Environment International 160 (2022) 107055

Contents lists available at ScienceDirect

Environment International

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

Improved science-based transformation pathways for the development of safe and sustainable plastics

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ARTICLE INFO

Handling Editor: Adrian Covaci

Keywords:
Plastic
Impact assessment
Safe & sustainable
Life cycle
Circular economy
Transition
Co-creation

ABSTRACT

Projected plastic production volumes are rising, as is societal and political attention to plastic pollution and possible health impacts. In line with ambitions for climate mitigation and the circular economy, various national and international policies and action plans address the reduction of impacts of plastics. Quantitative scenario analyses show that even if current ambitious targets to reduce plastics are achieved, plastics will remain a source of millions of tons of environmental pollution annually. To achieve a sustainable transformation of the global plastics economy, 'extraordinary effort' and 'coordinated global action' beyond current ambitions are needed. While mapping knowledge gaps for the effects of micro and nano plastics (MNP) is crucial, mapping alone is not enough to achieve the needed transition.

In this communication, we propose a scope for the exploration of societal transformation pathways to safe and sustainable plastics. To see which efforts are needed globally we need to advance in the following three areas: (i) embedding risk assessment methodologies in wider cost-benefit and life cycle analyses; (ii) using safe-and-sustainable design strategies that include alternative solutions and look at multiple life cycles, and (iii) reflecting on the societal transformation pathways with stakeholders by using co-created quantitative models. We believe that these practices are crucial in the coming decade to realise the extraordinary effort of defining safe and sustainable plastics.

1. Introduction

By now, it is common knowledge that plastics are ubiquitous and persistent in our environment. We find plastics in our drinking water and food, even in the most isolated corners of our planet (Lim, 2021), highlighting the urgency for action on reducing plastic pollution (Lim, 2021; Vethaak and Legler, 2021; Plastic Soup Foundation, 2021). Due to the diversity in plastic fragments, we do not sufficiently understand what the actual risks for human and environmental health are (Lim, 2021; Vethaak and Legler, 2021; World Health Organisation, 2021). On top of that, there is no satisfactory solution to reduce the environmental footprint that results from our plastic consumption (Borrelle, 2020; Lau, 2020; Nature Editorial, 2021). There is a need to significantly transform the plastic economy but with large uncertainties still present, actors are pointing at each other to take the first step (Nature Editorial, 2021).

Two ideas are currently the main drivers for change: the first is the ethical principle to stop the pollution of our planet with persistent contaminants (irrespective of whether these pose health risks). The

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https://doi.org/10.1016/j.envint.2021.107055
Received 6 September 2021; Received in revised form 30 November 2021; Accepted 18 December 2021

second is the precautionary principle that we should stop the increase of (micro)plastic concentrations in the environment, which is irreversible and may eventually lead to long-term damage on human health and ecosystems (REACH Regulation, 2019; European Commission). In some cases adverse effects have been identified, however we cannot currently prioritise which plastics are most harmful, based on risks for human and environmental health (Vethaak and Legler, 2021). Logical first steps are to reduce single-use plastic applications as these are dominantly found as litter in the environment (European Commission, 2019; Parker, 2018). This has resulted in policies worldwide banning or minimizing the production and use of several plastics (European Commission, 2019; McDowall et al., 2017; European Union, 2021; Xanthos and Walker, 2017). However, if the plastic demand is based on a societal need, this need still has to be addressed.

2. Essential and non-essential plastics and their alternatives

To assess if we can differentiate between which plastics and plastic products we need and which ones we do not, a scientific and societal debate was started. "Essential use" has been put forward as a principle to offer perspectives for action in prioritising which plastics and applications to phase out, as proposed for certain groups of chemicals (Cousins et al., 2019). The term 'essential use' has already been deployed in the context of prioritising the use of chemicals that can negatively impact the environment but have an essential, beneficial function (United Nations, 1987; European Commission, 2020). Essential use is defined as being necessary for societal health, desired for safety, or critical for the performance of society. In addition, no technically or economically feasible substitutes are available that are acceptable from the standpoint of environmental safety and health (European Commission, 2020). A crucial aspect is that classifications of essential use are time-restricted and context-dependent: they need constant re-evaluation against (potentially) new solutions that are potentially more sustainable or safe. This principle may be applied to plastics as well, lowering the diversity of plastics and restricting plastics use to those plastics we really need and that are safe. In this way, negative impacts on human health and the environment could be reduced in the long term.

