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Research article

Using systems mapping to understand the constraints and enablers of solutions to plastic pollution

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ABSTRACT

Plastic pollution is now considered globally ubiquitous, irreversible, and a planetary boundary threat. Solutions are urgently needed but their development and application are hampered by the complexity and scale of the issue. System dynamics is a technique used to understand complex behaviours of systems through model building and is useful for conceptualising the relationships between various interacting, dynamic factors, and identifying potential intervention points within the system where specific policies or innovations might have the greatest impact or meet with the greatest resistance. Here, twenty-five participants (all scientific researchers of various career stages, disciplines and nationalities working on plastic pollution) completed a series of exercises through an interactive, iterative group model building exercise during a one-day workshop. The process culminated in the generation of a causal loop diagram, based on participants' perspectives, illustrating the dynamic factors relating to the constraints and enablers of solutions to plastic pollution. A total of 18 factors and seven feedback loops were identified. Key factors influencing the system were *Effective legislation*, *Funding, Public education and awareness, Behaviour change*, *Innovation*, and *Effective waste management*. Our findings highlight that there is no single driver, or 'silver bullet', for resolving this complex issue and that a holistic approach should be adopted to create effective and systemic change.

1. Introduction

Global plastic production has grown exponentially since the 1950s and is currently estimated at 430 Mt annually (Organisation for Economic Co-operation and Development [OECD] 2022). Production is predicted to triple by 2060 if no action is taken (Organization for Economic Cooperation and Development [OECD], 2022). Due to this exponential increase in production and inadequate waste management, an estimated 9.2 Mt of plastic is leaked into the environment and 4.8–12.7 Mt enter the global ocean each year (Jambeck et al., 1979; Ryberg et al., 2019). As a result, there is increasing evidence of numerous mechanisms by which it is causing detrimental ecological,

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economic, and societal impacts (Beaumont et al., 2019). Plastic pollution is now considered globally ubiquitous, irreversible, and a potential planetary boundary threat (Villarrubia-Gómez et al., 2018). As such, solutions are urgently needed to abate the leakage of plastic into the environment, mitigate the harm caused by existing input and meet global environmental targets, such as the Sustainable Development Goals (e.g., SDG14 'Life below water') (Bachmann et al., 2023). The development and application of solutions is hampered, however, by the complexity and scale of the issue. For example, plastic production continues to increase due to a growing global population coupled with increasing per capita demand for plastic items, and a wide variety of stakeholders (e.g., scientists, industry, environmental groups and policymakers) approaching the issue from differing standpoints, inhibiting cohesive action (Chen et al., 2021; Lampitt et al., 2023). Knowledge of plastic waste flow pathways and the numerous positive and negative feedbacks to ecological and socio-economic systems is seriously lacking, and local and regional nuances complexify the problem (McMullen et al., 2023; Phelan et al., 2020). A variety of solutions to plastic pollution have been proposed, such as recycling, bioplastic alternatives, reusable products, bans and incentives, however many are ineffective or create unintended consequences (Homonoff et al., 2022; Muposhi et al., 2022). For example, in instances where disposable plastic bags have been banned or levied, knock-on socio-economic effects, such as job losses, profiteering, smuggling, shoplifting and food poisoning, have been observed (Muposhi et al., 2022). Additionally, regional context and social justice are important factors to consider since the negative effects of plastic across its life cycle, from production to pollution, are not distributed evenly; they disproportionately affect poor, disempowered and marginalized communities, who are not directly responsible for the current plastic crisis (Landrigan et al., 2023). As such, a multidisciplinary approach is required to identify and account for the many, often intricately linked, factors contributing to the plastic pollution cycle. Policies and strategies should therefore consider a holistic view of the problem.

System dynamics is a scientific field that attempts to understand complex behaviours of systems through model building and is useful for conceptualising the relationships between various interacting, hence dynamic, factors (Anastasiou et al., 2023; Haji Gholam Saryazdi et al., 2021). For plastic pollution, system dynamics could be effective at facilitating a better understanding of the relationships among the key factors that influence the development and success of potential solutions, where decisions are made by multiple value chain actors (e.g., producers, users and disposers of plastic products) (Phelan et al., 2020). It may also expose the potential risks posed by interventions and policies that could result in adverse unintended consequences (Mui et al., 2019).

