Journal of Environmental Management 374 (2025) 124104

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Assessing the ecological and economic transformation pathways of plastic production system

Ibrahim Issifu[a,*], Ilyass Dahmouni[a], U. Rashid Sumaila[a,b]

[a] Fisheries Economics Research Unit, Institute for the Oceans and Fisheries, University of British Columbia, 2202 Main Mall, Vancouver, BC, V6T 1Z4, Canada
[b] Department of Agricultural Economics and Rural Development, University of Pretoria, Pretoria, South Africa

ARTICLE INFO

Keywords:
Plastic pollution
GHG emissions
Carbon dioxide equivalents
External costs
Voluntary levy
Cooperative behavior

ABSTRACT

Plastic's incredible versatility drives its continuous production growth, contributing to 4.5% of global greenhouse gas (GHG) emissions. With an unsustainable 4% annual production growth rate, plastics' environmental impact is significant. Our study, using climate and economic models, assesses the effects of a voluntary plastic levy imposed on the top 100 resin producers. The results suggest a potential 70% reduction in global plastic production emissions by 2050, lowering emissions from business–as–usual levels to 1.62 Gt CO_2e. The proposed USD 82.5 billion levy over 25 years could fund recycling initiatives, increasing recycling rates by 73%. To align with the Paris Agreement target of 1.5 °C, plastic production growth would need to drop to approximately 2.9%–3.1% annually, achieving a 25% decrease by 2050. Implementing this levy could significantly enhance recycling and reduce emissions, mitigating climate change.

1. Introduction

The generation of waste, whether from production or consumption, is an inherent by–product of human activity. Plastic is one of the most widespread types of waste, with an estimated global production of 8,300 million metric tonnes (mmt) in 2015 dating back to when synthetic plastics were first manufactured in the beginning of the 20th century (Geyer et al., 2017). Today, plastics contribute approximately 4.5% of the world's greenhouse gas (GHG) emissions (Cabernard et al., 2022; IEA, 2018). In 2015 alone, 407 million tonnes of plastics were manufactured, growing at an average annual rate of 4% between 2010 and 2015. As a result of this production, GHG emissions have been estimated at 1.8 gigaton (Gt) of carbon dioxide equivalents (CO_2e) (Center for International Environmental Law, 2019). Should the prevailing annual growth rate of 4% persist, plastic–related GHG emissions are expected to reach 1.6 Gt per year by 2050, contributing to cumulative emissions of 129 Gt CO_2e by mid-century (Zheng and Suh, 2019). Mechanical recycling, frequently regarded as a remedy for plastic pollution, delivers only modest cuts, lowering CO_2e emissions by between (0.28 kg and 0.53 kg CO_2/kg) (Uekert et al., 2023).

Plastic pollution, particularly the CO_2 emissions resulting from its production, continues to have a significant impact on global environmental systems. The Intergovernmental Panel on Climate Change (IPCC) reported a significant correlation between cumulative carbon emissions and global warming, suggesting a temperature increase of 0.8 °C–2.4 °C per 1000 Gt CO_2e (IPCC, 2014, 2018, 2021). Building on these results, CO_2 emissions from historical plastic production are predicted to have accounted for between 0.007 °C and 0.021 °C of global warming. At current emission levels, plastic production on its own could potentially add between 0.035 °C and 0.106 °C of warming by 2050, and between 0.263 °C and 0.789 °C by the end of this century.

The detrimental consequences of plastic waste are not limited to climate change; it also constitutes a serious menace to terrestrial and aquatic environments (Stegmann et al., 2022; Zheng and Suh, 2019). The contamination of oceans and lands by plastic debris has become a pressing global policy concern, highlighted by Sustainable Development Goal (SDG) 14. Governments, civil society and consumers are placing escalating demands for solutions to curb the emissions and environmental footprint of plastics.

Several policies and regulatory actions have been launched at international and national levels in response to public pressure. For example, the Basel Convention now has an amendment to restrict cross-border trade in plastic waste (U.S. EPA, 2021). In addition, many jurisdictions have introduced bans on single-use plastics (NDRC & MEE, 2020; Karasik et al., 2020; Government of Canada, 2021; Hockenos, 2021). Industry driven efforts, such as the New Plastics Economy, aim to

---

* Corresponding author.
E-mail address: i.issifu@oceans.ubc.ca (I. Issifu).

https://doi.org/10.1016/j.jenvman.2025.124104
Received 14 January 2024; Received in revised form 11 October 2024; Accepted 8 January 2025

champion circular economy business practices, including the redesign, reuse, recycling and recovery of plastics. In addition, major companies have pledged to increase their packaging and recycling efforts (Diana et al., 2022). Transitioning to a circular economy—focusing on reuse, redesign, and recycling—is essential, particularly for reducing single–use plastic waste (FAO, 2021; Issifu et al., 2021). However, this shift requires scientific advancements in developing sustainable alternatives, improving recycling, and creating materials that maintain plastic's functionality without environmental harm (van der Oever et al., 2017; National Academies of Sciences, Engineering and Medicine, 2022).

Despite these efforts, the effectiveness of these strategies in tackling the scale of plastic pollution remains uncertain. The question therefore arises as to whether a private–sector–imposed levy on the production of virgin plastic could play a part in solving this problem. This research estimates the potential impact of reducing the production of virgin plastic through a voluntary levy on the top 100 polymer producing companies, which are the principal sources of harmful plastic compounds.

Drawing on the existing body of knowledge, we have carried out extensive data gathering and literature review to evaluate the environmental and societal impacts of global plastics production. Following a synthesis of peer–reviewed and grey literature, including government reports, we developed a conceptual model. This model demonstrates the links between plastic reduction interventions and their downstream effects on the environment, climate change and society. Fig. 1 shows the conceptual model, emphasising positive and negative economic and societal impacts of plastic reduction efforts.

2. Plastic production and its impacts

2.1. Plastic production

Plastics are the lifeblood of modern life, playing a vital role in everyday activities and across industries. From transport, telecommunications, clothing, and packaging to medical applications and renewable energy generation, plastics are valued for their lightweight, durable, and cost–effective properties. Their versatility supports the efficient transportation of goods, enhances energy efficiency in various sectors, and facilitates advancements in both consumer and industrial applications (Andrady and Neal, 2009), but their extensive use poses significant environmental challenges. Numerous studies in chemical engineering have investigated means of transforming waste into valuable resources, demonstrating the potential of these innovations to reduce environmental footprint. Scientists are particularly focused on converting waste, including plastics, into renewable forms of energy, addressing both waste management and energy durability. As an example (Benzennou et al., 2019), demonstrate how using biomass and waste, such as paper cups and plastics, instead of fossil fuels can significantly reduce greenhouse gas emissions, matching global efforts such as the Kyoto Protocol to combat global climate change. The study shows how pyrolysis, a process that transforms waste into oil, enables us to manage waste as well as create renewable energy that could displace fossil fuels. While biomass is frequently considered to be carbon–neutral, plastics play a more complex role owing to their great economic importance and their widespread use in contemporary society. A truly circular economy will require more than merely converting plastic waste: scientific breakthroughs in plastic waste conversion technologies will be needed, ensuring that they are progressive, economically feasible and long lasting.