Although operationalising essential use can be considered a solution to reduce plastic pollution, it requires a good understanding of its implications (Cousins et al., 2019). Plastic applications that receive such labelling because they address a (temporal) societal need, may still lead to (long-term) environmental impacts. Furthermore, phasing out certain types of plastic that are seen as non-essential will require alternative products or solutions if a certain societal need still needs to be fulfilled (Alaerts et al., 2019). These alternatives are often new or less common and thus, less studied but will also have their impacts and environmental footprint (Sackmann et al., 2018). Thus banning certain plastics or plastic applications does not necessarily lead to the most sustainable outcome (Herberz et al., 2020). Preventing and mitigating pollution is an essential starting point, but an adapted process with improved knowledge is needed to get to a truly sustainable economy.

3. Sustainable plastics

Transformative change of complex systems such as the plastics economy, is characterised by continuous knowledge developments and considerable uncertainties (van Bruggen et al., 2019). It is therefore impossible to transform to a long-term sustainable plastic economy with one-time measures (van Bruggen et al., 2019). To see which efforts are needed and to keep track of our actions globally we suggest to advance in three areas: (i) embedding risk assessment methodologies in wider cost-benefit and life cycle analyses; (ii) using safe-and-sustainable design strategies that include alternative solutions and look at multiple life cycles, and (iii) reflecting on the societal transformation pathways with stakeholders by using co-created quantitative, dynamic models to simulate different scenarios (Fig. 1). To transform systems, different types of models are required that each have their own form of stakeholder cooperation (van Bruggen et al., 2019). Modelling exercises can best contribute to societal transformation if learning occurs in iterative cycles and the degree of active participation is high. We believe that these three practices are currently not receiving the attention they deserve and are crucial in the coming decade to realise the extraordinary effort of defining sustainable plastics.

3.1. Embedding risk assessment methodologies

Plastics, including micro and nano-sized fragments, have different characteristics physically (e.g. size, shape, density), chemically (e.g. rigidity, additives, impurities) and biologically (e.g. the presence of microorganisms and/or pathogens on plastic fragments). It is the combination of these characteristics that determines their behaviour and effects (Li, 2020; Mitrano et al., 2021; Mughini-Gras et al., 2021; Beijer, 2021). It is due to the diversity in plastic fragments that, as yet, we do not sufficiently understand which combinations will determine