Group model building (GMB) is a participatory approach used within system dynamics that engages experts and key stakeholders to reveal the feedback structure of a system and its dynamicity (Rouwette and Vennix, 2020; Williams et al., 2020). Previous studies have shown that GMB facilitates diverse discussions of complex social, economic, and environmental issues, while generating new knowledge and stakeholder awareness of a given issue (Anastasiou et al., 2023; Valencia Cotera et al., 2022). A GMB process results in the identification of feedback, or causal, loops that are subsequently visualised as Causal Loop Diagrams (CLDs), that map the factors and visualise their dynamic interactions and relationships (Anastasiou et al., 2023; Mui et al., 2019). There are generally two types of feedback loops in the structure of any complex system; reinforcing feedback loops amplify or escalate the system's behaviour away from its current state. In contrast, balancing feedback loops converge the system towards equilibrium. CLDs can be translated to stock and flow diagrams for better illustration of the nature of factors and for mathematical simulation of the system. They can also be used to refine conceptual models of a given issue allowing users to explore hypotheses about a system's structure, as well as identify potential intervention points that may lead to adverse or desirable outcomes (Mui et al., 2019).

The purpose of this study was to use Group Model Building to understand the factors that act as constraints and enablers to finding solutions, as perceived by scientific researchers working on the issue of plastic pollution, and produce a systems map to identify potential intervention points within the system where specific policies or innovations might have the greatest impact or meet the greatest resistance. System maps were then used to produce a Causal Loop Diagram, following the process described above, through which it was possible to identify several reinforcing and balancing feedback loops regarding solutions to plastic pollution. The following section outlines the methods deployed in the study, providing detail relating to the structure of the GMB workshop. Results are presented, where specific feedback loops are identified and placed in context. Finally, the conclusion draws out the lessons derived from the study and emphasises the need for whole system interventions to tackle the prevailing and increasingly complex problem of plastic pollution.

2. Material and methods

2.1. Workshop

A one-day, in-person workshop was held in March 2023 whereby participants discussed the question, '*What are the constraints and enablers to finding solutions for plastic pollution?*'. This question was posed because it relates to a complex issue that can only be addressed by considering the factors and interactions that are influenced by a variety of actors and actions, making it well suited to the Group Model Building method. The workshop participants (n = 25) were researchers with expertise in plastic pollution, based at or affiliated to the University of Exeter and Plymouth Marine Laboratory (United Kingdom). An initial core group of potential participants was identified based on current or past collaborations and experience in the field. They were invited to the workshop via email and were requested to share the invite with relevant colleagues, utilising a snowball-like method to find other potential participants that were otherwise unknown to the organisers (Heckathorn, 2011). The resulting group of workshop attendees consisted of individuals from a range of disciplines (including ecology and conservation, environmental economics, ecotoxicology, engineering, geography, social science, and waste management), levels of experience (research assistant/technician, postgraduate student, postdoctoral researcher, lecturer, senior lecturer, assistant professor, and professor) and nationalities (Brazil, China, Colombia, Ecuador, France, Iran and the United Kingdom).

The participants were allocated to one of five groups for round-table discussion. There were five people per group, and each group consisted of at least one senior academic member. Efforts were made to ensure a mixture of different disciplines and expertise in each group, but due to the uneven representation of some disciplines it was not possible to represent them all throughout the five groups.

The workshop structure was as follows.

i) Background context: A short presentation on the theory of systems thinking and GMB was provided so the participants all understood the concept. The question ('*What are the constraints and enablers to finding solutions for plastic pollution'*) was asked and expanded on for clarity to initiate conversation (I.e., What resources are needed? What are the barriers? What tools are already available? How can they be maximised?)
ii) Round-table discussion: Within their groups, the participants were asked to introduce their area of expertise, and then to discuss and list the factors that they consider important to answer the question posed. As a group, they were then asked to rank the factors to identify, and reach a consensus on, the most important (e.g., top 12–15 factors).
iii) Connection circles: After selecting the most important factors, groups were asked to discuss the relationships that connect them.

These linkages were then plotted (drawn by hand on flipchart paper) using ‘connection circles’, whereby arrows between factors illustrate how they influence one another. A polarity indicator (±) beside the arrows indicates the direction of the association. I.e., a positive polarity (+) indicates that two factors change in the same direction when they are linked (e.g., an increase in one factor results in the increase of the other). A negative polarity (−) indicates the two factors change in the opposite direction when they are linked (e.g., an increase in one factor results in a decrease of the other) (Mui et al., 2019).

iv) Causal Loop Diagrams (CLDs): Once the connection circles were formed, participants were able to identify feedback loops which enable the visual representation of key factors, processes and leverage points that influence the system.

Throughout the workshop, the facilitators (EKM and SEN) joined each group to ensure the participants had understood the instructions of the activity and that all participants were given equal opportunity to contribute to the discussion. Further detail outlining the full method pipeline is displayed in Fig. S1 (Supplementary Material).

