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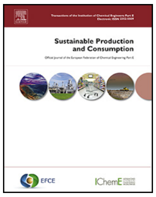

Research article

Closing the loop on plastics in Europe: The role of data, information and knowledge

Wan-Ting Hsu *, Teresa Domenech, Will McDowall

Institute for Sustainable Resources, University College London, 14 Upper Woburn Place, WC1H 0NN London, United Kingdom

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A B S T R A C T

Concerns over plastic waste and support for a plastic circular economy have been growing in recent years. Specific needs to promote re-circulation of plastics in terms of data, information and knowledge are poorly understood. Based on the multi-level perspective on socio-technical transitions and semi-structured interviews with key stakeholders, this paper aims to understand how information and knowledge issues may inhibit or foster the development of secondary plastics markets in Europe. Results highlight that key barriers associated with data-information-knowledge map across, and interact with, policies and standards, market and technology, socio-cultural norms, networks and business models. The packaging sector has drawn more policy attention, and institutions to support information sharing such as labelling and certification are more mature. The automotive and EEE sectors have illustrated knowledge diffusion through supply chain collaboration, while the construction sector appears to have slower practical progress on industry-level knowledge diffusion. This paper contributes to the multi-level perspective on transition studies by focusing the empirical work on a new area of plastic circular economy. The cases playing out across the whole value chain and four different application areas provide insights that are potentially more widely applicable to the circular economy transition processes in Europe.

1. Introduction

Recent years have seen growing concern around the fate of plastic waste, and increased interest in a more circular plastic system. According to OECD (2022)'s global plastics outlook, only 9 % of plastic waste was recycled globally in 2019, and 22 million tonnes of mismanaged plastic waste leaked into the environment. OECD (2022) suggested increasing the use of secondary plastics in order to reduce the carbon footprint and plastic leakage. Adopting secondary materials and changing the whole system towards more circularity can lessen negative sustainability impacts (Tseng et al., 2021).

There is high uncertainty around secondary plastic demand, which has been estimated to account for approximately 4–6 % of plastics consumed in Europe (European Commission, 2018; Hsu et al., 2021). The EU-led Circular Plastics Alliance aims to reinforce the market for secondary plastics, to ensure that 10 million tonnes of recycled plastics find their way into new products on the European market by 2025 (European Commission, 2019).

Yet the secondary plastics market still faces numerous barriers, which have to some extent been discussed in the literature. Existing studies focus mainly on the challenges and opportunities associated with mechanical recycling (Hahladakis and Iacovidou, 2019; Hopewell et al., 2009; Milios et al., 2018) and packaging (Bening et al., 2021), or specific actors in the value chain, such as converters (Dangis, 2018; Paletta et al., 2019), suppliers and retailers especially in fast-moving consumer goods industry (Gong et al., 2020). However, there is less evidence on how drivers and barriers for secondary plastics are playing out across different end-use sectors and across the value chain. There have been calls for further investigation of interactions across different types of barriers (Bening et al., 2021).

Alnajem et al. (2021) overviewed circular economy research between 2009 and 2018. They identified the system transition as a key gap for further research (Alnajem et al., 2021). In the plastic system transition, Royal Society of Chemistry (2020) suggested four major research themes: the impact of plastics throughout their life cycles; new sustainable plastics (e.g. bioplastics); closing the loop recycling; degradation of plastics. Following the direction for the future plastic circular economy research, including institutions, consumer behaviour, and system transition, suggested by Alnajem et al. (2021) and Royal Society of Chemistry (2020), this study mainly focuses on closing the loop through recycling plastic waste and using secondary plastics in the plastic

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* Corresponding author.
E-mail addresses: wan-ting.hsu.16@ucl.ac.uk (W.-T. Hsu), t.domenech@ucl.ac.uk (T. Domenech), w.mcdowall@ucl.ac.uk (W. McDowall).

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system transition. Secondary plastics have been defined according to the concept of 'recycled content' as laid down by ISO 14021.

Several studies have identified the lack of 'traceability' as a barrier to plastic circularity (European Commission, 2018; Milios et al., 2018; Paletta et al., 2019), but provide little understanding of how this barrier manifests in practice. Tseng et al. (2021) pointed out the research gap in understanding the barriers and drivers for different firms/actors to integrate a circular economy and data-information-knowledge within a changing socio-technical system in an Industry 4.0 era. This study aims to address this gap by investigating barriers related to data-information-knowledge in the transition to a circular plastic system. Jäger-Roschko and Petersen (2022) suggested future research to focus on: circular economy information exchange, access to information, incentives for circular economy information sharing, and differentiation between products.

We, therefore, focus on the role of data-information-knowledge for using secondary plastics in four application areas. The main research question addressed in this study is: How do data-, information-, and knowledge-related issues create barriers to the development of markets for secondary plastics in Europe?

This paper is structured as follows: Section 2 overviewed the plastic value chain and the barriers and drivers to a plastic circular economy transition. Section 3 explained the methodology and interview design. Section 4 presents and discusses the findings. The concluding remarks are summarised in Section 5.

2. Literature review

This section reviews the plastic value chain, barriers and drivers to a plastic circular economy. The literature review reveals the research gap on investigating the role of data-information-knowledge in the changing socio-technical system.

2.1. Plastic value chain

According to the comprehensive plastic material flow analysis conducted by Hsu et al. (2021), the EU produced over 66 million tonnes of plastic polymers/fibres and generated over 37 million tonnes of plastic waste in 2016. Among 10 identified destinations of plastic waste, only 4 million tonnes of secondary plastics were returned to the EU market (Hsu et al., 2021). It is still far from the target to use 10 million tonnes of secondary plastics in 2025.

Paletta et al. (2019) overviewed plastic value chain in the EU. Their study highlights the different technologies and recycling routes that can enable greater circularity and the variety of actors involved at different stages. The overall plastic value chain is shown in Fig. 1. Plastic production starts from oil and natural gas, through the cracking process to produce feedstock and monomers. Then, a large number of monomers are joined to become polymers, after which polymers are mixed with additives to make compounders. The compounders are further manufactured and assembled to be end products.

This study focuses on four main application areas: packaging, construction, automotive, and electrical and electronic equipment. In the end, these products become plastic waste and are sent to different waste treatments. Different recycling processes include mechanical recycling, solvent-based purification, depolymerisation, and feedstock recycling. Currently, mechanical recycling is still the main plastic recycling process in Europe. The other recycling processes are more or less at pilot scale or just about to be commercialised.