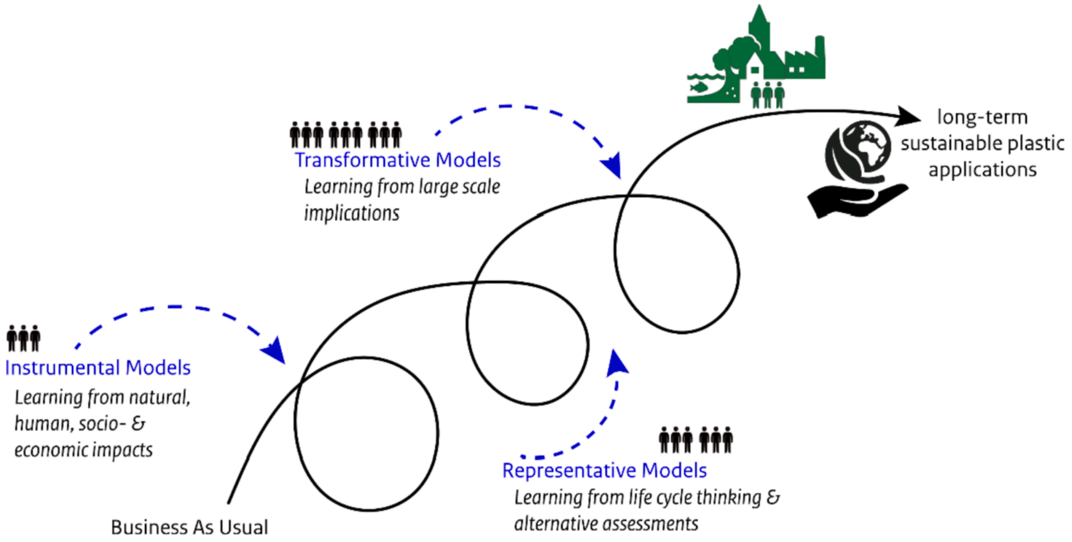

Fig. 1. Schematic representation of transformation pathway(s). Scheme inspired by Van Geels, social technical landscape developments (Geels et al., 2006). We study our observations (data, frameworks, strategies) and plan for action, act on these plans and reflect from different levels on the results. These processes reoccur in cycles of systemic learning (van Bruggen et al., 2019).

any observed effect (Vethaak and Legler, 2021; World Health Organisation, 2021). Although advances in risk assessment such as the use of grouping approaches are being made, next steps are necessary to provide an overview of costs and benefits and all impacts (Koelmans et al., 2020; Beijer, 2021). For a more holistic view, knowledge on human and ecological toxicology should be combined with socio-economic impacts by embedding risk assessment methods in wider cost-benefit and life cycle methods. In this way, themes that are relevant for plastics, such as land use (related to biodiversity), resource depletion, social perception, and also (economic) feasibility themes such as monitoring, compliance and enforcement, can be taken into account (Broeren et al., 2017; Blaeij et al., 2019; Traas et al., 2021).

For example, recycling of PVC flooring that contains phthalates that are restricted in use for safety reasons may be preferred over more energy and emission-intensive PVC production using raw materials. However, safeguarding toxicological thresholds of phthalates in recycled PVC may be challenging (Blaeij et al., 2019). In this case, risk assessment is integrated into a wider impact assessment, which typically builds on instrumental forms of stakeholder cooperation. In such a cooperation, individual stakeholders provide science-based input to improve models, increase their efficiency, and ensure outcomes are supported by all stakeholders (Fig. 1) (White, 1996). The embedding of risk assessment in a broader impact assessment across the life cycle provides a better understanding of the optimal solutions for, in this case, virgin and recycled plastic. It also prepares the relevant stakeholders for investing in areas where side effects may occur if a certain solution is chosen such as safeguarding toxicological thresholds.

3.2. Safe and sustainable design for multi-life cycles

To prevent and prepare for human, environmental, social and economic impacts, whilst finding optimal ways to design new products or compounds, the safe and sustainable by-design concept has been put forward (Van de Poel et al., 2017). The strategies are considered to be a useful approach, but a more sustainable solution may be overlooked if the scope is too narrow. This means that advanced safe and sustainable design strategies should be holistic, i.e. consider potential alternative solutions and reflect on multiple uses or life cycles (Traas et al., 2021; Zijp et al., 2017). For example, replacing plastic carrier bags with cotton ones may actually result in a larger environmental footprint, which is overlooked if impact assessments do not include the overall environmental footprint of alternatives of a typical plastic carrier bag (Bisinella et al., 2018). Thus, to avoid regrettable substitution, the entire life cycle, and even multiple life cycles, of a plastic application, as well as its potential alternatives should be taken into account (Sackmann et al., 2018; Bisinella et al., 2018) (Fig. 2). Safe and sustainable by design can then provide a valuable framework to minimise negative impacts and find optimal solutions.