2.2. Post-workshop processing

Following the workshop, the causal loop diagrams developed by each group of participants were digitalised using Vensim PLE (version 6.4E). These were then emailed to the workshop participants to be verified for accuracy and consistency with participants’ ideas and narratives. Once agreed, the five diagrams were combined into one ‘summary map’ (Fig. 1), consisting of themes from the entire group of workshop participants.

3. Results and discussion

The summary map (Fig. 1) is a culmination of the causal loop diagrams generated from each of the five workshop groups. It demonstrates the factors and sub-systems that the participants felt influence the development of solutions to the plastic pollution problem and shows how they are interlinked. These are discussed in the sections below. It should be noted that, although not displayed in the summary map, workshop participants felt that scientific research knowledge generation influences most, if not all, the loops within the system, either directly or indirectly.

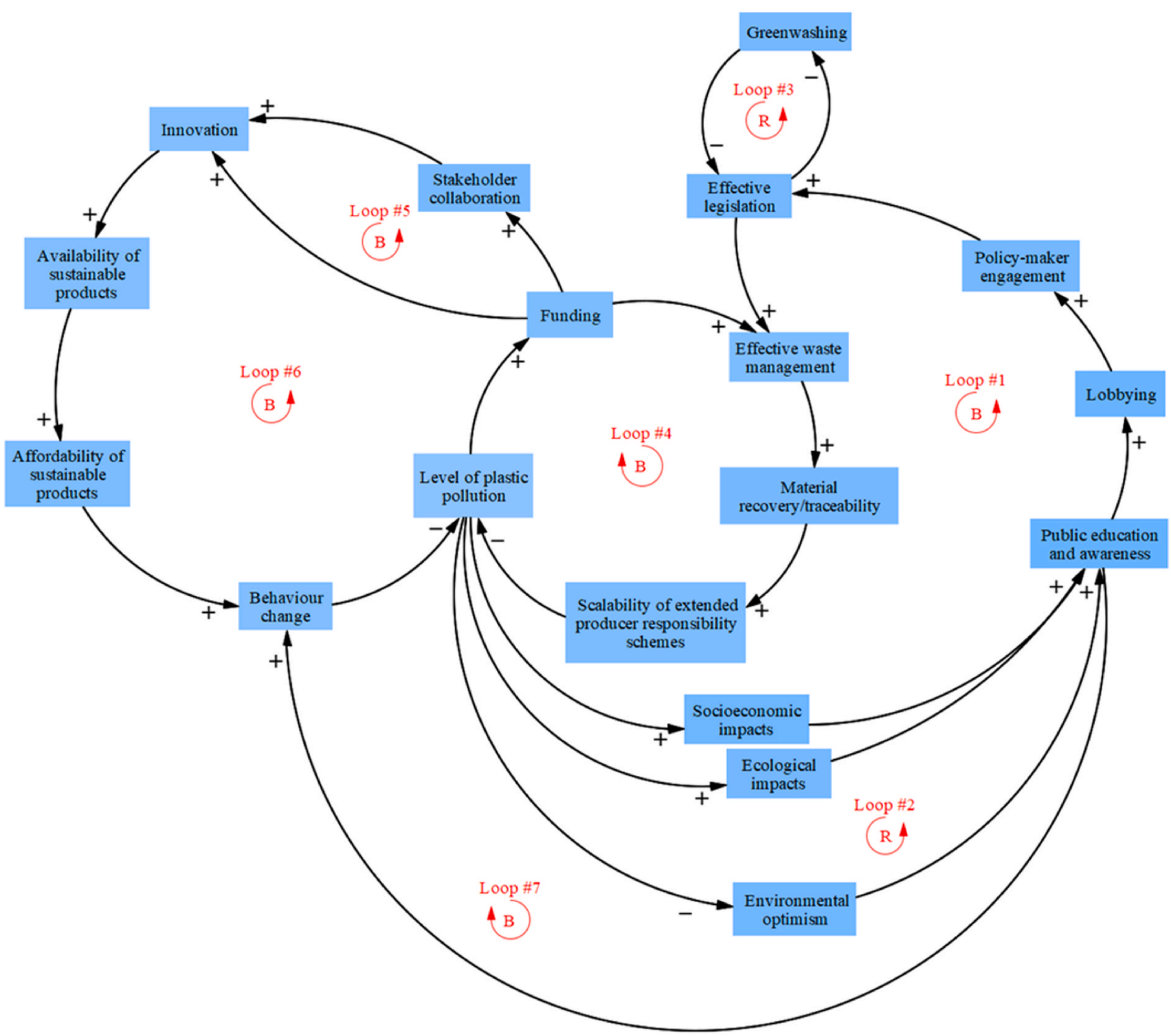

Fig. 1. Causal loop diagram displaying an overview of relationships relating to the barriers and enablers to finding solutions for plastic pollution. Whether a loop is reinforcing (R) or balancing (B) is indicated by an R or B.