Plastics are synthetic polymers with diverse chemical and physical properties, such as polyethylene terephthalate (PET), polyethylene, and polypropylene (Issifu et al., 2021). Most are hydrocarbon–based, derived from fossil fuels, and possess strong carbon–carbon bonds that resist biodegradation (Lebreton and Andrady, 2019; National Academies of Sciences, Engineering and Medicine, 2022). Over the last 50 years, global plastic production has surged nearly 20–fold (See Fig. 2), growing from 2 million metric tons (mmt) in 1950 to 460 mmt by 2019 (Plastics Europe, 2022; Geyer et al., 2017). Remarkably, almost half of all plastic was produced between 2003 and 2016, with Asia contributing 51% of global production in 2019 (Statista, 2022a).

In 2021, China accounted for 32% of the worldwide plastic production, making it the world's largest plastic producer by far (Statista, 2022a). North America was the second–largest plastic producing region that year, accounting for almost 20% of global production (Statista, 2022a). From 1950 through 2017, the world cumulatively produced 8.3 billion metric tons (bmt) of plastic of which 6.3 bmt had become waste

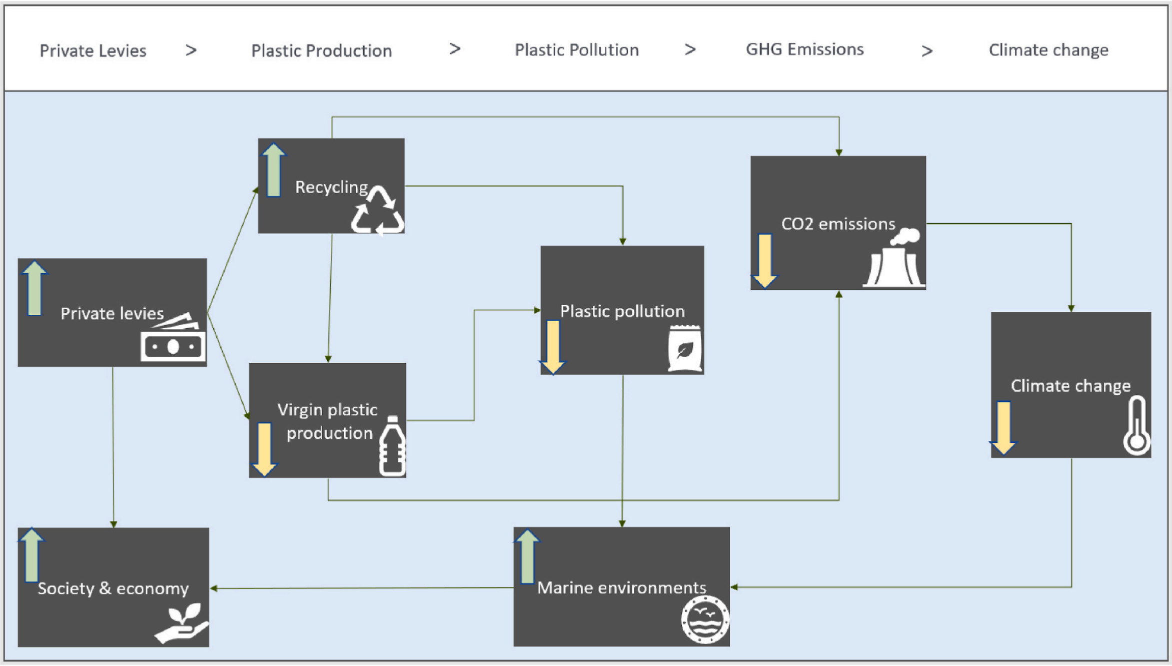

Fig. 1. Conceptual model of plastic reduction initiatives on the production of plastic and their downstream effects on society. Green upward arrows reflect positive effects while yellow downward arrows reflect negative effects.

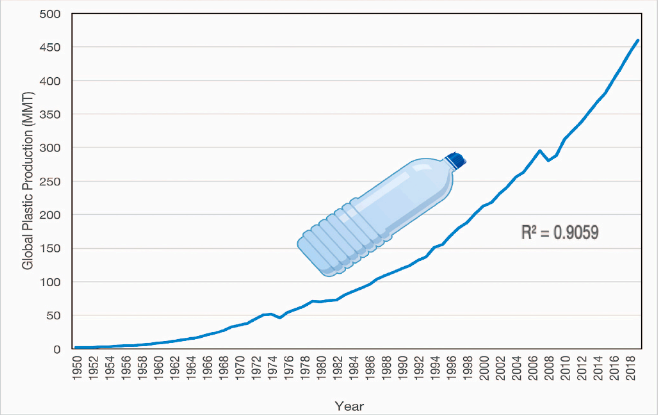

Fig. 2. Global plastic production trend. Our World in Data based on (Geyer et al., 2017) and the OECD Global Plastics Outlook.

in 2015 (National Academies of Sciences, Engineering and Medicine, 2022).

The persistent growth in plastic production is driven by its remarkable versatility, with the market value reaching approximately 593 billion USD in 2021 (Statista, 2022b). This market is projected to exceed 810 billion USD by 2030, with a compound annual growth rate of 3.7%, fueled by a growing population, increased demand, and higher purchasing power (Statista, 2022b). Plastics are expected to account for one–third of global oil demand by 2030 and nearly half by 2050, with petrochemicals and plastic production identified as key drivers of oil demand growth through 2050 (IEA, 2018; Center for International Environmental Law, 2019).

2.2. Negative consequences of plastic production, consumption, and disposal

Marine plastic pollution imposes significant environmental and societal costs (Forrest et al., 2019). The current plastic waste crisis is driven by the rapid increase in plastic production, particularly in household packaging. The fossil fuel and petrochemical industries continue to expand without accounting for the externalities of plastic waste, including air pollution from carbon dioxide, sulfur dioxide, methane, particulate matter, and harmful trace elements like dioxins and furans (Lebreton and Andrady, 2019; Edwards et al., 2018). In 2010, approximately 12.7 million metric tons (mmt) of mismanaged land–based plastic waste leaked into the marine environment (Jambeck et al., 2015). Middle–income countries, experiencing rapid economic growth, have become the epicenters of marine plastic pollution due to insufficient waste management infrastructure.