Even when products are more easily associated with an overall positive contribution, such as in the case of health care applications, the life cycle perspective is needed to assess the total balanced benefits in the long term (Smith et al., 2014; Zijp et al., 2021). All products or services are related to an environmental footprint, which includes greenhouse gas emissions. One of the impacts related to these emissions is temperature rise causing heat stress. Other health impacts include those related to transmission of climate-sensitive infectious diseases, such as Vibriosis, malaria, dengue and Zika (Kuvadia et al., 2020; Romanello et al., 2021). Thus, the increase of greenhouse gas emissions causes an increased burden of disease, negatively contributing to public health (Smith et al., 2014). To consider this from the positive side: if we cure person X in the hospital with the help of certain sustainable medical protective wear which has lower greenhouse gas emissions, we simultaneously lower the burden of disease for person Y outside the hospital (Zijp et al., 2021; Kuvadia et al., 2020). Greenhouse gas emissions are just one way of better understanding the environmental impacts and their relation to human health.

The examples of the carrier bag and the medical protective wear both illustrate the need and possibility of including a long-term life cycle perspective in the assessment of plastic products and alternatives. Because different stakeholders are involved to provide the necessary data and insights, such as scientists and product developers, alignment is needed to bridge differences in practices, jargon and frameworks (Zijp et al., 2017). This alignment challenge can be handled in an operational safe and sustainable design framework (Van de Poel et al., 2017; Zijp et al., 2017). Impacts can then be modelled in representative collaborations where stakeholders come together to create models that represent the scope of all (van Bruggen et al., 2019) (Fig. 1). This demands a more active participation of a wider audience of stakeholders in which they not only provide data but also think about requirements of models used, such as for technical performance or optimisation of distribution chains (Alaerts et al., 2019). For example, to develop sustainable medical protective wear to replace disposables, one could consider what is practically feasible for medical staff, the required technical performance producers need to realize, and what patients perceive as hygienic. A way

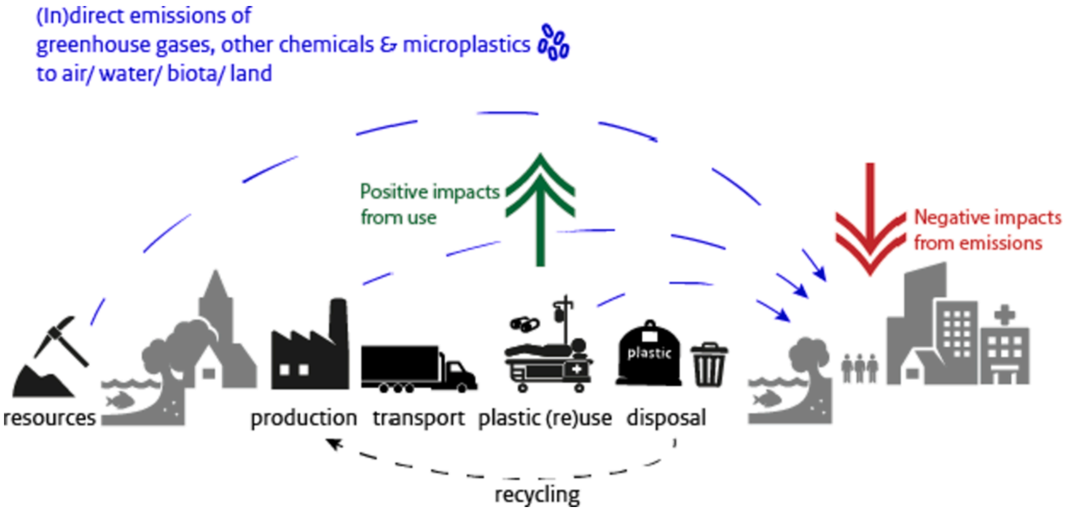

Fig. 2. Schematic representation of possible life cycles of a plastic with related (in)direct emissions, such as greenhouse gases, chemicals (production) and microplastics (use and end of life). Microplastics in the environment have physical, chemical and biological characteristics. Ideally, sustainable plastics have a net positive societal contribution (green arrow), minimising negative impacts, such as on human and environmental health (red arrow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to stimulate such cooperation is to work towards extended chain responsibility, in which overall positive sustainable performance and transparency are tracked and rewarded (Traas et al., 2021). Applying sustainability criteria in existing practices, such as procurement criteria or standard 'pollutant release and transfer register (PRTR)' reporting, may facilitate the implementation of such extended chain responsibility (Traas et al., 2021; Van de Poel et al., 2017).