3.1. Loops 1 and 2

Central to the overall system is the *Level of plastic pollution* factor. It has the highest number of direct interactions ($n = 6$), four of which demonstrate its effect on other factors (Fig. 1). The largest causal loop within the system is Loop 1 with 10 factors (Fig. 2). According to the workshop participants, *Socio-economic impacts* and *Ecological impacts* are influenced in the same direction as the level of plastic pollution, as shown by the positive polarity indicator (+). This suggests that when the level of plastic pollution increases, so might the socio-economic and environmental impacts. This view is supported by several scientific publications that acknowledge the likelihood of social, economic and environmental impacts increases as the plastic pollution crisis becomes more widespread and severe (Diggle and Walker, 2022; Kumar et al., 2021). For example, increased plastic pollution in coastal zones will likely impact key ecosystem services, such as fisheries, through contamination of seafood and damage to fishing equipment (Botterell et al., 2023; Do and Armstrong, 2023).

The *Environmental optimism* factor is influenced in the opposite direction as the *Level of plastic pollution* (Loop 2). That is, when a reduction in plastic pollution is reported (perhaps by a national government or trade body), the level of optimism increases and *vice versa*. Some believe that optimism is the key to motivating public engagement and instilling action, whereas others feel the opposite to be true in that hope and optimism may undermine the severity of the perceived threat (Dean and Wilson, 2023; Nelms et al., 2022). On the other hand, when the public experience or observe the impacts of plastic pollution, the levels of societal and environmental risk perception are likely to be strengthened (Syberg et al., 2018). The workshop participants therefore felt that *Socio-economic impacts* and *Environmental impacts,* combined with *Environmental optimism*, positively influence *Public education and awareness* which in turn can lead to activism that positively influences *Lobbying* and *Policy-maker engagement.* They believed that, as more people experience, become aware of, or feel empowered to tackle plastic pollution, new behavioural norms exert pressure on industry and governments to act, resulting in greater policy-maker engagement (Dauvergne, 2018). In turn, greater levels of *Policy-maker engagement* lead to more *Effective legislation* aimed at tackling plastic pollution. An example of this is the ban on the manufacture of products containing microbeads (in cosmetics, for example) which has occurred in many countries worldwide, mostly in the global north. In the early 2000s, evidence was growing that unnecessary microplastics were entering the waterways through domestic drains from 'rinse-off products', causing concern from scientists and activists. The anti-microbead norm strengthened and became widespread. By 2018, campaigners had successfully lobbied governments and manufacturers to ban the products in the United States, Canada, New Zealand, and several European Countries including the United Kingdom (Dauvergne, 2018). Conversely, although some research findings have directly influenced policy, the workshop participants discussed the need for greater research to fully understand the health implications of plastics. To date, much of the work carried out has sought to confirm its presence rather than identify any potential risks to