Many actors are involved in different lifecycle stages, including petrochemical producers, converters, compounders, manufacturers, distributors, traders, brand owners, retailers, consumers, municipalities, extended producer responsibility organisations, waste management companies, physical and chemical recyclers, and brokers. Between 2011 and 2018, the average number of the companies in the European plastic value chain is 2595 plastic producers; 54,586 plastic converters and manufacturers, among them, 8793 companies specifically for plastic packaging manufacturing; and 2400 companies of machinery (see Fig. S-1). Fig. S-2 shows the turnover in the upstream of plastic industry between 2011 and 2018. The total turnover of manufacture of plastics in primary forms and manufacture of plastics products had been growing to €368bn in 2018. However, Plastics Europe (2021) indicated that the plastic industry has been affected by the pandemic and the turnover has slightly dropped to nearly €330bn in 2020. In the downstream, there are more than 600 plastic recycling companies in 2020 with turnover more than €3bn, according to the statistical data from Plastics Recyclers Europe (2020). Approximately, 8.5 million tonnes installed recycling capacity in the EU in 2020.

The plastic value chain is embedded and operated within a socio-technical system. The plastic flows, actors and recycling technologies

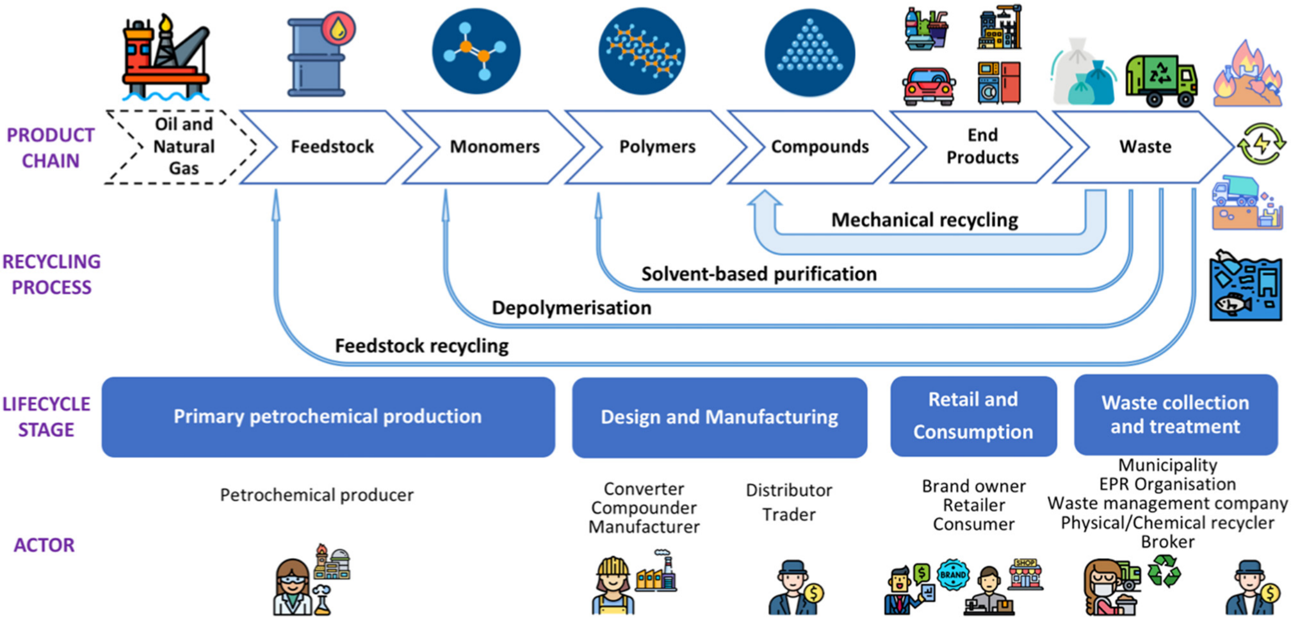


Fig. 1. The plastic value chain, showing the actors, life-cycle stages, and key routes for secondary materials.

have been identified, however, the information and knowledge flows and their interaction with different factors within the socio-technical system are still unclear.

2.2. Barriers and drivers to a plastic circular economy

Existing studies on the barriers and drivers to a plastic circular economy transition tend to discuss the economic, technical, regulatory and cultural barriers individually. Globally, OECD (2018) analysed the barriers to plastic recycling and potential interventions for the secondary plastics market. Hahladakis and Iacovidou (2019) reviewed challenges and trade-offs regarding mechanical recycling of plastic waste. They highlighted that communication and collaboration between stakeholders is the key to closing the loop on plastics. Their results reveal the importance to exchange data, information and knowledge across different actors in the plastic circular economy transition.

Milios et al. (2018) found that the main barriers to plastic recycling in the Nordic region are largely techo-economic, i.e. the higher cost and lower quality of secondary plastics. The main discussion in their study focused on the plastic waste from the municipal waste stream. According to their results, value chain coordination and investment in innovation and technology development are key enablers.

Paletta et al. (2019) investigated barriers and challenges to plastics valorisation through surveys of converters in Italy. Their findings show that legislative barriers are REACH Regulation and RoHS Directive; technical barriers are quality issues; economic barriers are lack of constant demand, availability and high cost; social and cultural barriers are either hostility or inert attitude to the innovation (Paletta et al., 2019). Socio-cultural norms and socio-demographic characteristics also influenced different actors' perception to the recycling and using secondary plastics (Galati et al., 2020). According to Paletta et al. (2019), the joint-venture business model between manufacturers/converters and mechanical recyclers is the main change along the plastic value chain between 2012 and 2018.

Recently, Gong et al. (2020) investigated 4 cases of the fast-moving consumer goods industry in the UK to explore suppliers' and retailers' motivations, enablers, and barriers associated with plastic circular economy initiatives. Bening et al. (2021) analysed the legislative barriers that interacted with economic and technical barriers on flexible plastic packaging in the municipal solid waste stream. Their study highlighted three challenging issues which are under debate, including the ambitious target of recycled plastics, degree of intervention on policies between demand-pull and technology-push, and the bioplastics as an alternative material. Bening et al. (2021) pointed out that it is needed to systematically investigate the interrelations of the barriers along the value chain, which we attempt to address in this paper.

