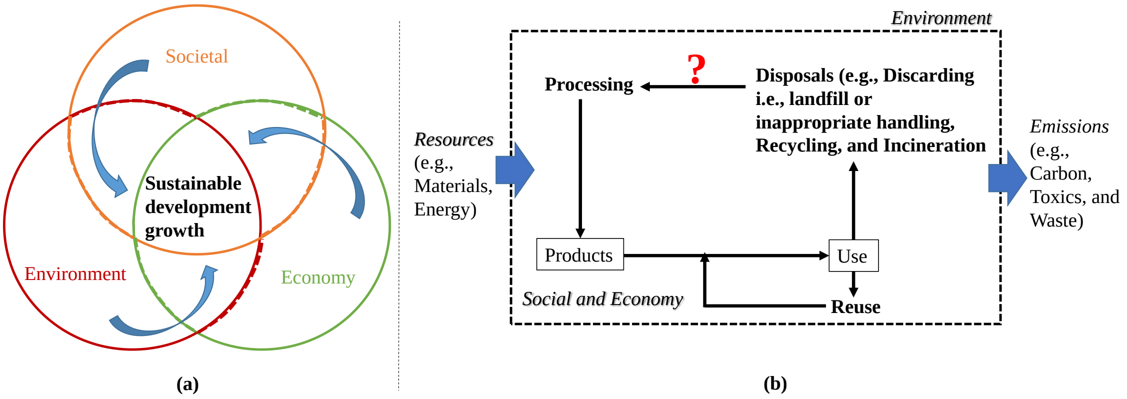

Figure 5. (a) Features of sustainable development, and (b) overview of life cycle of resources, and socioeconomic, and environment[40, 41].

Hence, adopting a comprehensive perspective, recognizing plastics as a critical waste stream requiring focused attention for ongoing and future sustainable development, this review seeks to examine the current state of global plastic waste management for both bio-based and fossil-based plastics. In pursuit of these objectives, we intend to address key questions aimed at uncovering critical issues, as outlined below:

(1) How is the current situation regarding the global fate of plastic waste?
(2) Is the current scenario conducive to the sustainable growth of the plastics industry?
(3) If not, then what are the possible reasons behind lack of sustainable growth of the plastic industries?
(4) What can be the possible solutions to achieve sustainable growth goals of plastic industries?

Based upon the answers, the future prospects to achieve the sustainable development growth in the plastic industry would be briefed. In this perspective paper, we consider the plastic waste management sector as an integral part of the plastic industry, encompassing both manufacturers and recyclers.

RESULTS and DISCUSSIONS

How is the current situation regarding the global fate of plastic waste?

Figure 6 presents global trends in plastic waste management spanning from 1980 to 2050. Notably, the overall proportion of discarded all-plastic waste is projected to substantially decrease from 100% to 6% by 2050. Concurrently, there are anticipated increases in incineration and recycling, reaching around 50% and 44%, respectively. It is essential to clarify that in Figure 6, "all waste" encompasses both bioplastics and fossil-plastics. Despite the lower production of bioplastics compared to fossilplastics (as depicted in Figure 1), the sub-figure in Figure 6 reveals that as of 2019, bio-plastic waste has not been generated. Additionally, it is crucial to note that about 41% of total bioplastics production (Figure 3) is non-biodegradable. However, the current plastic waste stream minimally includes biodegradable bioplastics, suggesting their limited impact on plastic waste management.

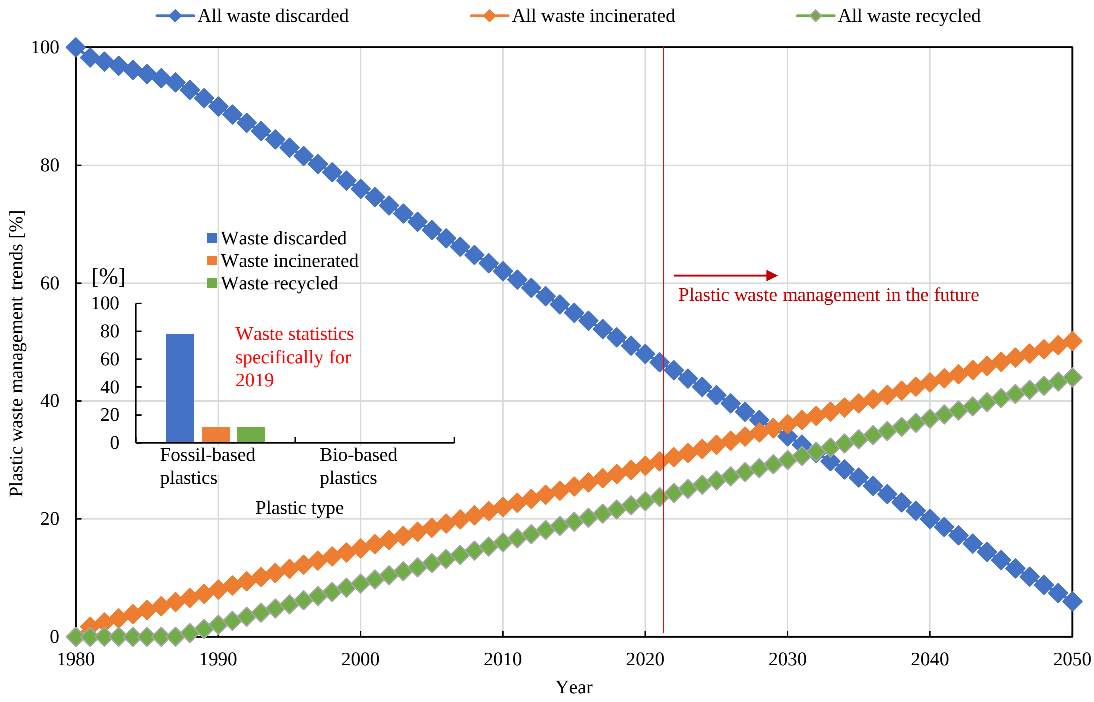

Figure 6. The all plastics (i.e., both fossil, and bio) waste management trends [%] of total plastic waste generation since 1980 to 2050[42]. The sub-Figure inside this Figure shows the fossil- and bio-plastic waste management trends [%] only for 2019[35, 43-45].