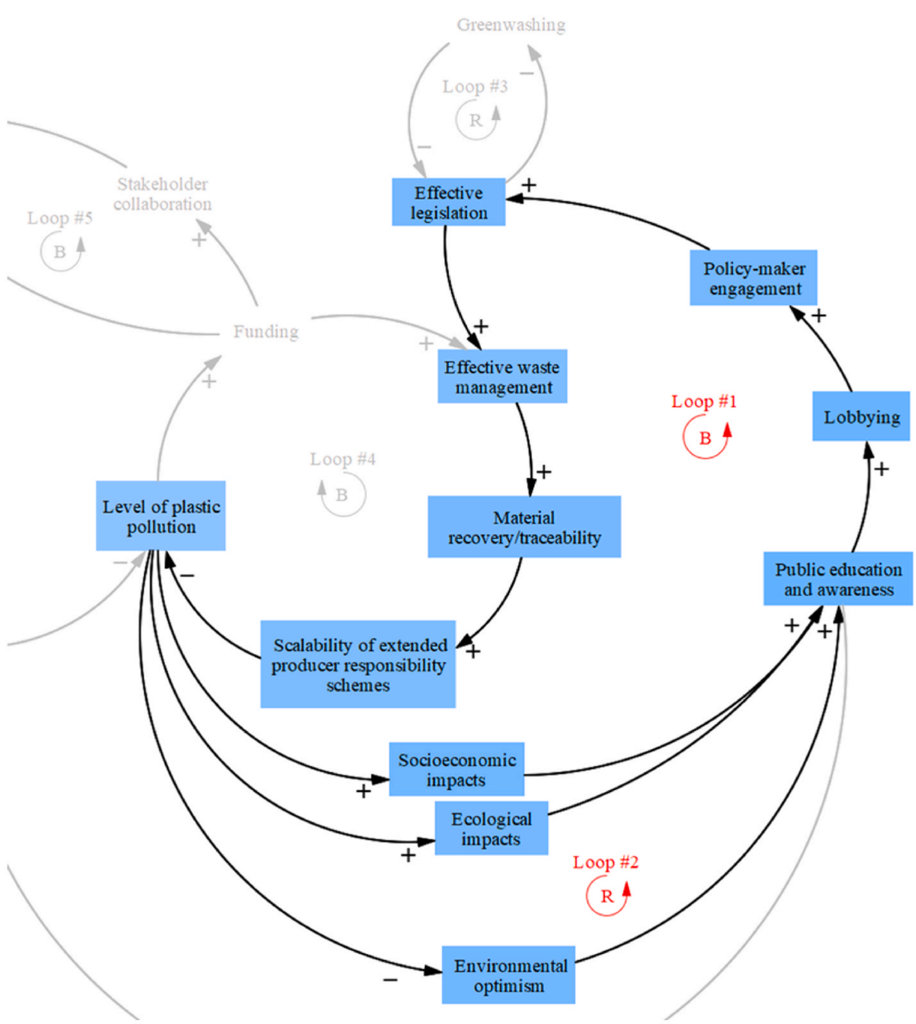

Fig. 2. Loops 1 and 2.

health. This may mean, therefore, that *Effective legislation* and *Policy-maker engagement* are limited until the implications of the issue are fully understood.

It was thought that *Effective legislation* positively influences *Waste management infrastructure* and subsequently *Material recovery/traceability* and *Scalability of producer responsibility schemes*, which ultimately negatively affect the *Level of plastic pollution.* A global effort to improve waste management infrastructure and enforce waste treatment techniques would dramatically reduce the leakage of plastic into the environment (Rajmohan et al., 2019). Higher recovery/traceability of materials will help promote a more circular life cycle for plastic instead of the current linear system. The set-up and scalability of extended producer responsibility schemes, such as deposit return schemes of plastic bottles, in which producers are responsible for the life-cycle management of their products, will itself improve the effectiveness of waste management structures and further promote a more circular economy (Di Foggia and Beccarello, 2021). However, the transition to a circular economy must be applied across the whole plastic value chain (design, production and use), not just waste management, if we are to reduce the levels of plastic pollution (Johansen et al., 2022).

3.2. Loop 3

The workshop participants believed that *Effective legislation* has a negative influence on the likelihood of *Greenwashing* (whereby manufacturers make unsubstantiated positive claims about the environmental performance of their products (Dangelico and Vocalelli, 2017; Napper and Thompson, 2019) (Fig. 3), possibly because clearer and stronger laws relating to the design and production of plastic alternatives or 'eco-friendly' options would mean they are better regulated in terms of delivering on the environmental credentials they use to market their products. The marketing of biodegradable single-use products is particularly affected by greenwashing due to the lack of regulation on what it means for a product to fully biodegrade in the environment (Moreno et al., 2023; Zhu and Wang, 2020). Conversely, the workshop participants considered that *Greenwashing* (and to some extent corruption) by organisations and governments may have a negative influence on *Effective Legislation* on a global scale. The use of misleading statements can generate confusion amongst the general public and policy-makers, negatively affecting how they engage with the movement toward a circular economy. This can create a sense of complacency which may ultimately hinder the implementation of legislation to reduce plastic pollution. Additionally, greenwashing can result in a false perception of progress, with policymakers believing that existing regulations are sufficient and being enforced. In fact, current technical standards, legislations, and labelling have the potential to mislead consumers and can encourage skewed purchase decisions and inappropriate disposal, which in turn can positively influence the level of plastic pollution (Nazareth et al., 2022).

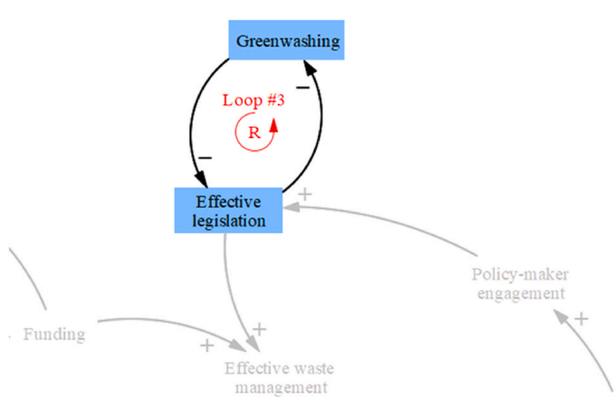

Fig. 3. Loop 3.