3.3. *Reflecting on the societal transformation pathways to sustainable plastics*

Consequences of evidence-based decisions on plastic use should be evaluated at the macro or international scale. Material flow analysis (MFA) can show how much plastic packaging or product (volume or mass) is used and distributed (import, export) (Kawecki et al., 2018). Alternatively, macro-economic models can be connected to environmental impacts, in so-called extended input–output analysis, to understand the impact of hotspots in sectors (Nakatani et al., 2020). While this type of analysis currently exists, it cannot yet satisfactorily connect material flows to environmental impacts and human health and link to perspectives for action (Blaeij et al., 2019; Müller et al., 2014). For instance, recycling targets may seem to have a positive environmental impact by lowering the demand for virgin resources (product level). However, recycling targets require an increased demand for waste as a resource. Energy-intensive processing is then still needed to create new products (societal level). In effect, this leads to less demand for creating products with longer lifetimes. Information at the product level and the societal level needs to be combined to find optimal solutions. 'Transformative' models can be used to increase the value and use of macro models substantially. Stakeholders in plastic chains learn and collaborate in such transformative models to combine different levels of knowledge and reflection (van Bruggen et al., 2019) (Fig. 1). These models help to empower stakeholders such as policymakers and industry to take ownership and engage in an iterative learning process in which they can set project goals, make decisions, and act together (White, 1996; Di Felice et al., 2021). Such a co-creative process was recently demonstrated in an international collaboration with scientific experts, NGOs and industry. Several future scenarios for circular plastics were jointly modelled, based on international policy action plans (PACE, 2021). Benefits, barriers and actions for these future scenarios were identified based on the themes 'resource use', 'climate change', 'human health and biodiversity', 'decent work' and 'economic wellbeing'. Although high level and mainly qualitative analysis, it is an example of a transformative model set-up that requires close collaboration between a varied group of stakeholders. It was found that a lack of insight into the environmental and socio-economic impacts of bio-based plastics hindered to see how sustainable biobased production truly is (PACE, 2021). Also, while recycling of plastics may lower certain environmental pressures, tracking hazardous substances can be difficult and cross-contamination to new products may occur (PACE, 2021). One of the things we can learn from this collaboration is that at this stage, it is premature for policy ambitions to aim for specific bio-based plastic targets, because we should include alternative solutions and invest in an improved understanding of the type of feedstock applications available and their impacts. This semi-quantitative analysis uses a variety of science-based models (e.g. risk assessment, life cycle analysis, social impact assessment) and stakeholder participation activities to consider the macro scale for the impacts of a transition to circular plastics. Based on these future scenario's, the international platform PACE has published action plans for different stakeholders and provides a platform for interdisciplinary and chain-wide collaborations (PACE, 2021). These will be crucial the coming decade for realising climate goals and circular economy ambitions (McDowall et al., 2017; European Commission).

A complementary example is the monitoring of voluntary agreements such as the Plastic Pacts around the world, in which stakeholders collaborate to reflect on the societal transformation of the plastic economy. Here, industry, NGOs and policymakers have agreed to make plastics more sustainable and formulated quantitative targets. To reflect on the progress made towards those quantitative targets, a monitoring system gathers information such as volumes, mass, type of plastic and recyclability (van Bruggen et al., 2020). Co-creation is required to gather input from industry on the type of available data and for scientists to define what data is needed to reflect objectively on progress. As with the 'micro-level' impact assessments, interests must also be balanced by defining the moments when input is gathered, scientific assessments are done, and outcomes are evaluated jointly with all stakeholders. Policymakers can then use these results to decide which plastics to phase out. If macro-level assessments such as the monitoring of plastic pacts are approached as an iterative learning process, the system can be transformed. The monitoring should be iteratively improved with knowledge from the impact assessments, such as the need to distinguish polymer types and improve understanding of chemical additives used (van Bruggen et al., 2020; Beekman et al., 2020). This is necessary information to prevent and minimise risks for human and environmental health (PACE, 2021). To do the right thing with the diversity of all parties and capacities, targets can be benchmarked progressively just as with the climate goals (Philibert and Pershing, 2001/01/01 2001). Progressive benchmarking also yields preparedness to benefit from rapid progress caused by innovations, in such a way that fixed sustainability targets do not suddenly drop below market standards as a result of new developments (Faulconbridge et al., 2018). Close stakeholder collaboration is required to improve data collection and interpretation. As more different parties are able to contribute, in time, data will become more widely representative, more reliable, and more useful. Scientists can then use the appropriate data that is required to improve models and assessments, which in turn, supports decisions on policy and of stakeholders to transform to the ideal of sustainable plastics (van Bruggen et al., 2020).