Is the current scenario conducive to the sustainable growth of the plastics industry?

The response to our second question suggests a significant lag in the plastics industry aligning with sustainable development. Critical insights from Figure 6 reveal that, in 2019, approximately 49.4% of generated plastic waste was discarded, a proportion expected to decrease to 6% by 2050. However, in 2019, an alarming 44.5% of the discarded waste ended up in landfills, leaving the remaining 55.5% mismanaged, as illustrated in Figure 7. With global societal and industrial expansion, landfill space is dwindling, raising concerns, particularly with the significant threat posed by the remaining 55.5% of mismanaged waste plastics to our environment if not addressed.

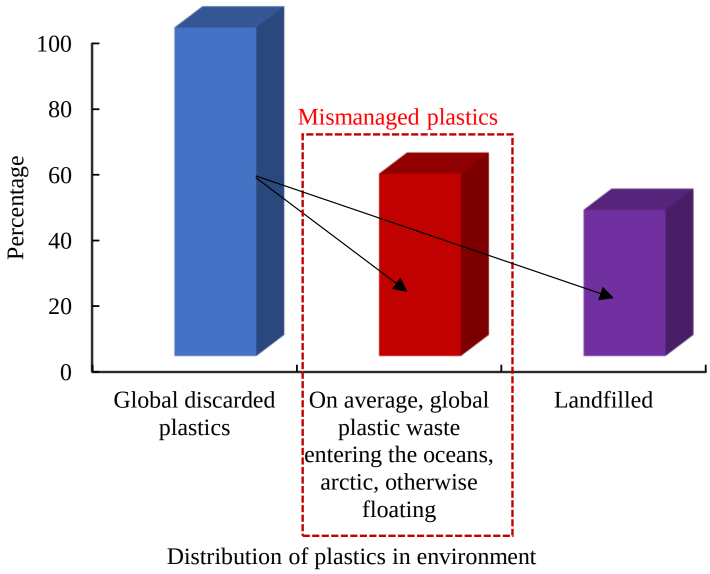

Figure 7. Distribution of global waste plastics discarded into mismanaged waste plastics (which entering the oceans, arctic, otherwise floating), and landfilling in 2019 [35, 46, 47].

If not, then what are the possible reasons behind lack of sustainable growth of the plastic industries?

As reported in Figure 7, the primary reason for plastic disposal is the convenience of single-use applications, with a substantial portion being casually discarded by individuals. These applications, characterized by a short lifespan (less than 1 to 5 months) and low pricing, especially for packaging foods and daily necessities, contribute to the problem, as depicted in Figure 8.

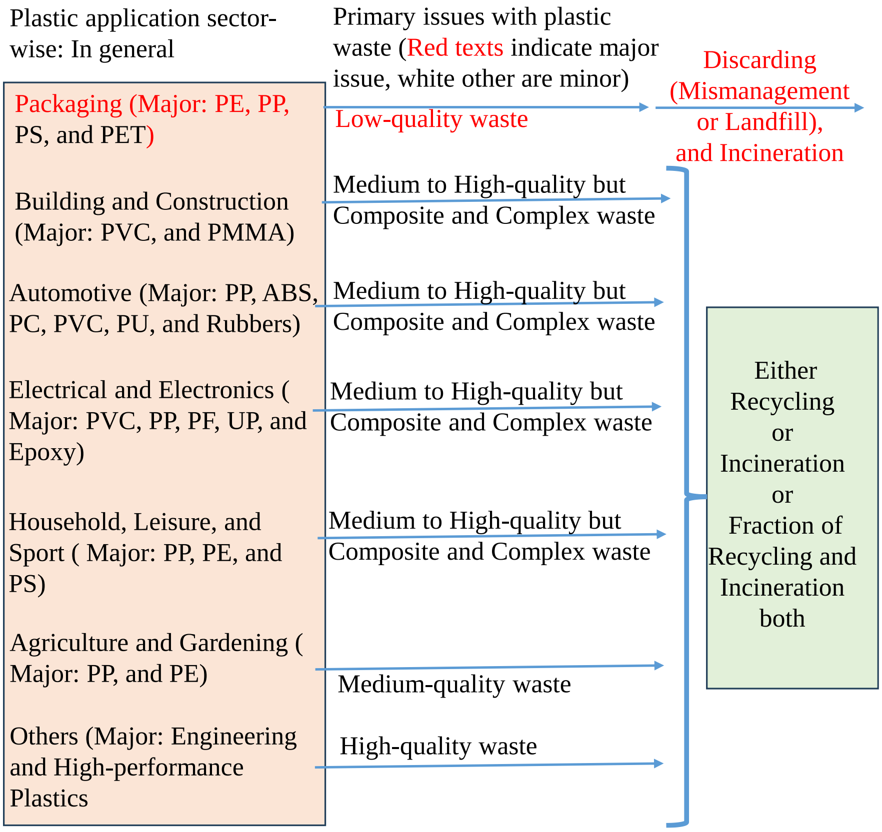

Figure 8. Applications of major plastics in various sectors, and reasons which decide their disposal options[2, 13, 41].