3.3. Loop 4

According to the workshop participants, the *Level of plastic pollution* is influenced in the same direction as Funding (Fig. 4). That is, as the amount of plastic pollution increases, so too does the amount of funding available to help tackle it, whether it be from governments or private funders. However, we were not able to find any evidence to demonstrate that the level of funding aimed at developing solutions to plastic pollution is linked to the real-world severity of the problem. In fact, between January 2015 and September 2019, the world's twenty largest banks financed the plastics supply industry by more than USD 1.4 trillion, indicating that there is still significant financial support for the sector (Banking Rolling Plastics, 2020). Additionally, many countries with the highest proportion of mismanaged waste are often developing or transitioning countries, which lack the funding for initiatives to reduce their mismanaged waste (Bundhoo, 2018). However, globally rising levels of plastic pollution have prompted the resolution of the UN Environment Assembly (UNEA) to draft a legally binding global plastics treaty by 2024, which will include financial mechanisms to tackle plastic pollution, including domestic and international funding and extended producer responsibility (UNEP, 2023).

It was felt that greater levels of *Funding* subsequently positively influence *Waste management infrastructure* which, as seen in Loop 1, positively influences *Material recovery/traceability*, *Scalability of producer responsibility schemes* and negatively influences the *Level of Plastic Pollution.*

3.4. Loop 5

It was believed that *Funding* positively influences *Innovation*, both directly and through increased *Stakeholder collaboration* (Fig. 5). Financial support through competitive grants and investment is essential for the development of initiatives and technologies aimed at reducing plastic consumption and leakage into the environment. The complexity of the issue also means that funding to facilitate knowledge-sharing across sectors is key. For example, financial incentives that encourage collaboration between product designers and those working in product recovery and waste management could help to ensure end-of-life considerations are built into the design of consumer items, thus creating a more circular model. *Innovation* relating to technologies for removing legacy plastics from the environment was not discussed during the workshop so is not included in the CLD. It is worth noting, however, that although such technologies are designed to reduce plastic presence,

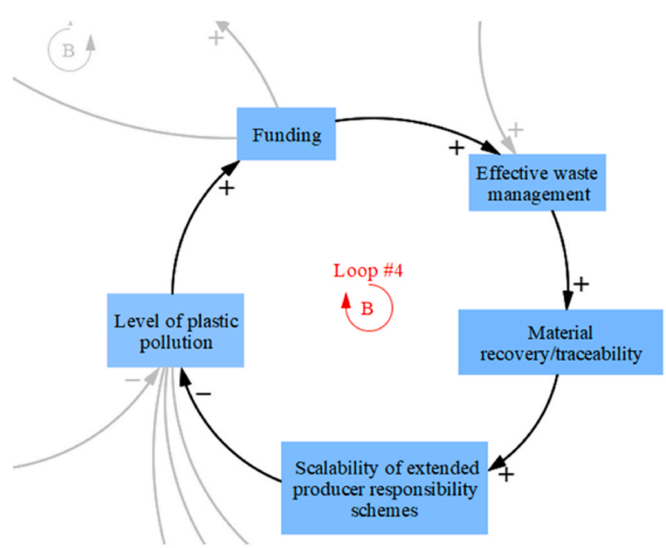

Fig. 4. Loop 4.

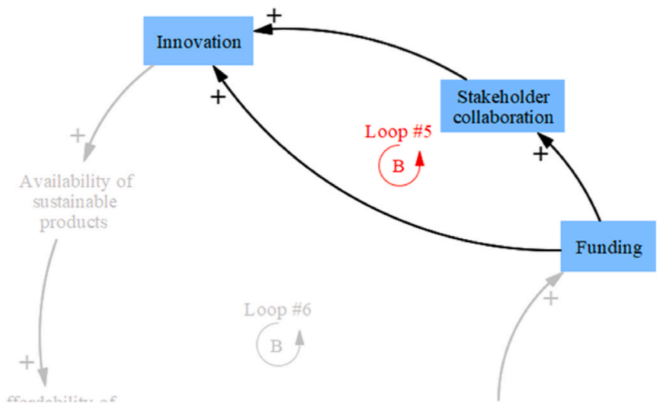

Fig. 5. Loop 5.

their influence on the overall *Level of plastic pollution* is likely to be negligible compared to inputs. Assessing the costs (financial or otherwise) of deploying clean-up technologies against their real-world benefits should be considered a priority to avoid these 'easy win' solutions distracting from other more challenging, but potentially more effective, measures.