Some previous research has also highlighted information-related barriers and knowledge gaps that inhibit the achievement of greater circularity (Kouhizadeh et al., 2019; Simpson, 2012). In order to transition the plastic system to meet SDG12 to create a circular and responsible consumption and production, designers (Hou et al., 2018) and manufacturers (Klemeš et al., 2021) need to provide more information and knowledge to the actors downstream, including retailers, consumers and recyclers. Some European firms have started to apply digital technologies to support the plastic value chain tackling barriers to lack of data and information for secondary plastics (Chidepatil et al., 2020; Tramutola, 2019). Galati et al. (2022) highlighted that information and knowledge regarding secondary plastics can shift the consumers' behaviour. van Bruggen et al. (2022) highlighted that different types of barriers preventing use of secondary plastics in the automotive sector are connected and require a system change, including improving the data collection and information sharing. However, no previous study has provided a systematic analysis on how the role of data-information-knowledge plays across different lifecycle stages, and what are the barriers and drivers for different actors to enhance the transparency and traceability of plastic waste and secondary plastics.

In a nutshell, the existing discussion emphasised the economic and technical barriers showing that the high cost and low quality of recycled plastics lock-in the transition towards the use of secondary plastics. Most of the discussion explained the barriers around economy and technology individually, with less attention to link these barriers to the data-information-knowledge issues. All the aforementioned references identified the barriers regarding lack of public awareness and lack of collaboration. The legislation, market, technology, socio-cultural norms and business networks have been rapidly changing in the past few years since the European Commission adopted the *European Strategy for Plastics in a Circular Economy*. This study responds to the need to further understand the role of data-information-knowledge and its interaction with different types of barriers and drivers that contribute to SDG12 and the ongoing development of European secondary plastics markets.

Jäger-Roschko and Petersen (2022) suggested future research applying a theoretical framework to explore the factors for improving information flows, while Borrello et al. (2020) suggested use of the multi-level perspective (MLP) transition theory to analyse circular economy transition and identify regime constraints. We, therefore, adopt a socio-technical systems approach inspired by the MLP (Geels, 2002) to structure our analysis. Some previous studies on circularity in the plastics sector have also used the MLP, including Oyake-Ombis et al. (2015) which evaluated the niche innovations to manage plastic waste in East Africa. Oyake-Ombis et al. (2015) also call for further investigation on the interactions at the regime level.

3. Methods

This section overviews the multi-level perspective conceptual framework of a socio-technical system and data-information-knowledge-wisdom (DIKW) hierarchy. Then, the qualitative research design explains the procedures of data collection and data analysis.

3.1. Conceptual framework: socio-technical systems

Our conceptual framework adopts a "socio-technical system" perspective. This perspective acknowledges the importance of heterogeneous elements beyond technologies and markets (including also non-market actors, institutions and cultural factors), and analyses how these interact to create stability or change within the plastics system as a whole. Our conceptualisation of the plastics socio-technical system is inspired by the MLP (Geels, 2002), which depicts the system as a set of co-evolving, semi-autonomous 'regimes': a technological regime, a policy regime, a user and market regime, a socio-cultural regime, and so on (Geels, 2004). These 'sub-regimes' together make up the socio-technical regime. Radical change in socio-technical regimes—such as the transition to a circular plastic system—is inhibited by mechanisms that stabilise the existing regime and prevent the breakthrough of alternative configurations.

Data, information, and knowledge play fundamental roles in the socio-technical systems change. Most obviously, innovation is strongly conditioned by learning processes, in which actors develop new knowledge about both technological possibilities and market opportunities, while users need to learn about new innovations if they are to be adopted. Knowledge development and diffusion are thus key elements in the emergence of new technological systems (Hekkert et al., 2007). Knowledge gaps about demands and technological possibilities, and a failure of knowledge diffusion among actors within the system clearly inhibit change.

Drawing on the data-information-knowledge-wisdom (DIKW) hierarchy (Ackoff, 1989; Rowley, 2007), we also highlight the distinction between data, information and knowledge. Data are elementary parameters derived from observation without context and interpretation. Information is processed data through sorting, classification, aggregation, and interpretation for a specific purpose. Knowledge represents the transformation of data and information with the combination of experience, capability, skills, training, and perception to be actionable instructions for decision-making support. Wisdom, as the highest level of the DIKW hierarchy, is more intangible and harder to measure than the other components, and we exclude it from our analysis.

The MLP highlights the fact that institutional structures contribute to the stability of existing systems, and this includes institutionalised measurement and data collection processes (such as data collected on material flows), or institutionalised forms of knowledge (such as standards and guidelines). Information and knowledge are subject to many of the forms of 'lock-in' and path dependence that inhibits change in socio-technical systems.

3.2. Data collection

We adopt a qualitative research design to investigate the empirical topic of data-information-knowledge in plastic circularity, based on the case study using in-depth interview methods as primary data gathering tool (Yin, 2003). The lessons from case studies of individual firms/actors using secondary plastics across packaging, construction, automotive, and electrical and electronic equipment are intended to be explainable and generalisable to more broadly plastic system transition situations in Europe (Yin, 2003).

We combined primary data collection through semi-structured interviews and a review of supporting documents as secondary data provided by interviewees, such as published case studies, brochures, project slides, firm websites, etc. The main interview questions are around the use of plastics and/or plastic waste, treatment options, key drivers and main barriers for the interviewees and/or their clients to use secondary plastics with a focus on data-information-knowledge issues, and discussion around the feasibility of different interventions to promote the use of secondary plastics (see supplementary material). The interview questions were further tailored depending on the participants' role and relevant business of secondary plastics in their firms.

In total, 25 firms/organisations (26 interviewees) were selected using a convenience sample and snowballing techniques to reach key stakeholders including the members of plastic industry associations and secondary plastic users (see Table S-1). The participants were drawn from across the plastic value chain, including petrochemical producers, manufacturers, a trader, brand owners, retailers, waste management companies, both physical and chemical recyclers, a broker, and an extended producer responsibility organisation. Based in Germany, the Netherlands, Belgium, France, Sweden, Austria, and the UK, the companies have/had operations spread across other European countries. These participants are representative of operations across the value chain and they are involved in European plastic circular economy networks such as Circular Plastic Alliance, and therefore represent pioneers of a plastic circular economy. The spatial system boundary of MLP is the EU28 as this study was started before Brexit.

The semi-structured interviews were held through video/audio call or face-to-face between Oct, 2019 and Nov, 2020. All the interviews were carried out in English. The interviews ranged in duration from 30 to 75 min. The interviews continued until the point of theoretical saturation was reached (Fusch and Ness, 2015; Mason, 2010).