Waste plastic from packaging, often made from thin films of PE and PP, is considered low quality, likely due to its design. The term "low quality" refers to the low value these PE and PP packaging wastes offer to recyclers. Despite the large volume of such waste, material recovery rates are low, even after significant effort. As a result, consumers tend to discard it, and recyclers are reluctant to collect it[47]. However, PE and PP used in other sectors—such as automotive or household—are more likely to be recycled due to their higher-quality waste, which adds more value for recyclers. This suggests that the problem lies not in the plastic itself but in the design of its applications. The concept of product design here refers to creating high-quality products, even if it leads to higher prices. This encourages consumers to retain waste products and hand them over to designated recyclers in exchange for compensation. When recyclers collect such high-quality waste, they can efficiently recycle it into reusable plastic materials and applications[48, 49]. However, the transforming PE and PP waste into monomers is only emerging but not yet feasible with current technologies, as this is in practicing in case of PET into reusable PET materials or monomers. This make PET is recycling favourable than PP, PE or PS[50, 51]. Beyond this, another factor which decline recycling is the highly complex composite products, which complicates the recovery of individual plastic types. Recycling is more efficient for singular plastic waste than for composite waste. For instance, recovered plastics from electronic and electrical waste, such as printed circuit boards (PCBs) or wire harnesses, consist of multiple plastic types, making them difficult to recycle and often leading to incineration[52, 53]. One of the key challenges in plastic waste management is that the profitability of recycling often falls short of the required investment in recycling facilities, leading to unsustainable practices such as discarding or incinerating waste[54]. Several major issues complicate recycling, including inefficient waste collection, high levels of contamination, and limited potential for decontaminating materials. These factors reduce both the technical and economic feasibility of recycling. The persistent problem of sorting further restricts the recycling potential of plastics in municipal waste, frequently resulting in their disposal or incineration, with or without energy recovery. For recycling to be effective, the purity of recycled plastics typically must exceed 99% to be used as a substitute for virgin materials. Another significant barrier is the relatively low market demand for recycled materials due to differences in properties compared to virgin plastics[47, 49]. For better results, the recycling sector should be an integral part of plastic manufacturing. Therefore, economic and technological collaborative efforts for recycling by plastic manufacturers, which may currently be insufficient.

What can be the possible technological solutions to achieve sustainable growth goals of plastic industries?

As discarding waste plastic is deemed inappropriate, the next viable option involves establishing circular systems for resources, carbon, and products. Fossil-based plastics derive from molecular units or monomers sourced from fossil resources, while bio-based plastics originate from molecular units or monomers derived from crude biomass. A circular approach for waste plastics involves adopting a product-to-product strategy, such as bottle-to-bottle, known as reuse. Reuse is considered the most suitable method for mitigating carbon emissions. While achieving a universal product-to-product approach may be challenging, reaching a rate of 20% or more could meet the World Economic Forum's 2023 target. Although, reuse can be accelerated if the certain technological factors such re-pair, re-fine, and re-design would be adopted in manufacturing of products. Subsequently, the focus shifts to recycling, encompassing the conversion of products back into plastics (e.g., PET bottle-to-PET) or transforming them into monomers or fossil resources. Chemical recycling, which involves recovering chemicals like monomers[51, 55-57] for reproducing similar virgin plastics or crude fossil resources for regenerating new plastics or repurposing chemicals as feedstocks[58, 59], and mechanical recycling, where plastic waste undergoes physical alterations for reuse [48, 49, 60, 61] facilitating the circulation of resources. These approaches are applicable to both fossil- and bio-based plastics. Achieving sustainable development growth necessitates a critical and swift expansion of waste plastic recycling. Unfortunately, as depicted in Figure 6, only about 25% of all waste plastic was recycled by 2023 by in terms of materials recovery, monomers recovery, other feedstocks recovery. Although there is ongoing research on how to apply upcycling of waste plastics (i.e., turning the waste plastic into new higher value plastics)[50] to improve the recycling rates, as depicted in Figure 9.

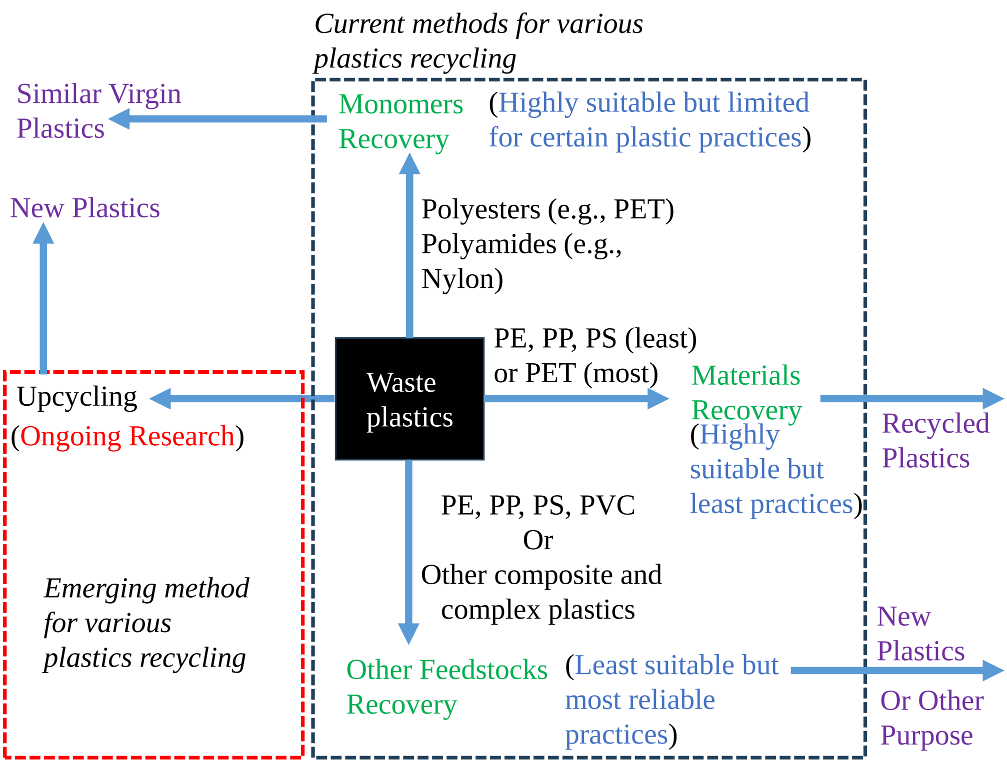

Figure 9. Current recycling options in waste plastics system.

However, evidence shows that low-quality waste plastics generated from packaging sector often resulting in it being discarded or incinerated, as illustrated in Figures 6 and 7. To tackle this issue, maintaining high-quality waste plastic requires a collaborative effort between manufacturers, consumers, and recyclers. Manufacturers can innovate through improved product designs and material re-shuffle, consumers can ensure proper disposal practices, and recyclers can adopt advanced collection, sorting, and recycling techniques[40]. Of these groups, manufacturers play a critical role. They can enhance the design of products and shift to using plastic, which is more easily recycled (e.g., packaging PP, PE, or PS can be replace by all PET packaging). Also, for manufactures logo and other product information on the package, the PET film should be only used, as depicted in Figure 10. If implemented, waste PET can be recycled into PET plastics or monomers, unlike PP and PE, for which monomer recovery is not feasible. Although recycling options exist for these materials, the costs associated with collection, separation, decontamination, and recovery of recycled PE, PP, PET, or PS often exceed the value of the recycled materials, as previously mentioned.