3.5. Loop 6

Innovation relating to the development of plastic-free alternatives, or scenarios where the materials from end-of-life plastic products are valued rather than becoming waste, positively influences the *Availability of sustainable products* which has a positive knock-on effect on the *Affordability of sustainable products* (Borrelle et al., 2020) (Fig. 6). Consumer green behaviour and purchase of sustainable alternatives have been strongly linked to price (Mark et al., 2023; Sheikh et al., 2014). This in turn has a positive effect on *Behaviour change* because consumers (including individuals and businesses) are more likely to opt for environmentally-friendly options when fewer perceived barriers exist, for example difficulty accessing plastic-free alternatives and/or the lack of resources, such as money or time (Heidbreder et al., 2020). It was felt that this behavioural change away from using non-sustainable plastic products (e.g., those manufactured from virgin plastic or not easily reused or recycled) would lead to a reduction in the amount of per capita plastic produced and consequently the *Level of plastic pollution*.

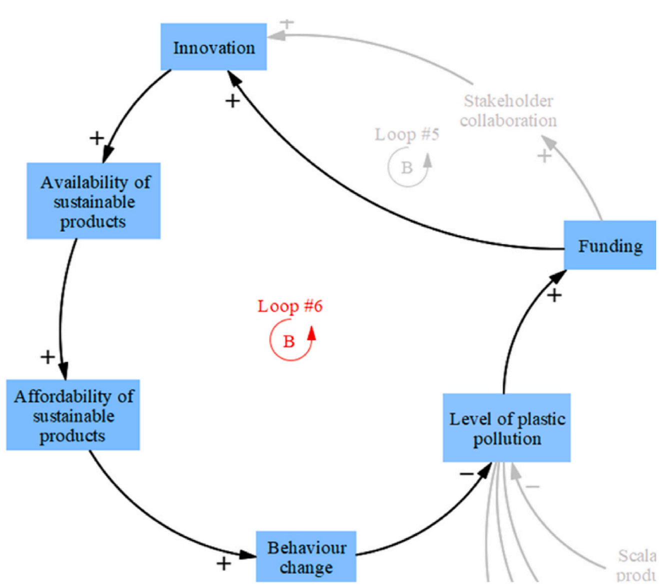

Fig. 6. Loop 6.

3.6. Loop 7

Lastly, the participants felt that the *Public education and awareness* arising from the *Socio-economic* and *Ecological impacts* caused by plastic pollution may be effective at generating *Behaviour change* which could influence the *Level of plastic pollution* (Fig. 7). Cordier et al. (2021) used socio-economic forecasting models to simulate the ecological impact of non-technological solutions to plastic waste and found that increasing the number of years spent at school (and hence environmental awareness) would lead to a 44% reduction in mismanaged plastic waste. Additionally, social networks (e.g. social media platforms), local governance and awareness-raising actions can be effective at changing the public's behaviour and reducing pollution (Rapada et al., 2021; Willis et al., 2022). However, as seen in Loop 6, *Public education and awareness* is just one factor that is needed to facilitate *Behaviour change*. Other drivers, such as such as food, energy, transport, housing and leisure, can put pressure on waste generation, consumerism, among others, which then can increase plastics and chemical contamination (GESAMP, 2015), which need to be further understood and were not mentioned during the workshop.

4. Conclusion

Coordinated efforts are needed to transform the global plastics system to reduce production, consumption, and ultimately, pollution (Borrelle et al., 2020). However, failure to consider the issue holistically will lead to piecemeal approaches and interventions that will not lead to systemic change. Using the Group Model Building approach, we mapped the system and identified a number of key drivers that likely exert significant influence on the development and efficacy of solutions aimed at tacking the issue of plastic pollution. Alongside the *Level of plastic pollution* itself, *Effective legislation* was a key driver of Loops 1 and 3, and *Funding* was a key driver of Loops 4 and 5/6. Other core factors were *Behaviour change*, *Public education and awareness*, *Innovation*, and *Effective waste management*, highlighting that there is no single driver, or 'silver bullet', for resolving this complex issue. Future work should seek to develop a system dynamics model whereby existing policies are evaluated. Additionally, our study is the result of viewpoints from one group of stakeholders (research scientists), therefore efforts should be made to consult a range of actors in order to include a diversity of perspectives (Lampitt et al., 2023).