An estimated 8 mmt of plastic debris enters the ocean annually, equivalent to dumping a garbage truck's worth of plastic into the ocean every minute. If current trends continue, plastic waste in the ocean could reach 53 mmt per year by 2030, almost half the total fish catch by weight (National Academies of Sciences, Engineering and Medicine, 2022). If unchecked, plastic waste may exceed fish biomass in the ocean by 2050 (World Economic Forum et al., 2016). Marine plastic pollution poses a significant threat due to its persistence and volume, with the UN describing it as a planetary calamity in 2019 (Villarrubia–Gomez et al., 2018; MacLeod et al., 2021).

Economic assessments of the damage caused by plastic pollution estimate annual losses of USD 783 million from the food sector, USD 355 million from soft drinks, and USD 232 million from the retail sector (Forrest et al., 2019).

3. Methods

3.1. Projected plastic production, emissions to 2050

In this study, a combination of climate models, economic assessments, and game theory were used to evaluate the ecological and economic impacts of plastic production. The climate models (e.g., Lau et al., 2020; Zheng and Suh, 2019) estimated GHG emissions from plastic production, specifically CO_2e, and their contribution to global warming under different scenarios. The economic models (e.g., Convery et al., 2007; Dikgang et al., 2012) analyzed the financial implications of implementing a voluntary plastic levy on the top 100 polymer producers, projecting revenue generation and the potential for increasing recycling. Additionally, a game–theoretical framework (e.g., De Giovanni and Ramani, 2024). explored the strategic behavior of plastic producers and policymakers, modeling different participation rates in the levy program and assessing their impact on plastic production, emissions reduction, and recycling investment. These approaches collectively provided a robust assessment of how policy measures could mitigate plastic–related environmental damage while fostering economic incentives for recycling.

Plastic production data reports the total of polymer resin and fibre production in metric tonnes, and these data are drawn from the work of Geyer et al. (2017). Projected plastic production values are based on the current 4% annual growth rate in production. This rate was projected based on the annual growth rates between 2010 and 2015 (Geyer et al., 2017). The current 4% growth rate closely aligns with the OECD's 2019 figures. Plastic emission data are calculated from CO_2e emissions from plastic production, assuming that CO_2 emissions are directly proportional to plastic production (Zheng and Suh, 2019). The same study estimated that the production of 0.41 Gt of fossil–based plastics in 2015 emitted 1.8 Gt of CO_2e over their lifecycle.

3.2. Voluntary plastic levy participation scenarios

Economists have generally proposed both demand and supply side measures to help reduce plastic pollution (Abbott and Sumaila, 2019). However, many previous studies on reducing plastic pollution have primarily focused on demand–side solutions such as plastic–bag taxes on consumers (Convery et al., 2007; Dikgang et al., 2012). This paper is a contribution that focuses on the supply side, estimating the impact of a voluntary plastic levy on the top 100 largest resin producers. Data from the Plastic Waste Makers Index (The Minderoo Foundation, 2021) is used to assess the production of targeted polymer companies. The framework emphasizes instructing stakeholders on potential gains or losses from participating in a private sector–led plastic levy.

The study evaluates several scenarios of producer cooperation in the levy, ranging from business–as–usual (BAU) (0% participation) to strong participation (75%). The goal is to project the impact of voluntary levies on plastic production and GHG emissions, ultimately affecting the level of marine plastic pollution.

To illustrate, the study presents a simplified game–theory model involving two players: the social planner and producers. The social planner can choose to "Incentivize" producers with carefully designed subsidies programme Kathie et al.) for adopting plastic levies or opt for "Not Incentive" (no rewards). Producers can decide to "Pollute" (BAU) or "Not Pollute" (environmentally responsible behavior). The interactions between these strategies aim to highlight how policy incentives and voluntary participation can influence outcomes in plastic reduction efforts. The game is summarized as follows:

1. Players: {Social Planner, Producers}.
2. Strategies:
   - o Social planner: {Incentivize, Not Incentive}
   - o Producers: {Pollute, Not Pollute}

3. Payoffs: In this model, both the social planner and producers aim to maximize their respective net benefits, assuming perfect information and symmetry between players. Pollution levels are reduced when producers decrease plastic production, leading to both economic and ecological benefits for all parties. To incentivize this reduction, the social planner compensates producers with side–payments. The payoff matrix, which details the outcomes and associated parameters for each player's decisions is provided in the tables below. This framework highlights the mutual advantages of cooperation in reducing plastic production.

   The four equilibrium possibilities are thus as follows:

- (Incentivize, Pollute): This case corresponds to the situation where producers do not abide by the voluntary plastic levy even when the SP promises monetary incentives. Producers then realize their BAU income, while the social planner incurs the costs of monitoring "C_S" and the environmental damage "D";
- (Incentivize, Not Pollute): In this case, both actors care about the environmental benefit and act accordingly. The producers see their income increase by the amount of subsidy "R" and decrease by the amount "c_pI". From an ecological point of view, the producers' situation improves with a better ecological ecosystem, "B_p". At the same time, the social planner benefits from the ecological and political advantages given by "B_S" and "G_S", respectively. On the other hand, it bears the incentive cost "R" and the policy control cost "C_S";
- (Not Incentive, Pollute): In this possibility, when everyone disregards the state of the environment, the outcome is BAU for both players and the damage "D" is absorbed by society;
- (Not Incentive, Not Pollute): Finally, although the social planner does not adhere to the green policy, the producers implement the voluntary plastic levies and, by using part of their income "cpI", contribute to the ecological benefits for all, i.e., "B_S" and "B_P".

Although cooperation is known to be socially optimal and beneficial for all players (e.g. Sumaila, 1997), the assumption is that each player will act rationally, focusing on maximizing their own outcomes. This means players will choose the strategy that offers the highest own payoff. The most socially preferred equilibrium is (Not Incentive, Not Pollute), where pollution is eliminated at no cost to society. The least preferred outcome is (Incentivize, Pollute), where producers continue polluting and society bears both environmental damage and monitoring costs.

The analysis reveals that all four possible outcomes could be stable equilibria, depending on model parameters. For example, in the (Not Incentive, Not Pollute) equilibrium, producers would voluntarily reduce pollution if their private benefit from green improvements (B_P) exceeds the cost of the plastic levy (C_PI). Additionally, the social planner would opt for the (Not Incentive) strategy if the political gain from green policies (G_S) outweighs the combined cost of monitoring and rewards ($C_S + R$). Thus, for this equilibrium to be stable, both the political and economic incentives for the social planner and producers must align (see Tables 1 and 2).