3.3. Data analysis

The audio and/or video recorded interviews were manually transcribed into written form. A thematic analysis method was conducted, through the NVivo 2020 software, to identify the themes across a qualitative data set (Braun and Clarke, 2006). The themes represent patterns of meaning. Patterns can help to identify the similarities and differences from the participants' viewpoints. Thematic analysis is applied based on six recursive phases: 1) Organisation of and familiarisation with data; 2) Coding data; 3) Searching for the themes; 4) Review themes; 5) Defining and naming themes; 6) Writing up results (Braun and Clarke, 2006). We coded a large number of drivers and barriers to circularity, and further identified how each of these factors relate to key 'sub-regimes' (i.e. the mutually re-inforcing but semi-autonomous systems that together comprise the socio-technical regime). This relates the barriers to a set of underlying dynamics within each sub-regime.

4. Results and discussion

This section overviews the MLP on plastic circular economy transition. The interaction of data-information-knowledge barriers with sub-regimes, and the ongoing development of data-information-knowledge, are analysed and discussed.

4.1. Overview the multi-level perspective on plastic circular economy transition

Fig. 2 shows the overall picture of a Multi-Level Perspective (MLP) on plastic circular economy transition. The key drivers at the landscape level are well-known, and re-confirmed by our participants: the drivers come from the circular economy initiatives especially from the Ellen MacArthur Foundation and European Commission's circular economy package, and also Sustainable Development Goals, restrictions imposed by the China's plastic waste import ban, climate change policies and increasing citizen concern about plastic pollution. Further MLP of plastic circular economy transition is analysed in supplementary material.

4.2. Barriers related to data, information and knowledge

In a linear system, upstream stages of primary extraction and manufacturing are not necessarily connected to disposal and waste processing. This creates discrepancies between what is expected and prioritised at different stages, reducing the economic and technical feasibility of plastic recycling. In a circular system, actors across the value chain are required to have a greater understanding of the technologies, material properties, quantity and direction of flows, so that specifications that work at a system level can be defined to ensure product quality and reliability with larger share of recycled content. The interviewees report limitations of information exchange and knowledge diffusion across actors in the linear system, suggesting that data-information-knowledge dimensions at the socio-technical regime level are critical for the transition towards a circular plastic system.

4.2.1. Barriers of data-information-knowledge at each lifecycle stage

The results summarised below show how data-information-knowledge aspects constrained actions across different lifecycle stage (Fig. 3), in order to identify the specific barriers for each actor.

4.2.1.1. Petrochemical production. Plastic users, including manufacturers of final products, brand owners and retailers, often wish to know whether their plastic contains secondary material, either because the use of recycled plastics is a regulatory requirement, or because of consumer pressure. However, plastic recycling systems generally offer limited traceability of secondary plastics.

A particular traceability challenge emerges in the context of chemical recycling, which enables the recovery of primary chemicals from which plastics can be generated. However, as they go back into the petrochemical production stage, it is impossible to trace the destination of the material derived from plastic waste. As explained by a petrochemical producer: *'If [material entering] crackers had a very small quantity of recycled feedstock, … it gets distributed across the whole network. The question is, where does it end up?… You don't find [that] today' (#4).* The potential solution to this information challenge is to use a 'mass-balance' approach which requires agreed standards of data collection and reporting, to enable certification *(#4, #21).*

4.2.1.2. Design. Designers lack understanding of recycling technologies; including both how to design for recycling and how to design products

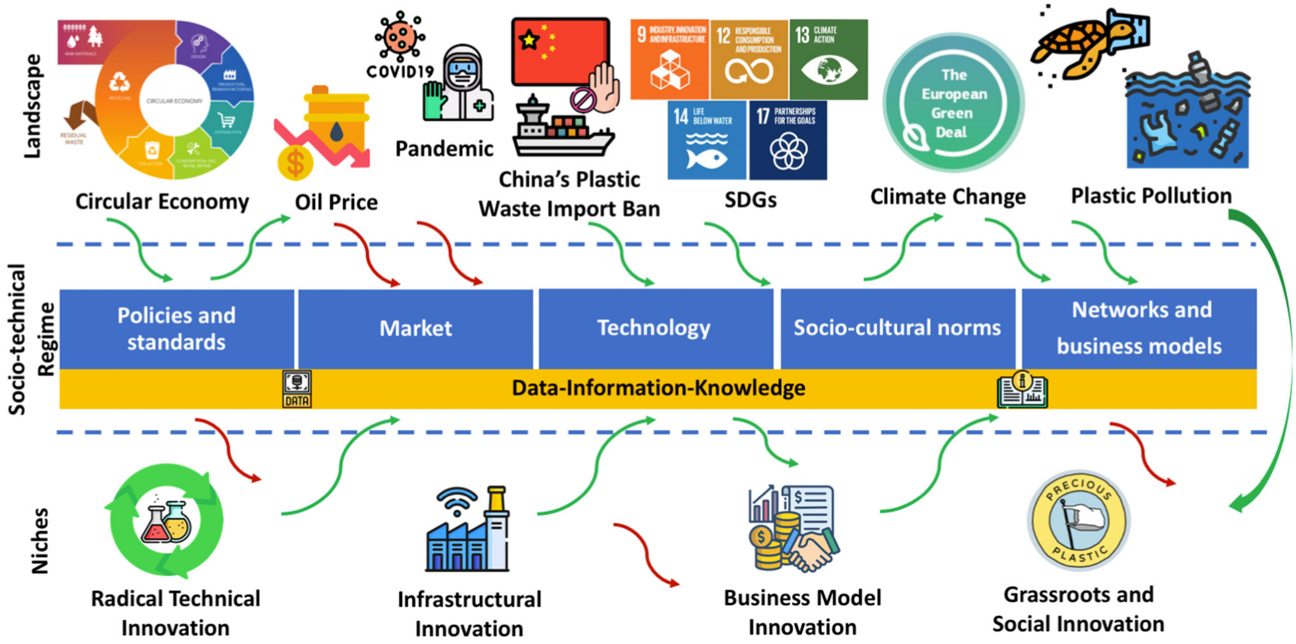
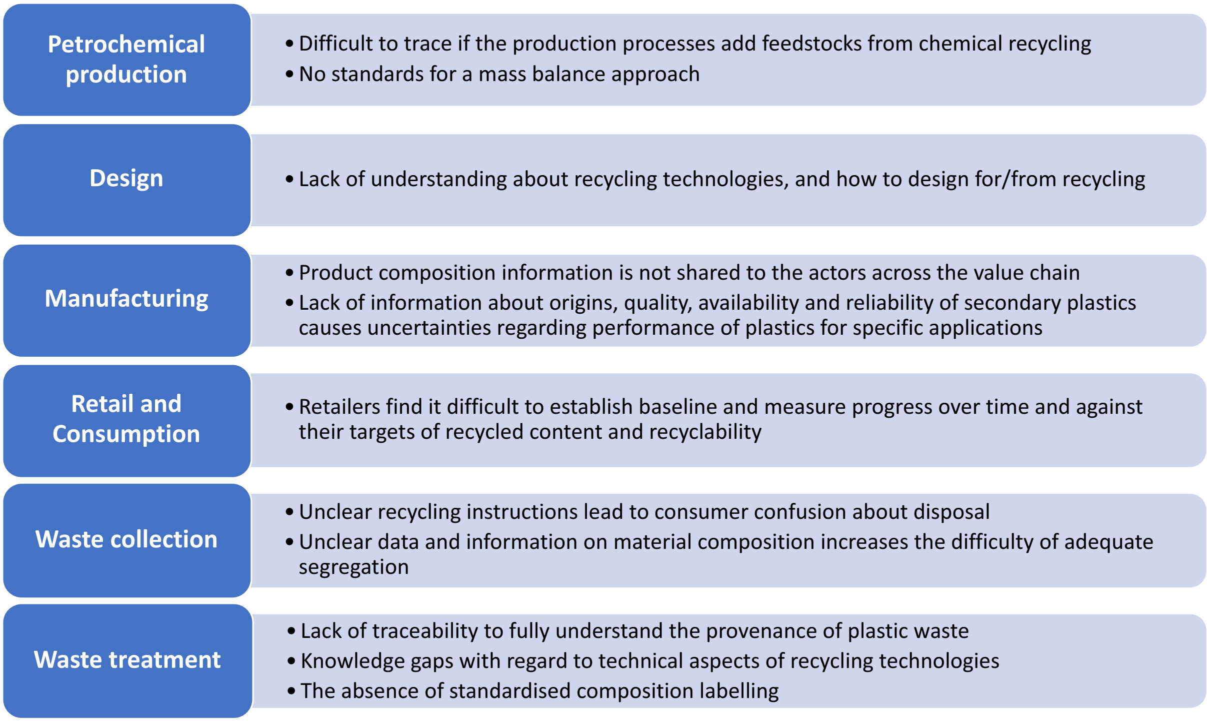