CRediT authorship contribution statement

E.K. Morasae: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Z.L.R. Botterell:** Writing – review & editing, Writing – original draft, Project administration, Conceptualization. **S. H. V Andrews:** Writing – review & editing, Writing – original draft. **N. Beaumont:** Writing – review & editing, Writing – original draft. **P. Boisseaux:** Writing – review & editing, Writing – original draft. **H. Chadwick:** Writing – review & editing, Writing – original draft. **R. Cherrington:** Writing – review & editing, Writing – original draft. **M. Cole:** Writing – review & editing, Writing – original draft. **R.L. Coppock:** Writing – review & editing, Writing – original draft. **K. Deakin:** Writing – review & editing, Writing – original draft. **E. M Duncan:** Writing – review & editing, Writing – original draft. **D. Flor:** Writing – review & editing, Writing – original draft. **T.S. Galloway:** Writing – review & editing, Writing – original draft. **S.L. Garrard:** Writing – review & editing, Writing – original draft. **B.J. Godley:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **D. Harley-Nyang:** Writing – review & editing, Writing – original draft. **C. Lewis:** Writing – review & editing, Writing – original draft. **P.K. Lindeque:** Writing – review & editing, Writing – original draft. **P. McCutchion:** Writing – review & editing, Writing – original draft. **R. Nolan:** Writing – review & editing,

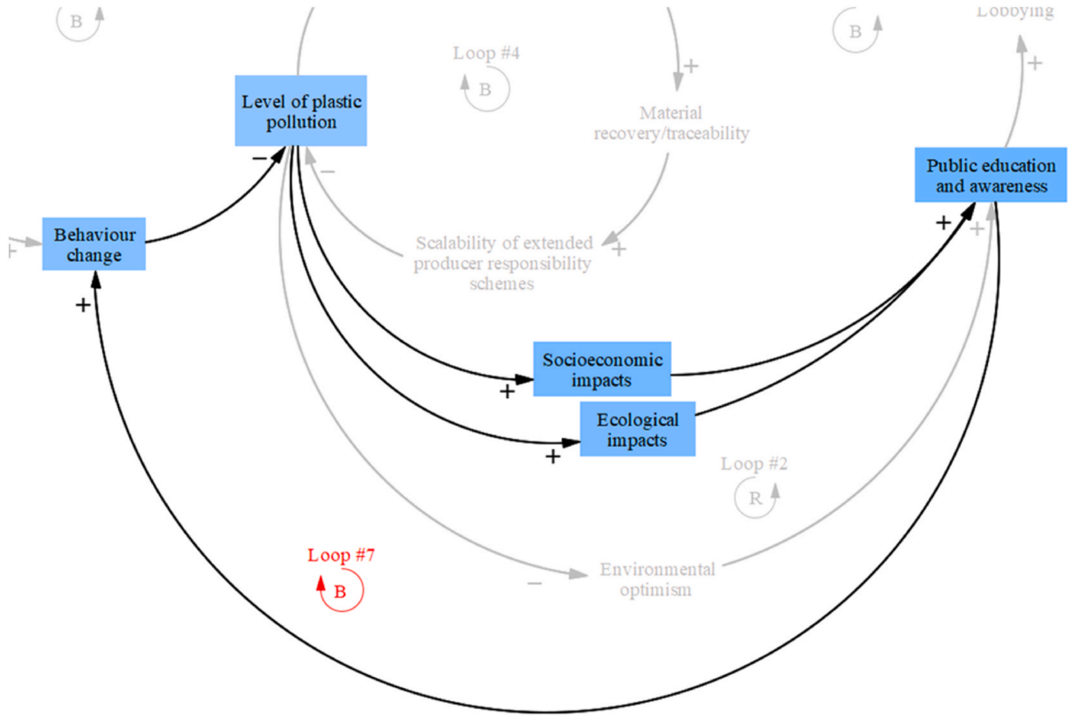

Fig. 7. Loop 7.

Writing – original draft. **A. Osorio Baquero:** Writing – review & editing, Writing – original draft. **L.M. Pinheiro:** Writing – review & editing, Writing – original draft. **G. Savage:** Writing – review & editing, Writing – original draft. **L. Storer:** Writing – review & editing, Writing – original draft. **E. Thrift:** Writing – review & editing, Writing – original draft. **D. R. Wilson:** Writing – review & editing, Writing – original draft. **C. Woodhouse:** Writing – review & editing, Writing – original draft. **M. Xavier:** Writing – review & editing, Writing – original draft. **X. Yan:** Writing – review & editing, Writing – original draft. **S.E. Nelms:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122994.

Data availability

No data was used for the research described in the article.

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