Table 1
Payoff matrix.

	Producers		
		Pollute	*Not Pollute*
Social Planner (SP)	*Incentivize*	($-C_S - D$; I)	($B_S + G_S - C_S - R$; $R + (1 - c_p)I + B_P$)
	Not Incentive	($-D$; I)	(B_S; $(1 - c_p)I + B_P$)

Table 2
Definition of variables.

Variable	Definition
B_S	Social benefit associated with environmental improvement: Obtained by the public.
B_P	Private benefit obtained by the producers from ecological improvement.
G_S	Political reputation the SP obtains from the implementation of green policies.
G_p	Economic reputation for the producers by adhering to the green policies.
D	Environmental damage due to plastic pollution.
C_S	Cost of monitoring the green policy by the SP.
c_p	Per unit Cost of the voluntary self–imposed plastic levies as a share of the income.
R	Reward (or subsidy) received by the producer from the SP for adhering to voluntary plastic–imposed levies.
I	Income of the producers in BAU situation.

3.3. Scenarios of plastic production and emissions

We used two methods to derive model input data. First, we estimated annual plastic production from the 1990s onwards, calculating that the cumulative production level since 1950 reached 8,300 million metric tons (mmt), based on the 2015 estimate of 407 mmt by Zheng and Suh (2019). Projections assume a 4% annual growth rate in plastic production through to 2050.

For emissions data, we calculated CO_2e emissions from plastic production, assuming they are directly proportional to output (see Fig. 3). In 2015, 4.07 mt of CO_2e was emitted per gigaton of plastic, accounting for emissions from resin production, end–of–life processes, and conversion (Zheng and Suh, 2019).

The relationship between warming and cumulative CO_2 emissions from plastic shows a near–linear correlation. The linear equation (Warming $= 0.00067 * CO_2$) indicates that for every gigaton (Gt) of CO2 equivalent emissions from plastic. This relationship demonstrates the warming effect of cumulative plastic emissions over time. Projections based on a 4% annual growth in plastic production until 2050 estimate significant CO_2 emissions, reflecting trends from 2010 to 2015. According to the IPCC AR5 Synthesis Report (IPCC, 2014), models suggest that for every 1000 gigaton (Gt) of cumulative carbon emissions (equivalent to 3650 Gt of CO_2e), global temperatures could rise by 0.8–2.4 °C. This highlights the substantial impact of continued plastic production on global warming.

We developed four scenarios– BAU, weak participation (25%), moderate participation (50%), and strong participation (75%)–to assess potential reductions in plastic input and emissions from 2015 to 2050. Three sets of values were parameterized for each scenario to estimate

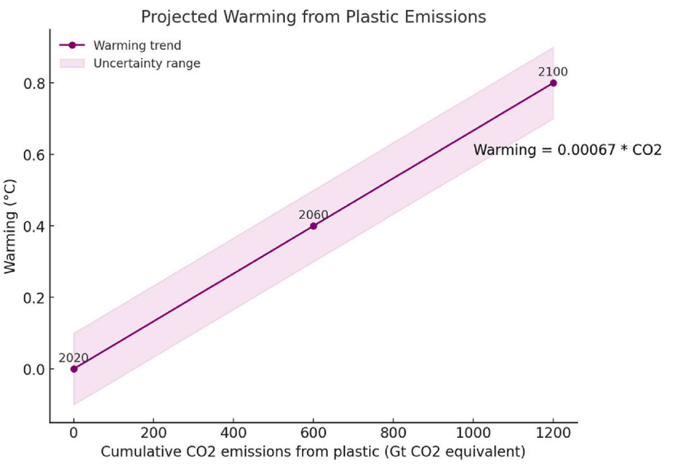

Fig. 3. Relationship between warming and cumulative CO_2 emissions from plastic.

the impact of a plastic levy on production. The four scenarios were selected to represent a broad spectrum of potential industry engagement with the voluntary plastic levy. The BAU scenario serves as a baseline with no intervention, while the partial participation scenarios (25%, 50%, 75%) were chosen to reflect varying levels of industry commitment, from minimal to strong. These scenarios provide a balanced understanding of the policy's potential impact on reducing plastic production and emissions, enabling us to assess both conservative and optimistic outcomes. This range allows for comprehensive insights into the effectiveness of the levy under different participation levels.

4. Results and discussion

This study examines the top 100 fossil–based plastic producers, responsible for over 95% of global single–use plastic waste, with ExxonMobil leading at 5.9 million metric tonnes (mmt) and Dow contributing 5.5 mmt (The Minderoo Foundation, 2021). These companies span across Asia (11), Europe (4), North America (3), the Middle East (1), and Latin America (1) (Please refer to Table 3 in appendix for the list of 100 companies and their production of in-scope polymers). Key financial backers of these companies include HSBC, Barclays, Bank of America, JP Morgan Chase, and Citigroup. A major concern addressed is why profit–driven companies would engage in a voluntary plastic levy. We argue that profit maximizing companies will participate if the perceived benefits to them from environmental improvements outweigh the cost of the levy. Moreover, public perception of environmental responsibility offers reputational advantages.

Our interventions across various scenarios show different levels of pollution reduction, particularly under the plastic levy scenarios. To manage plastic production and emissions effectively, solutions must reduce input into the environment. Under BAU scenario, plastic production is projected to increase by 2050 to 3.2 times the 2015 level, reaching 1,297 mmt/y. This trend is driven by population growth and increased per capita plastic consumption. A weak scenario (25% participation) reduces 2050 plastic production by 24%, lowering it to 988 mmt/y, while a moderate scenario (50% participation) achieves a reduction to 617 mmt/y. Only a strong scenario significantly reduces production by 71%, bringing it down to 371 mmt/y.

In terms of emissions, the plastic emission rate in 2050 is projected to rise to 3.2 times the 2015 level, reaching 5.4 Gt of CO_2e. A weak scenario reduces emissions by 20% to 4.3 Gt of CO_2e, while a moderate scenario reduces emissions to 2.97 Gt of CO_2e. A strong scenario achieves a 70% reduction, bringing emissions down to 1.62 Gt of CO_2e. Our analysis highlights that without strong action, plastic pollution will continue at unsustainable levels. Fig. 4 illustrates the reduction in plastic production and corresponding emissions under various plastic levy scenarios.

4.1. *What should the amount of the voluntary plastic levy be?*

To estimate the plastic levy, we first calculated the cost of producing a tonne of plastic, finding that the average price of polymer per tonne is approximately $1,200. Globally, annual per capita plastic consumption ranges between 16 kg and 69 kg (OECD, 2022).