Fig. 2. MLP on plastic circular economy transition.

with recycled plastics. Historically, product designers rarely designed with recycling in mind, nor have they considered how best to design to encourage the use of secondary materials. An interviewee described, *'If we have this demand coming from the consumer, the manufacturer wants to fulfil the demand, but sometimes he [sic] can't because he doesn't know how to handle recycled materials' (#24).*

It is important for designers to acquire relevant information and knowledge on recycling technologies from a design perspective. A consultant explained, *'If you understand recycling, then you can actually change your packaging. If you don't know what's happening, then how can you design something that is actually recyclable?' (#16).*

4.2.1.3. Manufacturing. At the manufacturing stage, a key barrier is that product composition information is not always shared across the value chain. The lack of information about origins of secondary plastics and material composition of products causes uncertainties for manufacturers. Information on quality, availability and reliability of secondary plastics is needed across different application areas. An interviewee



Petrochemical production	• Difficult to trace if the production processes add feedstocks from chemical recycling • No standards for a mass balance approach
Design	• Lack of understanding about recycling technologies, and how to design for/from recycling
Manufacturing	• Product composition information is not shared to the actors across the value chain • Lack of information about origins, quality, availability and reliability of secondary plastics causes uncertainties regarding performance of plastics for specific applications
Retail and Consumption	• Retailers find it difficult to establish baseline and measure progress over time and against their targets of recycled content and recyclability
Waste collection	• Unclear recycling instructions lead to consumer confusion about disposal • Unclear data and information on material composition increases the difficulty of adequate segregation
Waste treatment	• Lack of traceability to fully understand the provenance of plastic waste • Knowledge gaps with regard to technical aspects of recycling technologies • The absence of standardised composition labelling

Fig. 3. Barriers of data-information-knowledge at each lifecycle stage.

said, *'From the production side, we see that…manufacturing companies don't really know the quality they get, …[and] the quality is varying all the time' (#24)*.

4.2.1.4. Retail and consumption. Circular economy pledges have recently been made by many brand owners or retailers, however, some have found it challenging to access data and information to build a baseline of secondary plastic use and, thus, to measure progress over time and against their targets. Currently, there is no harmonised standard to measure the recycled content as well as to assess the degree of recyclability of plastic products, which could also lead to the risk of double counting. This is dependent on institutional frameworks, collection systems and recycling infrastructures in different countries. A retailer/brand owner explained the case of their firm: *'Every country has a different measuring system, sometimes it is labelled or not, and also standards are not clear' (#12)*.

4.2.1.5. Waste collection. At the waste collection stage, unclear recycling instructions and differences in segregation and collection systems across regions and countries lead to consumer confusion about disposal, while unclear data and information on material composition increase the difficulty of adequate segregation for waste collectors and sorters in the pre-treatment stage.

Barriers to the labelling are also identified, especially on the packaging. A retailer mentioned, *'At the moment, it is always confusing because country by country is different' (#12)*. Another interviewee said, *'in different countries, recycling works differently. So we don't put any labels on how to dispose of products' (#13)*.

In the construction, electrical and electronic equipment (EEE) and automotive sectors, it appears that detailed information on secondary plastics and their material composition is rarely provided to end consumers and recyclers. The only data shown to the consumers, if any, may be the percentage of secondary plastic used in the products for marketing purposes. An interviewee pointed out that poor information on material composition for plastic components embedded in products creates difficulties for further segregation and treatment when the plastics enter waste streams: *'How do you know what kind of material it is? You don't know. It's not known. And that is a lack of information and it is lack of communication' (#7)*.

4.2.1.6. Waste treatment. At the waste treatment stage, there are barriers including lack of traceability to understand the provenance of plastic waste, and knowledge gaps with regard to technical aspects of recycling technologies. Three key factors were identified by those interviewed: i) the complexity of the material composition of plastic-containing products, ii) the absence of standardised composition labelling, and iii) the cross-contamination issues as a result of collection of mixed plastic waste streams. A manufacturer said, *'So the biggest problem of recycled material is the provenance. So, where it comes from? It's understanding the provenance and then also understanding the mixture of it. If you're post-consumer waste, you have no idea where it's coming from, you don't know what contamination is in there' (#6)*.