Figure 10. Re-design and Re-shuffle illustration of PE, PP, or PS to all PET in packaging.

Last but least favourable, if some waste plastics are unsuitable for recycling for appropriate reasons such as waste originate form hospitals which is likely unhygienic for manual handling, repurposing as energy through thermal processing methods like incineration is an alternative[62-64]. The energy generated can vary depending on its use for electricity generation, combined heat and electricity, or as a solid waste fuel in blast furnaces and cement kilns[65, 66]. Predictions indicate an increase in incineration, reaching up to 50% by 2050, a trajectory misaligned with sustainable development goals as incineration does not contribute to the net-zero carbon aim under SDGs due to its unsuitability for carbon capture utilization (CCU) and carbon capture storage (CCS). In all, reuse, and recycling is a more favorable option. Implementing CCU and CCS could aid in developing carbon-neutral processes. As aforementioned, plastics such PVC loaded with various additives, so, choosing methods must consider in recycling. Considering all, Figure 11 present a proper circular economy model for plastic waste management.

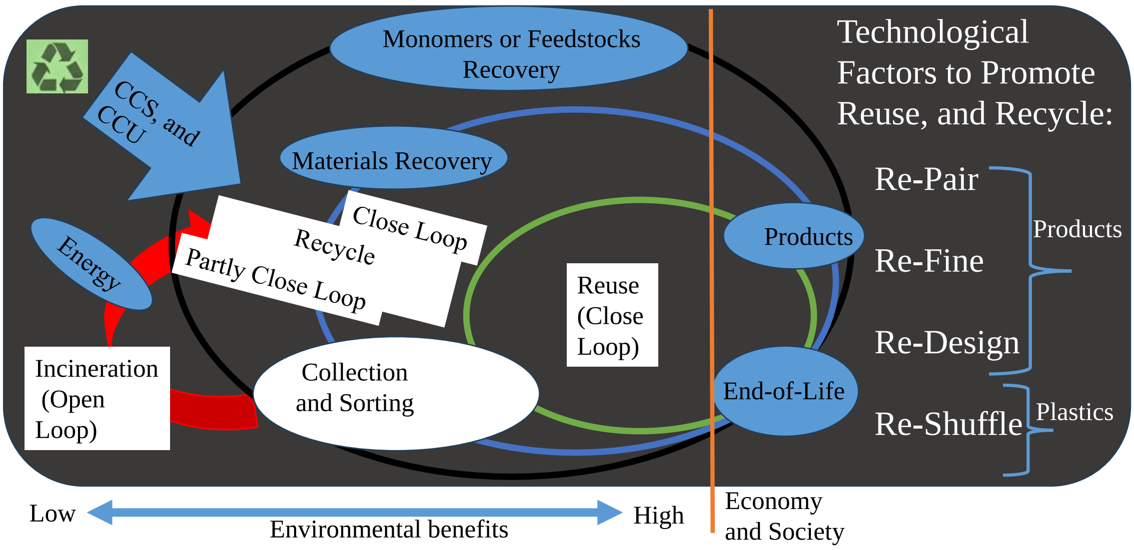

Figure 11. The circular economy model for sustainable development growth of both fossil-and bioplastics.

BRIEFING AND FUTURE PROSPECTS FOR ACHIEVING SUSTAINABLE DEVELOPMENTS

Considering bioplastics as a practical alternative to fossil-based plastics appears more like an aspiration than an imminent reality[67, 68]. This is evident from the historical and current growth of the bioplastics industry, which has been significantly slower, constituting only a about 1% share in overall plastic production compared to the rapid expansion of fossil-based plastics, as shown in Figure 1. It is unlikely that bioplastics will replace fossil-based plastics in the next 27 years, extending up to 2050. Even with an increasing proportion of bioplastics in total plastic production, assuming they could contribute to sustainable development without the need for recycling or reusing products may not be feasible[69]. This is primarily due to the fact that approximately 41% of bioplastics are currently not biodegradable, as indicated in Figure 3. Therefore, these products must undergo recycling for subsequent reuse[70]. Achieving sustainable development necessitates a re-evaluation of fossil-based plastics product development and waste management strategies as suggested aforementioned; because in 2023, only 25% of plastic waste is recycled, while 31.2% is incinerated and 43.8% goes to landfills or is improperly disposed of. By 2050, recycling could rise to 44%, but incineration may still reach nearly 50%. Also, there is a pressing need for innovative approaches to promote the reuse and recycling of products[40]. The persistent failure to establish closed carbon loops contributes to the ongoing depletion of non-renewable resources, leading to significant environmental carbon leakage into soil, water, and air. This poses a severe threat to human habitats and biodiversity[71-74]. Without addressing this issue, the current global waste management system is anticipated to face a collapse in the midst of the 21st century, driven by current practices of landfilling and inadequate management of plastic waste, exacerbating climate-related challenges.

Nevertheless, this is a perspective paper comprehensively examines the historical, current, and prospective landscape of plastics production and waste management. Ongoing studies in recycling have yielded various advanced technologies supported by thorough documentation and evidence. Consequently, the subsequent papers would take a more focused approach by delving into past, present, and future research on technologies for plastic waste management, aiming to establish closed carbon loops in the evolution of circular plastic development.

APPENDIXES: FORECASTING MATHEMATICAL MODELS AND RESULTS

Appendixes 1 and 2 present the development of a mathematical forecasting model for global plastic production: Growth Rate-Based Model, and Waste Management trends: An Autoregressive Integrated Moving Average (ARIMA) Model. Figures appendix1.1 to appendix1.4 present the Forecasting of fossil-based plastics generation, Forecasting of Post-consumer recycled plastics generation, Forecasting of Bio-based plastics generation, and Forecasting of Total plastics generation. Moreover, Figures appendix2.1 to appendix2.3 presents the Forecasting of Discarded Waste, Forecasting of Incinerated Waste, and Forecasting of Recycled Waste.