We estimate that a voluntary plastic levy of US$75 to US$100 per tonne is needed to encourage the collection and recycling of fossil–based plastics. The levy is expected to have a minimal impact on polymer prices, increasing costs by 6.25% in low estimates and 8.33% in high estimates. The overall economic and social impacts are anticipated to be negligible, as the price increases are projected to have a minimal effect on the cost of living, representing a small fraction of gross national income (Fig. 5).

In a strong scenario, where the levy is set at US$100 per tonne, the total revenue generated from the top 100 polluters could reach about US $3.3 billion over the next 25 years. This represents 1–2% of the estimated US$2.2 trillion in damages caused by fossil–based plastic pollution (Forrest et al., 2019). We projected annual revenue from plastic levy of US$3.3 billion, accumulating to US$82.5 billion over 25 years, would increase recycling rates by 73%, raising recycled volumes from 116 mmt to 200.4 mmt (See Fig. 6 in Appendix). For comparison (Pottinger et al., 2023), suggest that a US$100 billion investment could lead to a 109% increase in recycling by 2050, significantly exceeding the BAU scenario.

4.2. *A fair allocation of plastic cost reduction*

The study explores the feasibility of reducing plastic production growth from 4% to 3.1% annually to meet the Paris Agreement targets, focusing on the top 100 resin producers. While theoretically effective, implementing this reduction faces two significant challenges. First, much of the pollution from plastic production is untraceable, making it difficult to directly link production to environmental damage, thus complicating regulation. Second, ensuring the sustainability of such a solution over time requires cooperation from producers across different jurisdictions. A flat cost reduction for all producers might be seen as unfair, as it doesn't account for differences in profitability, necessity of products, or financial situations, which could hinder broad adoption.

The study highlights the potential of strategic interaction theory, particularly cooperative behavior, in addressing these challenges. Shapley's (1950) value is proposed as a fair and equitable solution for cost distribution, assigning each producer a share of the levy based on fairness principles. This solution is praised for its fairness and

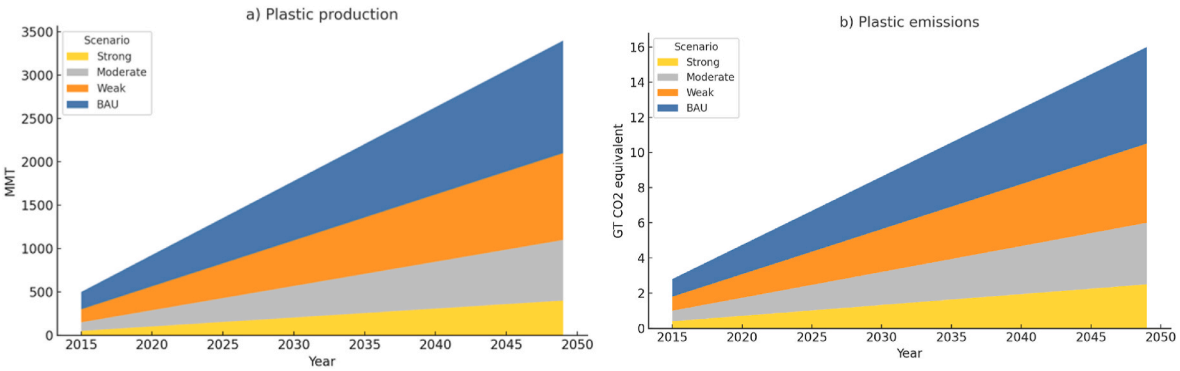

Fig. 4. Projections of global plastic production (a) and emissions (b). Annual plastic production under different plastic levy scenarios (a), projections of annual plastic production based on an initial 2015 estimate of 8300 mmt of plastic produced (Geyer et al., 2017) with status quo projections of 4% growth of plastic production to 2050 are based on an average growth between 2010 and 2015 in plastic demand and production (Zheng and Suh, 2019). Different pathways of emissions reductions over time under different voluntary plastic levy scenarios (b), 2015–2050. Calculation of emissions from plastic production from Zheng and Suh 2019 and assume CO_2e emissions are directly proportional to plastic production. This is equal to 407 mt of CO_2e produced per gigaton of plastic from the 2015 estimate.

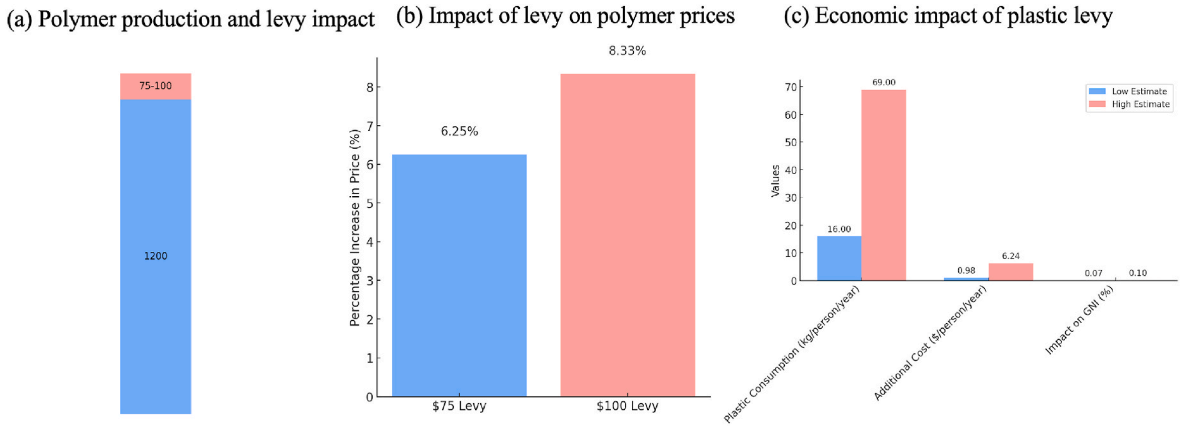

Fig. 5. Assessment of the social and economic impacts of plastic levy. a) Polymer production and levy. A levy of USD$75–100 per tonne, based on the 2015–2019 rolling average price $1,200 for all polymer types. b) Impact of levy on polymer prices. The levy is projected to increase polymer prices marginally, ranging from 6.25% in low estimates to 8.33% in high estimates. c) Economic impact of the plastic levy. The analysis reveals negligible adverse social or economic impacts. While the levy is expected to increase average polymer prices by 6–8%, its effect on the overall cost of living remains minimal since it constitutes a fraction of gross national income.

uniqueness, ensuring each participant bears a fair share of the burden.