4.2.2. Interaction of data-information-knowledge barriers with sub-regimes

A key strength of the socio-technical systems conceptual framework underpinning this paper is that it highlights the interaction—and co-evolution—of heterogeneous elements. It thus directly responds to calls in the literature for analysis that examines the interaction of barriers. Here we explore how the barriers associated with data-information-knowledge map across, and interact with, each of the sub-regimes of the socio-technical regime. This analysis draws on the above mapping of barriers across the value chain, but now explores how these barriers interact. The interactions are summarised in Fig. 4. The figure shows that the barriers are mutually reinforcing, creating a 'web of constraints' (Domenech et al., 2017).

4.2.2.1. Policies and standards. The evidence presented in the previous section highlights that across the value chain there is weak institutionalisation of data and information flows. This includes limited standardisation of rules for information disclosure or standardised ways of measuring secondary plastics. For example, measurement standards are not in place for measuring recycled feedstock from chemical recycling. *'At the moment, there is no ISO standard or there's no international standard or European standard on this mass balance approach' (#4)*. Codification of data and information flows and knowledge resources through regulations, standards and certification processes are essential for building trust and mutual understanding across the value chain. More obviously, weak data hampers efforts to improve policies.

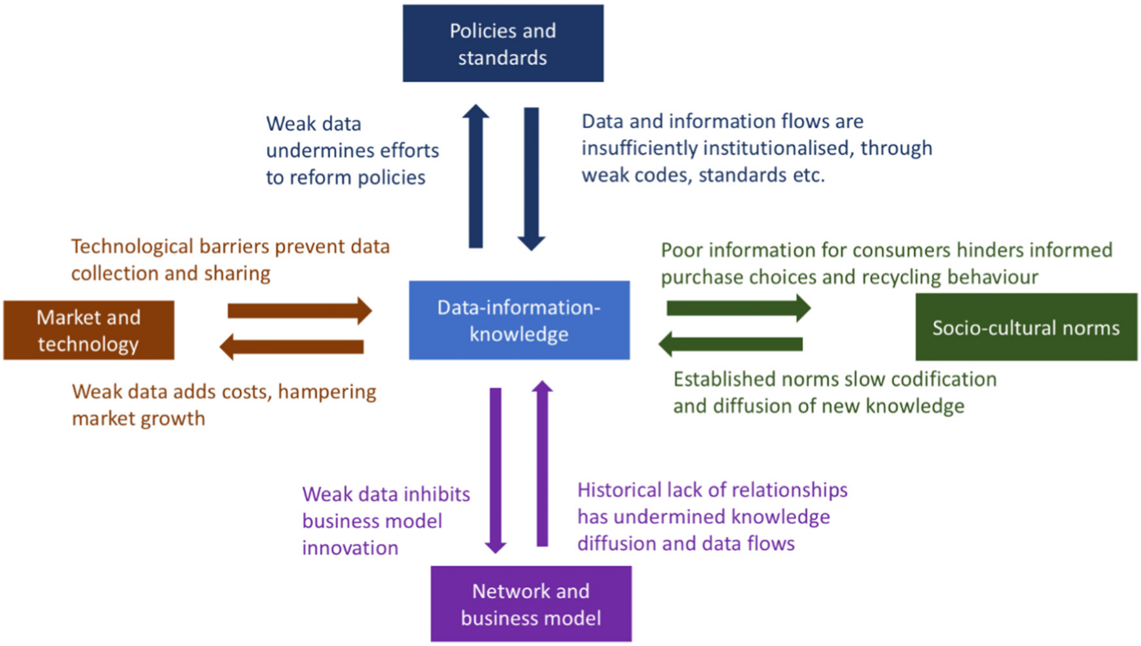


Fig. 4. Summary of interaction of data-information-knowledge barriers with sub-regimes.

4.2.2.2. Market and technology. Data-information-knowledge issues reinforce market and technology barriers. Tracing, sensing and testing plastic waste and the performance of secondary plastics is costly and time-consuming. This adds costs and uncertainties to the use of secondary plastics, reducing their market attractiveness. Both the car manufacturer and a recycler we interviewed highlighted these costs in relation to end-of-life vehicles: *'We had to spend quite a lot of money testing to make sure that the plastic didn't contain unwanted additives like lead or cadmium or banned flame retardants' (#18).*

Similarly, using recycled plastics requires extra laboratory testing, either by secondary plastic sellers or buyers, to ensure that it can meet the specific demands of the product. This is especially important for technical plastics and food contact plastics.

At the same time, market and technology barriers prevent development of data (due to limitations in tracing and sensing technologies, for example); while concerns about loss of intellectual property inhibit data sharing and knowledge diffusion.

4.2.2.3. Socio-cultural norms. Established routines and cultural norms in many industries tend to overlook secondary materials, as they are not part of the existing supply chains and lack a track record regarding quality and performance. Such routines and habits take time to shift, while in the meantime reinforcing existing systems: *'years ago... when I was selling (recycled granules for PVC windows) to try to get a product into specifications to architects in design some new buildings, you'd find that the people designing the building would cut and paste the information from a previous job, which might be completely out of date and wrong, but it is easier... So they would cut and paste the information…, which would stop you giving them a better product because the specification now is wrong' (#19)*. Routines and cultural norms within business communities can slow codification and diffusion of new knowledge.

Although consumer awareness and perception about plastic issues have changed in the past few years, consumer norms and habits related to purchase decisions and waste disposal behaviours are identified as barriers according to the interviewees. In some cases, it is technically achievable to use a higher percentage of secondary plastics, however, consumers may not accept and be willing to buy the products. An interviewee explained, *'there is maybe absolutely no difference to the products, but if consumers perceive it to be dirty or whatever, then you know you have a challenge to communicate some of those things to consumers' (#11).* On the other hand, consumers lack understanding about the impact of waste disposal and recycling: *'consumers are not really aware of what is the impact of the sorting… if I put this waste on the other bin, I don't care if it will be the same results because I don't have any visibility of this sorting' (#25).*

4.2.2.4. Networks and business models. Historically, there has been a lack of collaborative engagement among companies across the supply chain since it was not necessary in a linear system. The relationships that enable information and knowledge to flow across the value chain take time to establish. Data and information sharing may raise concerns about intellectual property and disclosure. Therefore, new business networks based on collaboration need to emerge to enable knowledge sharing while overcoming fears about losing intellectual property to competitors. The need for new knowledge to facilitate circularity is already generating knowledge-based entrepreneurship, through the establishment of consulting services, providing legal information and recycling technology knowledge to the brand owners, retailers and packaging companies. Control over (and access to) data is likely to be an important source of competitive advantage in a future circular ecosystem, and efforts to secure intellectual property are likely to hamper the open exchange of data that would facilitate greater circularity.