CONFLICTS OF INTEREST

There are no conflicts to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix

Sustainable Development in the Plastic Industry: A Promising Future or Just a Hoax? Past, Present, and Future Perspectives from a Global Viewpoint

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Appendix1. Model Description (a growth rate-based model) for forecasting the global plastics production trend based upon the historical data:

The forecasting model employed in this analysis is a basic exponential growth model. It is designed to project future plastic production based on historical growth trends. The core idea is to extend the observed growth rate into the future, if the historical growth pattern will persist. Percentage Change Calculation: The model calculates the annual percentage change using:

$$P = (Y_c\text{-}Y_P)/Y_P$$

Where, P, Y_c, and Y_p are the Percentage change, current Year Value, and Previous Year value.

Then Average Growth Rate is estimated. The mean of these annual percentage changes is computed to determine the average growth rate. This growth rate is used to project future values. Once you have the percentage changes for each year, compute the average of these percentage changes to get the Average Growth Rate. This is done using:

$$G = \sum(P)/N$$

Where, G, and N are Average Growth Rate, and Number of Change.

Next is Forecasting, where Exponential Growth Formula is adopted. Future values are projected using the exponential growth formula:

$$\text{Forecasted Value} = (\text{Last Known Value}) \times (1+\text{Average Growth rate})^{(\text{Year-Last known Year})}$$

The Confidence Intervals is estimated using standard deviation of historical percentage changes (residuals) is used to measure variability. This helps estimate how much the forecasted values might vary from the actual future values. This is done using:

$$\text{Upper Bound} = \text{Forecasted Value} \times (1+1.96 \times \text{Residual Standard Deviation})$$

$$\text{Lower Bound}=\text{Forecasted Value} \times (1+1.96 \times \text{Residual Standard Deviation}$$

The factor 1.96 is used to represent a 95% confidence level, meaning there is a 95% chance that the actual future values will fall within this range.

Brief Snapshot of Model in Python code was used for throughout the calculations. Full Python code will be provided on individual request:

```
# Calculate growth rate and forecast
last_known_value = df['Total plastics'].iloc[-1]
df['pct_change'] = df['Total plastics'].pct_change()
growth_rate = df['pct_change'].mean()
forecast_periods = 30
future_years = np.arange(df.index[-1] + 1, df.index[-1] +
forecast_periods + 1)
forecast = [last_known_value * (1 + growth_rate)**(year -
df.index[-1]) for year in future_years]
```

NEXT HERE ARE PLOTTED RESULTS OF FORECASTING OF VARIOUS TYPE OF GLOBAL PLASTIC PRODUCTION TRENDS:

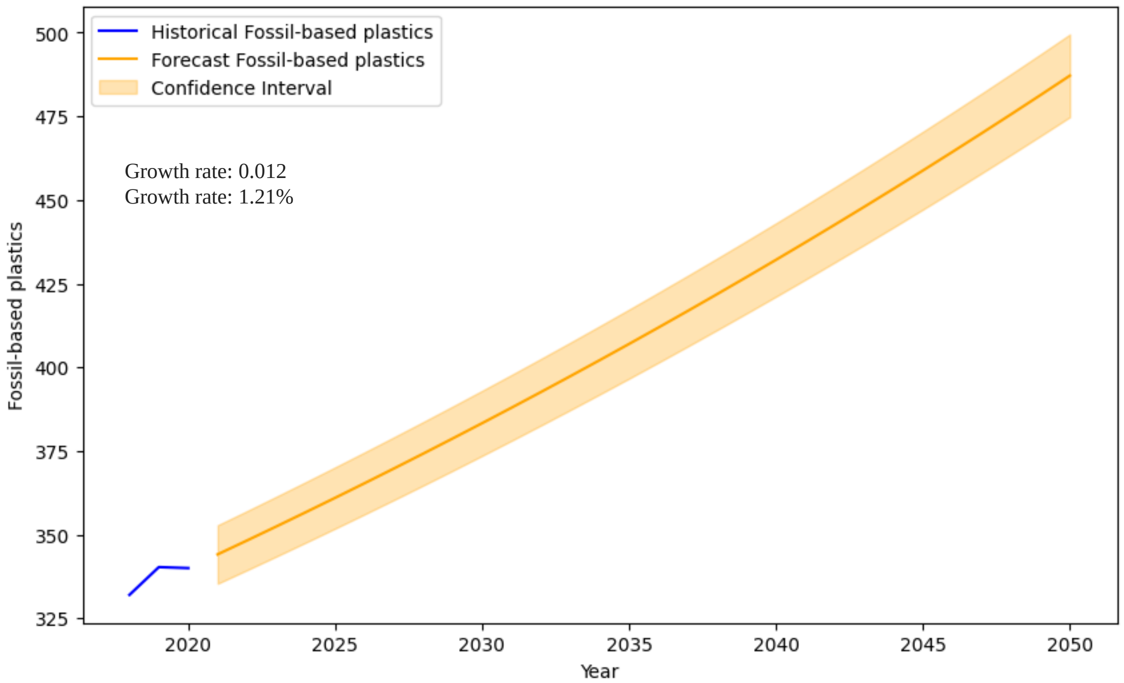

Figure appendix1.1. Forecasting of fossil-based plastics generation in million tonnes.