To maintain cooperation over time, the study emphasizes the need for time–consistency, ensuring that no party has an incentive to deviate from the initial agreement. Time–consistency ensures that commitments made in the short term remain valid and beneficial in the long term. Zaccour's (2008) work on time–consistency is recommended as a useful framework for applying these principles to environmental and pollution–related cost reduction efforts, offering guidance for maintaining cooperation over the agreed time horizon.

5. Conclusion

This study explores the economic impacts of a voluntary plastic levy under various hypothetical scenarios, focusing on how such a levy could influence plastic production, CO_2 emissions, and global warming. It provides an estimate that a plastic levy could reduce global plastic production emissions by 70% by 2050, lowering CO_2e emissions from BAU levels to 1.62 Gt (95% CI: 1.43–1.81), with an average 20% reduction for every 1 °C of warming. To meet the Paris Agreement's 1.5 °C target, the annual growth rate of plastic production would need to drop from 4% to 3.1%, resulting in a 25% reduction in production by 2050. This suggests that implementing a voluntary levy could be an effective tool to curb greenhouse gas emissions from plastic production and mitigate climate change.

However, the study notes negligible potential unintended social and economic consequences, as seen in other studies on plastic interventions. For instance, when restrictions or bans were placed on plastic production, the demand for alternatives such as plastic garbage bags often increased, as evidenced in Taiwan, California, and Italy. Taiwan's plastic bag ban in 2003 was retracted in 2006 due to its ineffectiveness. Similar patterns were observed when single–use plastic consumption rose by 12% in Italy after a bag ban. Economic tools like fees, taxes, and duties have been implemented globally to reduce plastic waste, but their success varies by region. Our study models a US$75–100 per tonne levy on plastics, which is expected to cause a slight price increase—6.25% in low estimates and 8.33% in high estimates. The economic analysis indicates minimal adverse impacts on overall living costs, as the price increase represents a small fraction of gross national income (GNI) as illustrated in Fig. 5. These findings align with studies from the (OECD, 2022; Charles and Cumming, 2024), which also report negligible negative economic effects from plastic levies.

This study presents pathways for transforming plastic production systems but faces few limitations. It assumes uniform emission factors across all plastics and progress in recycling technology, ignoring the varied environmental impacts of different types, which reduces emissions estimate accuracy. The policy scenarios assume global compliance with a plastics levy, overlooking regional differences and market responses. Future research should address these limitations, particularly by disaggregating plastic types, for more targeted policy recommendations.

CRediT authorship contribution statement

Ibrahim Issifu: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Ilyass Dahmouni:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **U. Rashid Sumaila:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by the SSHRC sponsored Solving FCB Partnerships & New Frontiers in Research Fund –International sponsored Coastman project.

Appendix

Table 3
Sample of polymers producers, contribution, production and estimated plastic levies.

Rank	Polymer Producer	Total contribution to SUP waste (mmt)	Production of in–scope polymers (mmt)	*Voluntary Plastic Levy in million USD before 2050*
1	ExxonMobil	5.9	28.084	204.5
2	Sinopec	5.6	26.656	194.1
3	Dow	5.6	26.656	194.1
4	Indorama Ventures	4.6	21.896	159.5
5	Saudi Aramco	4.3	20.468	149.1
6	PetroChina	4	19.04	138.7
7	LyondellBasell	3.9	18.564	135.2
8	Reliance Industries	3.1	14.756	107.5
9	Braskem	3	14.28	104.0
10	Alpek SA de CV	2.3	10.948	79.7
11	Borealis	2.2	10.472	76.3
12	Lotte Chemical	2.1	9.996	72.8
13	INEOS	2	9.52	69.3
14	Total	1.9	9.044	65.9
15	Jiangsu Hailun Petrochemical	1.6	7.616	55.5
16	Far Eastern New Century	1.6	7.616	55.5
17	Formosa Plastics Corporation	1.6	7.616	55.5
18	China Energy Investment Group	1.5	7.14	52.0
19	PTT	1.5	7.14	52.0
20	China Resources	1.3	6.188	45.1
21	Nova Chemicals Corporation	1.2	5.712	41.6
22	Siam Cement Group	1.1	5.236	38.1
23	Phillips 66	1	4.76	34.7
24	Zhejiang Wankai	1	4.76	34.7
25	Sumitomo Chemical	1	4.76	34.7
26	Jiangyin Chengxing Industrial Group	0.9	4.284	31.2
27	Chevron Corporation	0.9	4.284	31.2
28	Hanwha Chemical	0.9	4.284	31.2
29	China Coal	0.8	3.808	27.7
30	Rongsheng Group	0.8	3.808	27.7
31	Mitsubishi Chemical Corporation	0.8	3.808	27.7
32	SIBUR	0.8	3.808	27.7
33	Abu Dhabi National Oil Company	0.8	3.808	27.7
34	GAIL India	0.7	3.332	24.3
35	LG Chem	0.7	3.332	24.3
36	Westlake Chemical Corporation	0.6	2.856	20.8
37	Mitsui Chemicals	0.6	2.856	20.8
38	Sasol	0.6	2.856	20.8
39	Zhejiang Hengyi Group	0.6	2.856	20.8
40	Eni	0.6	2.856	20.8
41	Yanchang Group	0.6	2.856	20.8
42	Repsol	0.6	2.856	20.8
43	Indian Oil Corporation	0.6	2.856	20.8
44	Nan Ya Plastics Corporation	0.5	2.38	17.3
45	SK Innovation Co	0.5	2.38	17.3
46	Oil and Natural Gas Corporation	0.5	2.38	17.3
47	Octal	0.5	2.38	17.3
48	JBF Industries	0.5	2.38	17.3
49	MOL Hungarian Oil and Gas	0.5	2.38	17.3
50	Bakhtar Petrochemical	0.5	2.38	17.3
51	Shell	0.4	1.904	13.9
52	Neo Group	0.4	1.904	13.9
53	Haldia Petrochemicals Ltd	0.4	1.904	13.9
54	China National Offshore Oil Corporation	0.4	1.904	13.9
55	Tasnee	0.4	1.904	13.9
56	Eastern Petrochemical Company	0.4	1.904	13.9
57	Qatar Petroleum	0.4	1.904	13.9
58	Shinkong	0.4	1.904	13.9
59	Sahara International Petrochemical	0.3	1.428	10.4
60	Formosa Chemicals and Fibre Corporation	0.3	1.428	10.4
61	Korea Petrochemical Industrial	0.3	1.428	10.4
62	Gatron Industries	0.3	1.428	10.4
63	Equate Petrochemical Company	0.3	1.428	10.4
64	Baofeng	0.3	1.428	10.4
65	National Petrochemical Company (Saudi Arabia)	0.3	1.428	10.4
66	PT Chandra Asri Petrochemical	0.3	1.428	10.4
67	PKN Orlen	0.3	1.428	10.4
68	Dhunseri Petrochem	0.3	1.428	10.4
69	Bazan Group	0.3	1.428	10.4