4.3. Ongoing development of data, information and knowledge

To tackle the aforementioned barriers, strategies have been suggested to enhance data and information flows, and knowledge development and diffusion, both of which are important in enabling the development of a more circular socio-technical system. In this section, we draw on our interviews to highlight progress with regard to product composition information from manufacturers, secondary plastics information for manufacturers, developing and diffusing knowledge through research and development (R&D) and collaboration, codifying knowledge through purchase and design guidelines. Where relevant, we provide examples across four different plastic application areas (packaging, construction, automotive and EEE).

4.3.1. Developing and institutionalising data and information flows

4.3.1.1. Product composition information from manufacturers. Information provided by manufacturers on the content of their products is important for facilitating subsequent recycling. Various international standards and EU policies (e.g., ISO 1043, ISO 11469, SAE J 1344, and various EU Directives) have long regulated labelling of goods to facilitate recycling, and the provision of information to assist dismantlers of EEE and end of life vehicles. Shamsuyeva and Endres (2021) overviewed the existing standards at the international and European levels on plastics recycling, product-specific plastic recyclates, and data requirements for the characterisation of plastic polymer recyclates. However, progress to transparent secondary plastic markets has been limited. Emerging digital tracking technologies are creating new opportunities in this area.

The automotive industry requires plastic labelling standards, however, while this has been identified as a key barrier for over 10 years (Duval and MacLean, 2007), specific progress has been slow. Several leading car manufacturers established databases such as International Material Data System introduced in 2000, while the EEE manufacturers and brand owners have also followed full material declaration approaches to document product composition information, however, these databases are restricted to the upstream partners who are involved in the collaboration. In recent years, new circular businesses have emerged in both EEE and automotive sectors by applying digital technologies to share the product composition information across the whole value chain (Tramutola, 2019).

For packaging, an example is manufacturers and brand owners using digital track-and-trace technology to record and share the product composition information with consumers, collectors and recyclers, as described by a manufacturer: *'We think the ability to track and trace all materials… if you're making composite products, you can embed in the data set…the material grade, what its properties are, so on and so forth… So, understanding that key data set to see what can be combined together and used is an absolute key driver' (#8).*

The construction industry has been discussing materials passports and BIM-based (building information model based) material passports, although these seem not to have much practical progress yet. The data and information, such as the technical datasheets, certificates of regulatory compliance, provide the material traceability and share with actors across the value chain through digital platforms. This kind of best practice will take time to develop and scale up.

4.3.1.2. Secondary plastic information for manufacturers. Manufacturers using secondary plastics need better information about those materials. In some cases, manufacturers simply wish to demonstrate that they are using secondary materials, and need data only on the volumes of secondary materials within their inputs. In other areas, manufacturers need detailed and accurate data on the provenance and composition of secondary materials, to ensure that the material meets their quality criteria and regulations. For example, those involved in food packaging must ensure that recyclers can provide information regarding safety and traceability to manufacturers to fulfill EU Regulations (e.g. REACH, Food contact legislation (EC No 1935/2004, EC No 282/2008)) (De Tandt et al., 2021).

Manufacturers thus look to their suppliers—often recyclers or converters, but also brokers and collectors, to provide data that clarifies origins, quality and quantity of secondary materials. Part of the challenge relates to the collection of data. In order to measure the amount of secondary plastics used in the new products, Monitoring Recyclates for Europe platform organised by many plastics associations has been working on secondary plastic data collection since 2018.

Intermediaries in the plastic value chain, including distributors and brokers, help their customers access specific secondary plastics to meet their requirements, however, this ad hoc process tends to lack traceability beyond those involved in it. Work to standardise and institutionalise data, to ensure comparability, is thus increasingly important. Many certifications have been developed to improve traceability, such as Recycled Plastics Traceability Certification by RecyClass.

A number of technologies have been developed to mechanically segregate plastic and track polymer composition of specific materials. A waste management company explained a good practice in their waste treatment facilities: *'We have lots of big data on recycling. So we know on an individual packaging based on the barcode, how it actually ends up at our sorting centre. So we know how it is sorted. And with that, we also know which type of recycler it will go' (#16)*. This could potentially be mainstreamed in the future, easing the problems associated with traceability. Better traceability through consistent data and information flows can be enabled through regulations, new digital and tracking technologies, better coordination across the supply networks and new business models.

About the quality of secondary plastics, many ISO/EN standards for recycled plastics have existed since 2007 (Villanueva and Eder, 2014). However, these generic technical characteristics of different recycled plastic polymer types are difficult to fit the different specifications of diverse applications in actual practice. As secondary plastic information regarding quantity, quality, availability and reliability presents still numerous gaps, actors in different areas of applications have been developing labels and/or platforms for information sharing. Some examples are selected from the interviews:

In packaging, some products indicate the percentage of secondary plastics used, using labelling schemes such as global recycled standard (GRS) and Blue Angel ecolabel. EPR schemes are also driving data collection around secondary materials in packaging.

In EEE, application-specific technical requirements may generate additional challenges for manufacturers using secondary materials, with important implications for information flows. An interviewee described their project working on developing a trading platform: *'If you want to produce a smartphone and you're looking for material out there for a second material, you are never really sure about the quality of the material specifications...We really want to put all the numbers on the material specifications online… If a seller has a material to offer, he should specify how much he has to offer and how long he can offer this material and with this quality... also, we want to indicate the reliability of the seller' (#24)*.

Some car manufacturers have developed their own grading system for recycled plastics to provide quality information codifying material properties of secondary plastics. An interviewee described, "*from the beginning, when I worked inside the [automotive manufacturing] group, everybody from engineering department said to me that, 'you have to take the same specification like virgin plastic'…. That's the reason that [ELV recycling] company and my company want to assure every time for each recycling grades have the same performance" (#9)*. This example also shows the process of transformation from data and information into knowledge through codification of know-how experience.

4.3.2. Knowledge development and diffusion

In addition to the developments in data and information explored above, there are ongoing efforts to develop, diffuse and codify new knowledge required for greater circularity.