4. Outlook

By developing the three crucial practices; embedding risk assessment methodologies; using safe-and-sustainable design strategies for multiple life cycles; and reflecting on the societal transformation pathways, a further integration will occur of human, environmental, social and economic long-term impact assessments for both the plastic application and its alternatives. This will help us to achieve the best possible overview of risks and benefits. The risks and benefits can, in turn, be used in methodologies called 'social cost-benefit analyses', in which different stakes are made transparent, scored and weighed. The outcome can be used to formulate evidence-based sustainable solutions for certain societal needs. Intrinsic to the complexity of achieving truly safe and sustainable plastics are the uncertainties that come with combining the different topics and quantitative and qualitative data. Sensitivity analysis may help to show the range of the uncertainties (van Bruggen et al., 2019; Blaeij et al., 2019; Di Felice et al., 2021). At the same time risk awareness and communication may help dealing with these uncertainties and different views when decisions have to be made (Blaeij et al., 2019; Di Felice et al., 2021; Kwakkel, 2017). International organisations, such as the OECD and PACE have published action agenda's and considerations that help to provide best possible overviews and insights in trade-offs (PACE, 2021; OECD, 2021). These organisations also provide a platform for collaborations and modelling exercises on the next needed steps (Di Felice et al., 2021). At the same time, there has to be a new mind set on the need of making transparent choices, which do need to be monitored, evaluated and reconsidered in time, with the current knowledge at hand.

We propose that the pathway to safe and sustainable solutions should be a science-based discourse with learning in iterative cycles, whereby first learnings will be mostly qualitative and increasingly quantitative. The role of science is to provide an objective foundation to be used for a balanced assessment of health and environmental risks, to support the development of alternatives, and to support decision-making by exploring large-scale implications of the decisions made. Understanding and preventing negative implications and promoting truly sustainable plastics requires a learning process between scientists, policymakers, NGOs, industry and civil society. This will not necessarily simplify decision-making, but will make it easier to understand what the consequences of these decisions are and in which direction we should take the next leap.

CRediT authorship contribution statement

Susanne Waaijers-van der Loop: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Anne van Bruggen:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Nick R.M. Beijer:** Writing – review & editing. **Adrienne Sips:** Writing – review & editing. **Ana Maria de Roda Husman:** Writing – review & editing. **Flemming Cassee:** Writing – review & editing, Funding acquisition. **Willie Peijnenburg:** Investigation, Writing – review & editing.

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.

Acknowledgments

The authors like to thank Theo Traas, Yvonne Staal, Richard Luit, Arianne de Blaeij, Silke Gabbert, Marcel Mengelers, Jeanine Ridder and the RIVM plastic working group, for the fruitful discussions and critical reviews on the subjects of toxicology, international chemical legislation, environmental economics, essential use concept, food contact materials and systemic societal changes.

Funding

This work was funded by the Strategic Research Program of the Dutch National Institute for Public Health and the Environment (RIVM) in project S/010015/.

Author contributions

Conceptualization, SLWvdL and ARvB; investigation, SLWvdL, ARvB, and WP; writing—original draft preparation, SLWvdL and ARvB; writing—review and editing, SWvdL, ARvB, NB, AS, AMRH, FC, WP; visualization, SLWvdL; supervision, SLWvdL; funding acquisition, FRC. All authors have read and agreed to the published version of the manuscript.

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