(*continued on next page*)

Table 3 (*continued*)

Rank	Polymer Producer	Total contribution to SUP waste (mmt)	Production of in–scope polymers (mmt)	*Voluntary Plastic Levy in million USD before 2050*
70	Daelim Group	0.3	1.428	10.4
71	KAP Industrial Holdings	0.3	1.428	10.4
72	Petroleos Mexicanos	0.3	1.428	10.4
73	Pucheng Clean Energy	0.3	1.428	10.4
74	Qatar Petrochemical Company	0.3	1.428	10.4
75	TK Chemical	0.3	1.428	10.4
76	Saudi Kayan	0.3	1.428	10.4
77	Oriental Energy	0.3	1.428	10.4
78	Jam Petrochemical Company	0.3	1.428	10.4
79	Nizhnekamskneftekhim	0.3	1.428	10.4
80	Prime Polymer	0.3	1.428	10.4
81	Yansab	0.3	1.428	10.4
82	Petronas	0.2	0.952	6.9
83	Amir Kabir Petrochemical Company	0.2	0.952	6.9
84	State Oil Company of Azerbaijan Republic	0.2	0.952	6.9
85	Henan Coal Chemical Industry Group	0.2	0.952	6.9
86	Fude Energy	0.2	0.952	6.9
87	USI Group	0.2	0.952	6.9
88	Ecopetrol	0.2	0.952	6.9
89	Idemitsu Kosan	0.2	0.952	6.9
90	Kazanorgsintez	0.2	0.952	6.9
91	HPCL–Mittal Energy Ltd	0.2	0.952	6.9
92	Pan Asia PET Resin	0.2	0.952	6.9
93	Koksan	0.2	0.952	6.9
94	Novapet	0.2	0.952	6.9
95	Xingxing	0.2	0.952	6.9
96	Sanyuan	0.2	0.952	6.9
97	North Huajin	0.2	0.952	6.9
98	Shahid Tondgooian Petrochemical	0.2	0.952	6.9
99	Dragon Special Resin	0.2	0.952	6.9
100	Advanced Petrochemical	0.2	0.952	6.9
	Total	**95.2**	**453.2**	**3300**

Source: Estimated by Authors based on Minderoo Foundation report 2021.

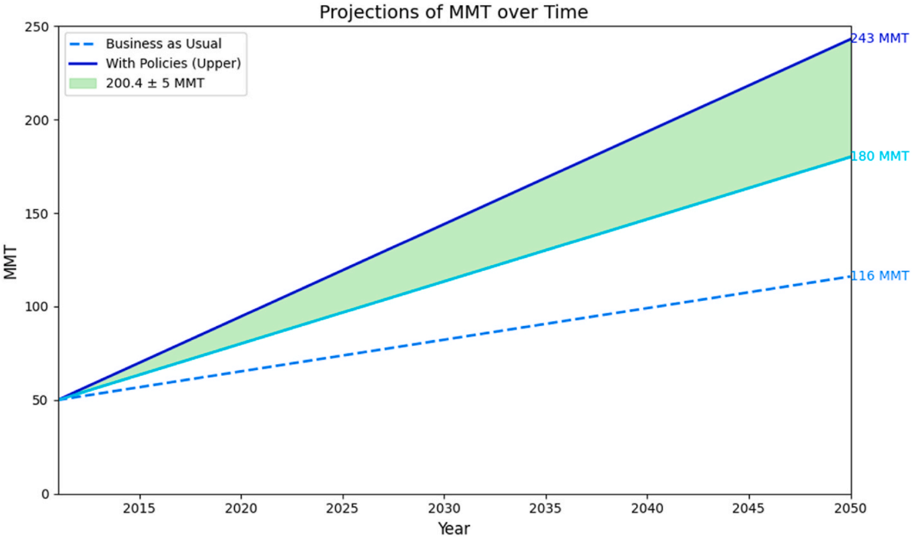

Fig. 6. Global annual rate of recycling as million metric tons. Modified from Pottinger et al. (2023). An investment of USD 100 billion (resp. USD 50 billion) will lead to a 109% (resp. 55%) increase in recycling by 2050 compared to BAU, i.e. from 116 mm to 243 mmt (resp. 180 mmt). We estimated USD 82.5 billion plastic levy could fund investment in recycling would increase recycling by 73% (200.4 vs BAU 116 mmt) over the next 25 years.

Data availability

Data will be made available on request.

References

Abbott, J.K., Sumaila, U.R., 2019. Reducing marine plastic pollution: policy insights from economics. Rev. Environ. Econ. Pol. 13, 327–336.

Andrady, A.L., Neal, M.A., 2009. Applications and societal benefits of plastics. Philos. Trans. Roy. Soc. Biol. Sci. 364, 1977–1984.

Benzennou, S., Laviolette, J.P., Chaouki, J., 2019. Kinetic study of microwave pyrolysis of paper cups and comparison with calcium oxide catalyzed reaction. AIChE J. 65 (1).

Cabernard, L., Pfister, S., Oberschelp, C., Hellweg, S., 2022. Growing environmental footprint of plastics driven by coal combustion. Nat. Sustain. 5, 139–148.

Center for International Environmental Law, 2019. Plastic and Climate: The hidden costs of a plastic planet from. https://www.ciel.org/wp-content/uploads/2019/05/Plastic-and-Climate-FINAL-2019.pdf. (Accessed 7 February 2023).

Charles, D., Cumming, P., 2024. The Polymer Premium: A Fee on Plastic Pollution. Minderoo Foundation.

Convery, F., McDonnell, S., Ferreira, S., 2007. The most popular tax in Europe? Lessons from the Irish plastic bags levy. Environ. Resour. Econ. 38, 1–11.

De Giovanni, P., Ramani, V.A., 2024. Selected survey of game theory models with government schemes to support circular economy systems. Sustainability 16, 136.

Diana, Z., Reilly, K., Karasik, R., Vegh, T., Wang, Y., Wong, Z., Dunn, L., Blasiak, R., Dunphy–Daly, M.M., Rittschof, D., Vermeer, D., Pickle, A., Virdin, J., 2022. Voluntary commitments made by the world's largest companies focus on recycling and packaging over actions to address the plastics crisis. One Earth 5, 1286–1306.

Dikgang, J., Leiman, A., Visser, M., 2012. Analysis of the plastic–bag levy in South Africa. Resour. Conserv. Recycl. 66, 59–65.