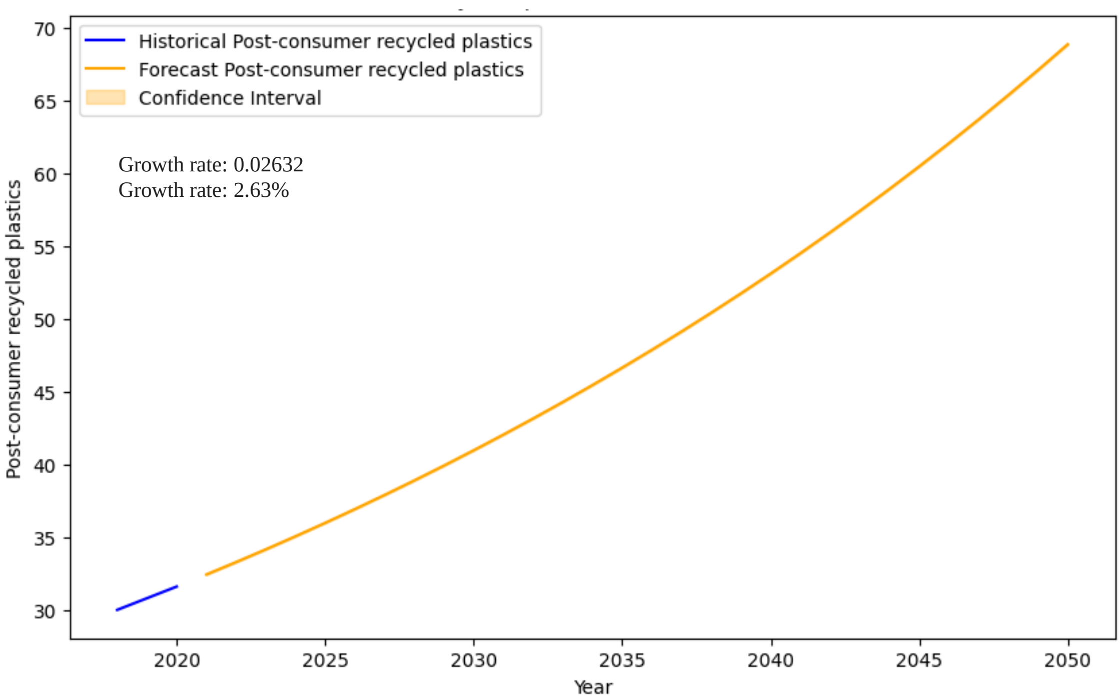

Figure appendix1.2. Forecasting of post-consumer recycled plastics generation in million tonnes.

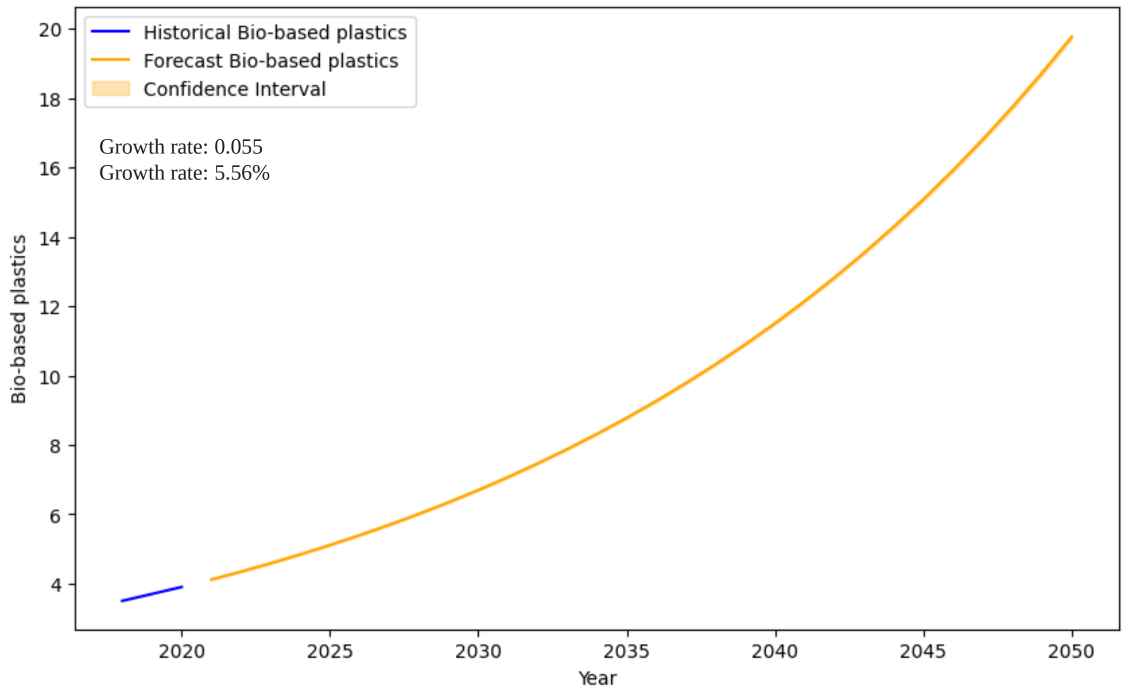

Figure appendix1.3. Forecasting of Bio-based plastics generation in million tonnes.

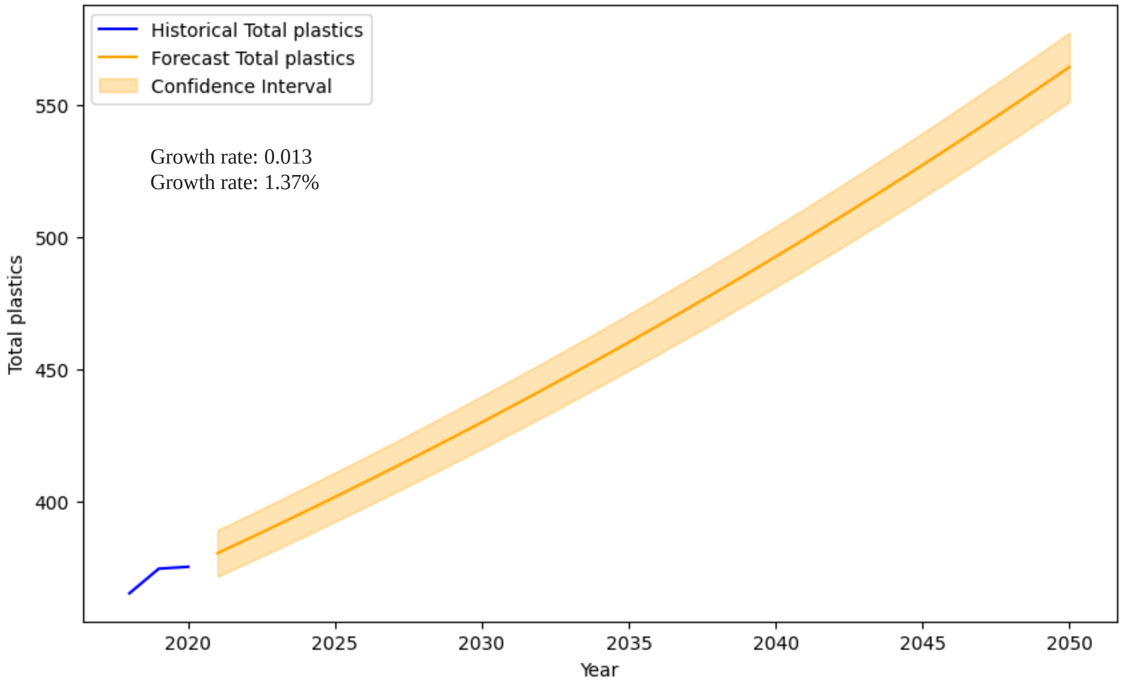

Figure appendix1.4. Forecasting of Total plastics generation in million tonnes.