4.3.2.1. Developing and diffusing knowledge: R&D and collaboration. The development of new knowledge depends on formal R&D, as well as learning by doing, and learning by interacting with suppliers, customers and others (Malerba, 1992). Formal R&D is important both because it increases technical knowledge specific to particular problems, but also because it builds skills and capacity that enable research active organisations to absorb new ideas developed elsewhere (Cohen and Levinthal, 1990). Both private and public R&D on circularity for plastics has increased in recent years, with the creation of new public funding streams specific to the circular economy from the European Commission and many European member states (Circular Plastics Alliance, 2021).

In recent years, companies across the plastics value chain have established collaborations and networks that facilitate learning-by-interacting. Such collaborations have aimed to overcome knowledge gaps created by a historical absence of collaboration across the value chain in a linear system. Several interviewees described their collaborative activities specifically in terms of addressing knowledge gaps. For example: '*We work together with third partners, R&D groups, technology developers, recyclers to develop chemical recycling of polystyrene…The recycling activities…required chemical producers because you need know-how to handle styrene…' (#3)*.

Some companies have developed formal collaborative networks. For example, we heard about a co-operative organisation with 70 members, across the value chain, developed in order to generate and share understanding about collection methods and tolerances for impurities in secondary plastics (PolystyreneLoop, 2019).

4.3.2.2. Codifying knowledge: purchase and design guidelines. An important mechanism for facilitating the diffusion of knowledge required for greater circularity is the codification of knowledge, in the form of guidelines, instruction manuals and so on. This includes: guidelines within firms, which help to co-ordinate design criteria, input purchase decisions, and so on; guidelines firms use to manage their own supply chains; and public guidelines produced to communicate to the entire supply chain. Interviewees described a range of examples, including:

- Procurement guidelines to overcome knowledge gaps about the opportunities to use secondary materials *(#15)*.
- Brand owners codified knowledge to manage their supply chains. An interviewee described their experience: *'The guidelines are out there based on our experiences. So, when we started the programme, we learned that it's not easy to use recycled plastic, so we have a lot of problems in the beginning… and then, quite often the final product didn't meet the requirements… So, we decided to be much more structured about how we do this…with guidelines' (#10)*.
- Guidelines for product designers to help them understand the characteristics of secondary materials*: 'And that's why we have design guidelines. … we have to show companies and manufacturers how they can use actually recycled plastics, what are the processes and production requirements for recycled plastics' (#24)*.
- Efforts by recyclers to develop guidelines for packaging designers, something that has been supported by the Plastics Recyclers Europe and Circular Plastics Alliance. For example, one recycler familiar with such guidelines explained: *'We're mainly looking at…Can your packaging be recycled? So, try to use mono-material, try to use the standard types of plastic that are used a lot, and recycled a lot. Don't choose sleeves or labels, all that kind of thing' (#16)*.

Both the packaging and EEE have had developed industry-level design guidelines specifically for plastics. Public guidelines in the EEE sector not only focus on design for recycling but also design from recycling (Berwald et al., 2021). Industry-level guidelines for automotive and construction products are still developing.

The paper remains subject to some clear limitations. In particular, the study design means that a) we did not interview consumers; b) the sample size was limited, given the broad coverage of application areas and value-chain stages, and; to further compare the drivers and barriers between different geographical regions would need a higher volume of interviewees. In addition, this study mainly focuses on the circular economy strategy of 'closing the loop', as the EU target is that 10 million tonnes of secondary plastic need to be used in the market by 2025. Nevertheless, the authors acknowledge the importance of other circular strategies in a plastic circular economy transition.

5. Conclusions

A system transition is required to reach greater circularity in the production and consumption of plastics and the achievement of SDG12. This paper has addressed a key gap in the literature, related to the role that data-information-knowledge play in hindering progress towards that transition. Unlike most previous studies, we examine barriers across the value chain, and in a range of application areas.

Here, we highlight the conclusions and main contributions from this analysis. First, we find that a circular economy is much more data- and knowledge-intensive than a linear economy, since it requires actors to access data, information and knowledge from across the entire value chain. Second, we show how these barriers are reinforced across the value chain, because of historically weak networks and communication. We further show that data-information-knowledge barriers relate to, and are reinforced by, diverse dimensions of the plastics socio-technical regime, including institutions, social norms, market and technology factors. This creates a 'web of constraints' that inhibits progress. Finally, we demonstrate differences across key application areas, highlighting those in which progress has been greater in codifying and institutionalising the data-information-knowledge that is necessary for a circular transition.

The findings have implications for policy and practice. Data and information can unlock significant value, by enabling the wider use of secondary materials and thus creating attractive propositions for green-minded consumers and for brands. In many cases, this can be enabled through strategies that are largely win-win, such as the establishment of standards, and the codification of guidelines and knowledge that facilitate mutually beneficial design changes. However, such initiatives may be hampered by high transaction costs, co-ordination barriers and weak networks. There is a clear case for public policy support for such efforts, and for R&D that underpins technology development.

However, the circular ecosystem is also one in which control and management of data-information-knowledge will be a source of competitive advantage. The companies we interviewed are increasingly investing in knowledge assets such as digital tracking technologies, databases and consulting services. From a public policy perspective, there is a case for policies that require data disclosure, since openness can benefit the system as a whole through knowledge spillovers. However, such policies would risk undermining incentives for entrepreneurial investments in data collection and processing. Further research is necessary to support policymaking that balances these competing objectives.

We offer some recommendations for stakeholders involved in the plastics value chain. Designers, plastic producers, manufacturers need to share information on quantity, quality, availability and reliability of product composition and secondary plastics, recycling instructions, and environmental impacts to their customers, end-consumers and recyclers. The upstream actors are encouraged to codify and diffuse knowledge on how to integrate secondary plastics within products. Brand owners, retailers and NGOs need to inform end-consumers about plastic recycling and the safety and environmental sustainability of secondary plastics. Recyclers need to educate the designers, plastic producers, manufacturers on how to design for recycling. Solutions to overcome the barriers regarding the traceability for both plastic waste and secondary plastics rely on digital technologies, business networks, labelling and certification. Technology support relies on technical startups, machinists, producers, manufacturers. Financial support relies on brand owners and governments, whilst the harmonised legislation, labelling and certification regarding recycling and secondary plastics rely on policymakers and third-party authorities.

Finally, from a theoretical perspective, the paper has illustrated the utility of a socio-technical perspective, which acknowledges that the interrelatedness of diverse elements (social, technical, legal etc.) in shaping the stability of the plastics system in response to pressures to change.

For the future research, we recommend addressing the drivers and barriers to the other circular strategies in a more holistic picture. Further MLP research of the plastic circular economy can analyse the other circular economy strategies such as repair, product-service system and alternative bio-materials.

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

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