Edwards, J., Burn, S., Crossin, E., Othman, M., 2018. Life cycle costing of municipal food waste management systems: the effect of environmental externalities and transfer costs using local government case studies. Resour. Conserv. Recycl. 138, 118–129.

FAO, 2021. Assessment of Agricultural Plastics and Their Sustainability: A Call for Action. Food and Agriculture Organization of the United Nations, Rome. https://doi.org/10.4060/cb7856en.

Forrest, A., Giacovazzi, L., Dunlop, S., Reisser, J., Tickler, D., Jamieson, A., Meeuwig, J. J., 2019. Eliminating plastic pollution: how a voluntary contribution from industry will drive the circular plastics economy. Front. Mar. Sci. 26, 1–11.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use and fate of all plastics ever made. Sci. Adv. 3, 25–29.

Government of Canada, 2021. Zero plastic waste: Canada's actions from. https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/reduce-plasticwaste/canada-action.html. (Accessed 5 December 2022).

Hockenos, P., 2021. Bold single–use plastic ban kicks Europe's plastic purge into high gear. Yale Environment 360 from. https://e360.yale.edu/features/europes-drive-to-slash-plasticwaste-moves-into-high-gear. (Accessed 16 December 2022).

IEA, 2018. The future of petrochemicals from. https://www.iea.org/reports/the-future-ofpetrochemicals. (Accessed 10 December 2022).

IPCC, 2014. In: Pachauri, R.K., Meyer, L.A. (Eds.), *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, p. 151. Geneva, Switzerland.

IPCC, 2018. In: Masson–Delmotte, V., Zhai, P., Portner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Pean, C., Pidcock, R., Connors, S., Mathews, J.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), Summary for Policymakers. World Meteorological Organization, Geneva, Switzerland, p. 32.

IPCC, 2021. Summary for policymakers. In: Masson–Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. (Eds.), Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge et al.

Issifu, I., Deffor, E.W., Sumaila, U.R., 2021. How COVID–19 could change the economics of the plastic recycling sector. Recycling 6, 1–11.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347, 768–771.

Karasik, R., Vegh, T., Diana, Z., Bering, J., Caldas, J., Pickle, A., Rittschof, D., Virdin, J., 2020. 20 years of Government responses to the global plastic pollution problem: the plastics policy inventory. In: Nicholas Institute for Environmental Policy Solutions. Duke University, Durham, NC.

Lau, W.W.Y., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., Koskella, J., et al., 2020. Evaluating scenarios toward zero plastic pollution. Science 369 (6510), 1455–1461.

Lebreton, L., Andrady, A., 2019. Future scenarios of global plastic waste generation and disposal. Palgrave Commun. 5, 1–11.

MacLeod, M., Arp, H.P.H., Tekman, M.B., Jahnke, A., 2021. The global threat from plastic pollution. Science 373, 61–65.

National Academies of Sciences, Engineering, & Medicine, 2022. Reckoning with the U.S. Role in Global Ocean Plastic Waste. The National Academies Press, Washington, DC. https://doi.org/10.17226/26132 from. (Accessed 1 January 2023).

NDRC & MEE (National Development and Reform Commission and the Ministry of Ecology and Environment), 2020. Opinions on further strengthening the treatment of plastic pollution from. https://www.china-ipif.com/en-gb/media/2020-07-07_01/ArtcleA.html. (Accessed 15 December 2022).

OECD, 2019. Plastic use in 2019 from. https://stats.oecd.org/viewhtml.aspx?datasetcode=PLASTIC_USE_6&lang=en. (Accessed 20 January 2023).

OECD, 2022. Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options. OECD Publishing, Paris. https://doi.org/10.1787/de747aef-en.

Plastics Europe, 2022. Plastics – the Facts 2022 from. https://plasticseurope.org/wp-content/uploads/2022/12/PE-PLASTICS-THE-FACTS_FINAL_DIGITAL.pdf. (Accessed 26 January 2023).

Pottinger, A.S., et al., 2023. Combining game design and data visualization to inform plastics policy: fostering collaboration between science. In: Decision–Makers, and Artificial Intelligence. University of California, Santa Barbara from at. https://global-plastics-tool.org/#detailed. (Accessed 26 November 2023).

Shapley, L., 1950. A value for n–person games. In: Kuhn, H., Tucker, A. (Eds.), Contributions to the Theory of Games II. Princeton University Press, Princeton, pp. 307–317.

Statista, 2022a. Global plastic production 1950–2021 from. https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/. (Accessed 26 January 2023).

Statista, 2022b. Market size value of plastics worldwide from 2021 to 2030. from. https://www.statista.com/statistics/1060583/global-market-value-of-plastic/. (Accessed 26 January 2023).

Stegmann, P., Dailoglou, V., Londo, M., Vuuren, D.P., Junginger, M., 2022. Plastic futures and their CO_2 emissions. Nature 612, 272–276.

Sumaila, U.R., 1997. Cooperative and non-cooperative exploitation of the Arcto-Norwegian cod stock. Environ. Resour. Econ. 10 (2), 147–165.

Uekert, T., Singh, A., DesVeaux, J.S., Ghosh, T., Bhatt, A., Yadav, G., Afzal, S., Walzberg, J., Knauer, K.M., Nicholson, S.R., Beckham, G.T., Carpenter, A.C., 2023. Technical, economic, and environmental comparison of closed loop recycling technologies for common plastics. ACS Sustainable Chem. Eng. 11, 965–978.

U.S. EPA, 2021. What types of plastic scrap and waste are controlled under the Basel Convention? from. https://www.epa.gov/hwgenerators/international-agreements-transboundary-shipments-hazardous-waste#basel. (Accessed 18 January 2023).

van der Oever, M., Molenveld, K., van der Zee, M., Bos, H., 2017. Bio–based and Biodegradable Plastics: Facts and Figures. Wageningen Food & Biobased Research. Wageningen University & Research. https://doi.org/10.18174/408350.

Villarrubia–Gómez, P., Cornell, S.E., Fabres, J., 2018. Marine plastic pollution as a planetary boundary threat: the drifting piece in the sustainability puzzle. Mar. Pol. 96, 213–220.

World Economic Forum, 2016. The new plastics economy–rethinking the future of plastics from. https://ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-futureof-plastics. (Accessed 15 December 2022).

Zaccour, G., 2008. Time consistency in cooperative differential games: a tutorial. INFOR. Inf. Syst. Oper. Res. 46 (1), 81–92.

Zheng, J., Suh, S., 2019. Strategies to reduce the global carbon footprint of plastics. Nat. Clim. Change 9, 374–378.