Appendix2. Model Description for forecasting the global waste plastic management trend based upon the historical data:

For this forecasting, ARIMA model was adopted based upon the suitability of historical data and forecasting more accurate results. In this forecasting, we realized that considering growth rate is not suitable based upon waste management historical data as we chose plastic production forecasting. Thus, we chose ARIMA to generate forecasting with fine-tune. The ARIMA model leverages historical time series data to make predictions about future values. The mathematical components involve autoregressive terms, differencing for stationarity, and moving average terms, all optimized based on AIC and BIC. Forecasts are generated using these optimized models, with confidence intervals providing a range of uncertainty around the predictions.

The ARIMA model is a combination of three components:

1. AutoRegressive (AR) Component
2. Integrated (I) Component
3. Moving Average (MA) Component

1. AutoRegressive (AR) Component

The AR component models the current value of the time series as a function of its previous values. It is characterized by the parameter *p*, which represents the number of lagged values used in the model.

The AR(p) model can be expressed as:

$$X_t = \phi_1 X_{t-1} + \phi_2 X_{t-2} + \ldots + \phi_p X_{t-p} + \epsilon_t$$

where:

- X_t is the value at time t.
- $\phi_1, \phi_2, \ldots, \phi_p$ are the AR coefficients.
- ϵ_t is the white noise error term.

2. Integrated (I) Component

The I component involves differencing the time series to make it stationary (i.e., constant mean and variance over time). The parameter *d* represents the number of times differencing is applied.

If the original series X_t is not stationary, differencing is applied:

$$\Delta^d X_t = (1-B)^d X_t$$

where Δ is the differencing operator and B is the backshift operator ($BX_t = X_{t-1}$).

3. Moving Average (MA) Component

The MA component models the current value of the time series as a function of past error terms. It is characterized by the parameter q, which represents the number of lagged forecast errors included in the model.

The MA (q) model can be expressed as:

$$X_t = \mu + \epsilon_t + \theta_{1\epsilon t-1} + \theta_{2\epsilon t-2} + \ldots + \theta_{q\epsilon t-q}$$

where:

- μ is the mean of the series.
- $\theta_1, \theta_2, \ldots, \theta_q$ are the MA coefficients.
- ϵ_t is the white noise error term.

ARIMA Model

The ARIMA model combines these components and is denoted as ARIMA (p, d, q):

$$\text{ARIMA (p,d,q)} : \underbrace{(1- \phi_1 B - \phi_2 B_2 - \ldots - \phi_p B_p)}_{\text{AR Part}} \underbrace{\Delta^d X_t}_{\text{I Part}} = \underbrace{(1 + \theta_1 B + \theta_2 B_2 + \ldots + \theta_q B_q)\epsilon_t}_{\text{MA Part}}$$

Model Fitting and Evaluation

1. **Fitting the Model:**
   - The model is fit to the historical data using Maximum.

Model Evaluation:

2. **AIC (Akaike Information Criterion)**

$$AIC = -2\log(L) + 2k$$

where L is the likelihood of the model, and k is the number of parameters. Lower AIC values indicate a better model fit.

3. **BIC (Bayesian Information Criterion):**

$$\mathrm{BIC} = -2\log(\mathrm{L}) + k\log(n)$$

where n is the number of observations. BIC penalizes more for the number of parameters compared to AIC.

Brief Snapshot of ARIMA Model in Python code was used for throughout the calculations.

Full Python code will be provided on individual request:

```
# Define parameter ranges
p = range(0, 4)  # p values from 0 to 9
d = range(0, 3)   # d values from 0 to 8
q = range(0, 4)  # q values from 0 to 9

# Storage for results
results = []
```

NEXT HERE ARE PLOTTED RESULTS OF FORECASTING OF GLOBAL PLASTIC WASTE MANAGEMENT TRENDS:

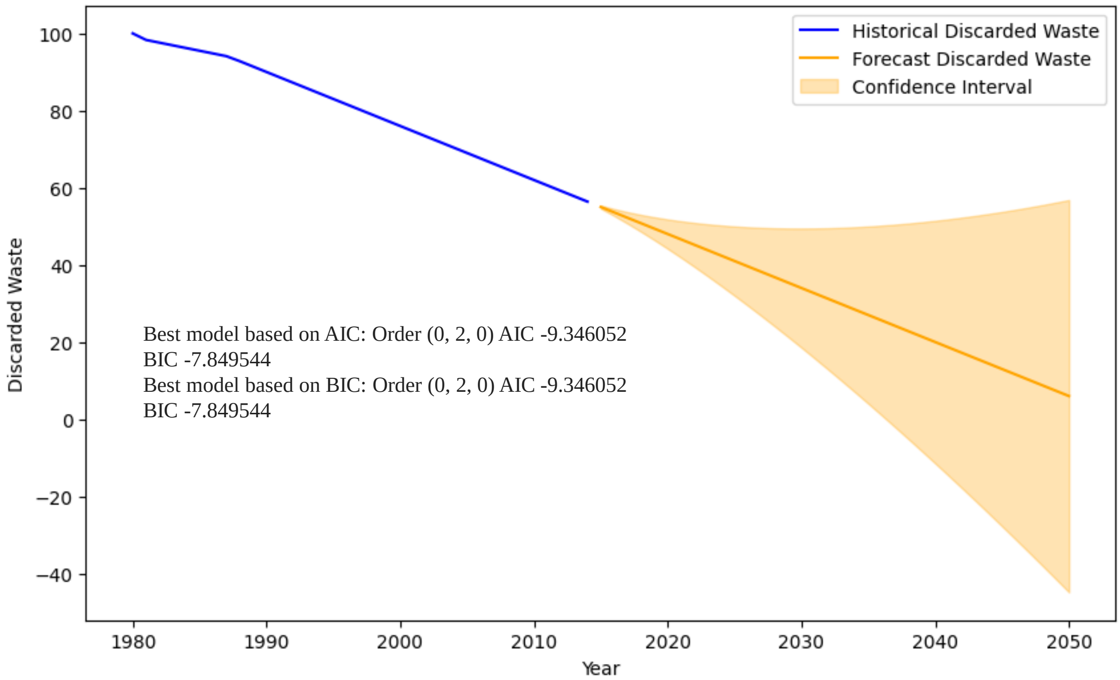

Figure appendix2.1. Forecasting of Discarded Waste in percentage.

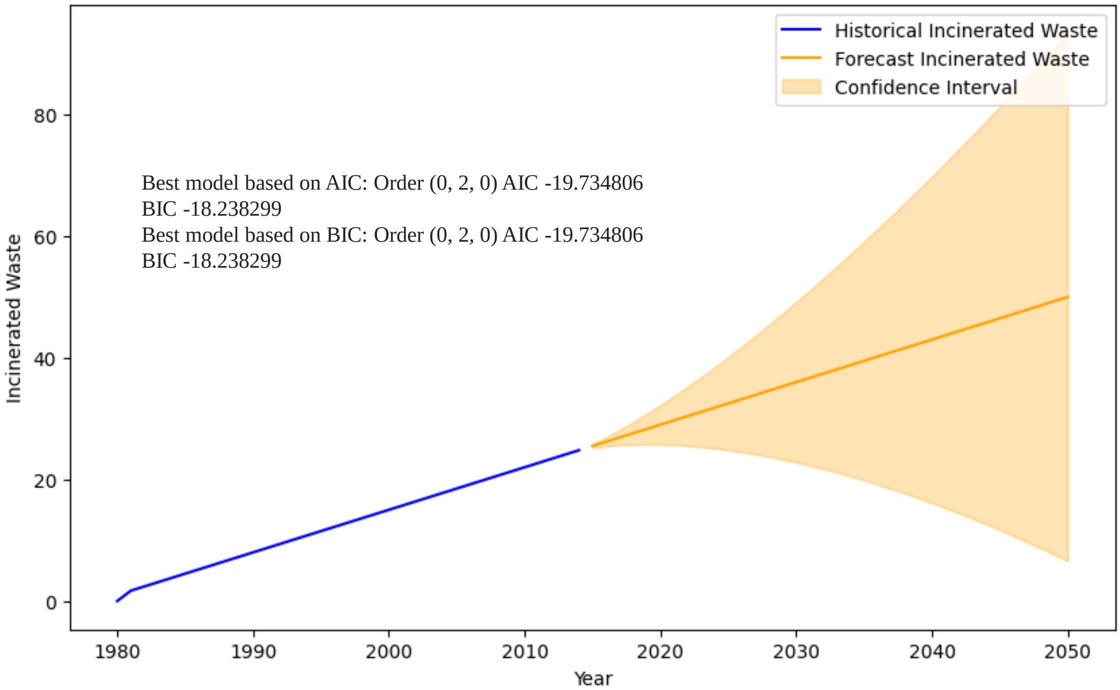

Figure appendix2.2. Forecasting of Incinerated Waste in percentage.

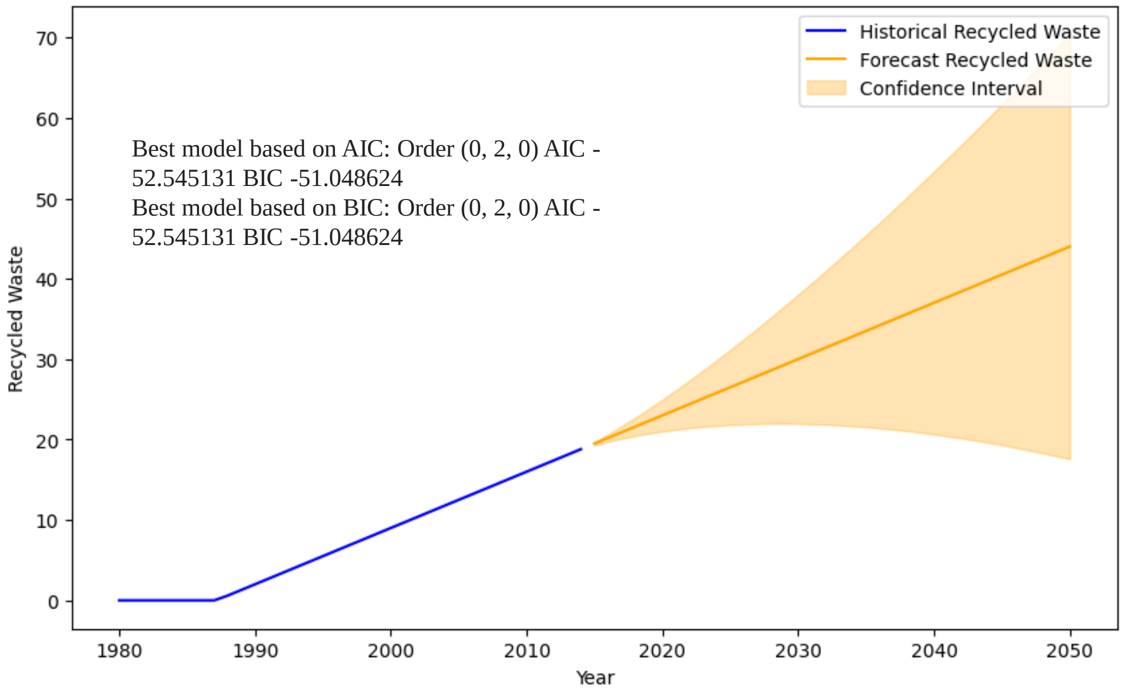

Figure appendix2.3. Forecasting of Recycled Waste in percentage.