



Whereabouts unknown – plastic tracing technologies for circularity

A global review of solutions, challenges and opportunities

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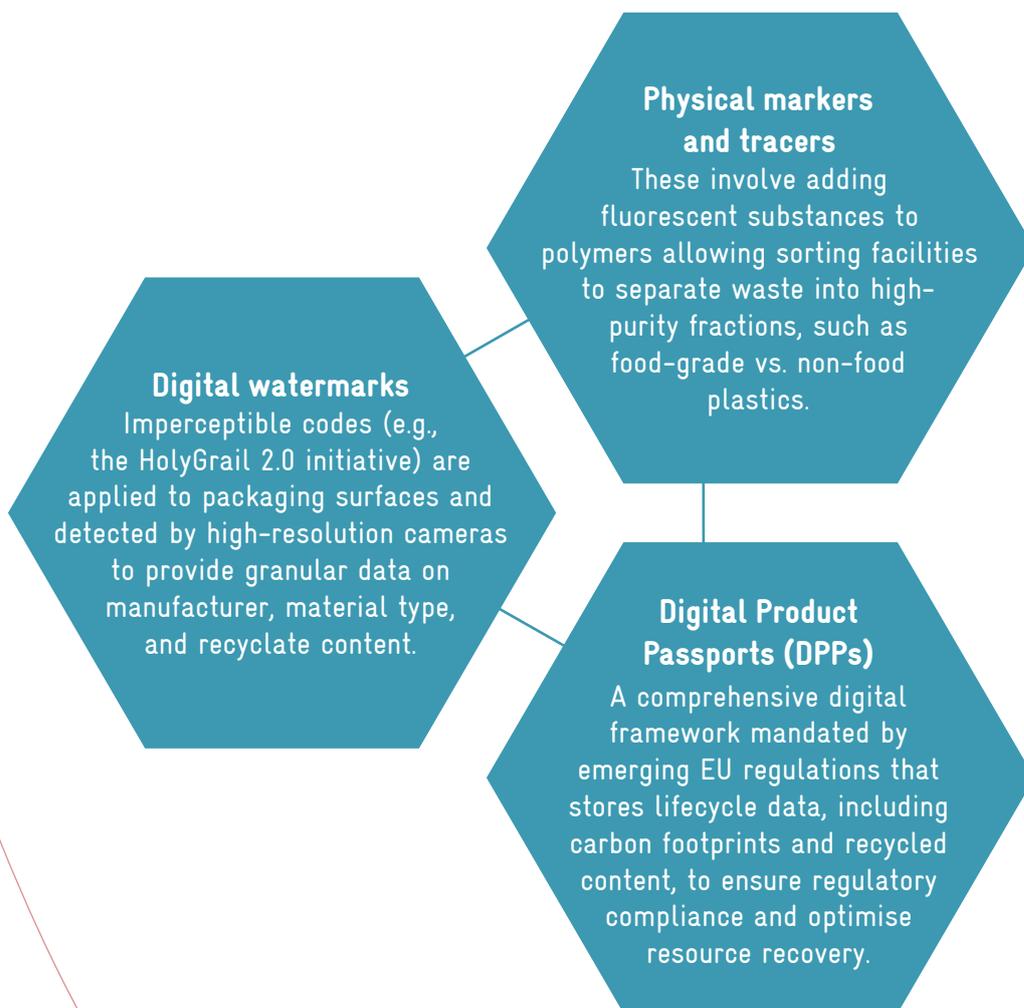
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Executive summary

The overall objective of this report is to provide a global review of the technologies, challenges, and opportunities associated with plastic material tracing as a key enabler for a circular economy. While plastic is indispensable in modern medicine and food systems, its global consumption is projected to double by 2060. Currently, only about 10 per cent of plastic is recycled globally, leading to significant environmental degradation, including microplastic accumulation and high CO₂ emissions. A primary barrier to increasing these rates is the ‘intransparency’ of the value chain; recyclers often lack critical data on the material composition and history of plastic waste, making it economically riskier and more expensive to process than virgin materials.

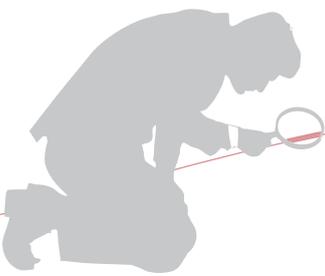
Against this background, the report identifies **three primary technological approaches** to bridging this information gap:

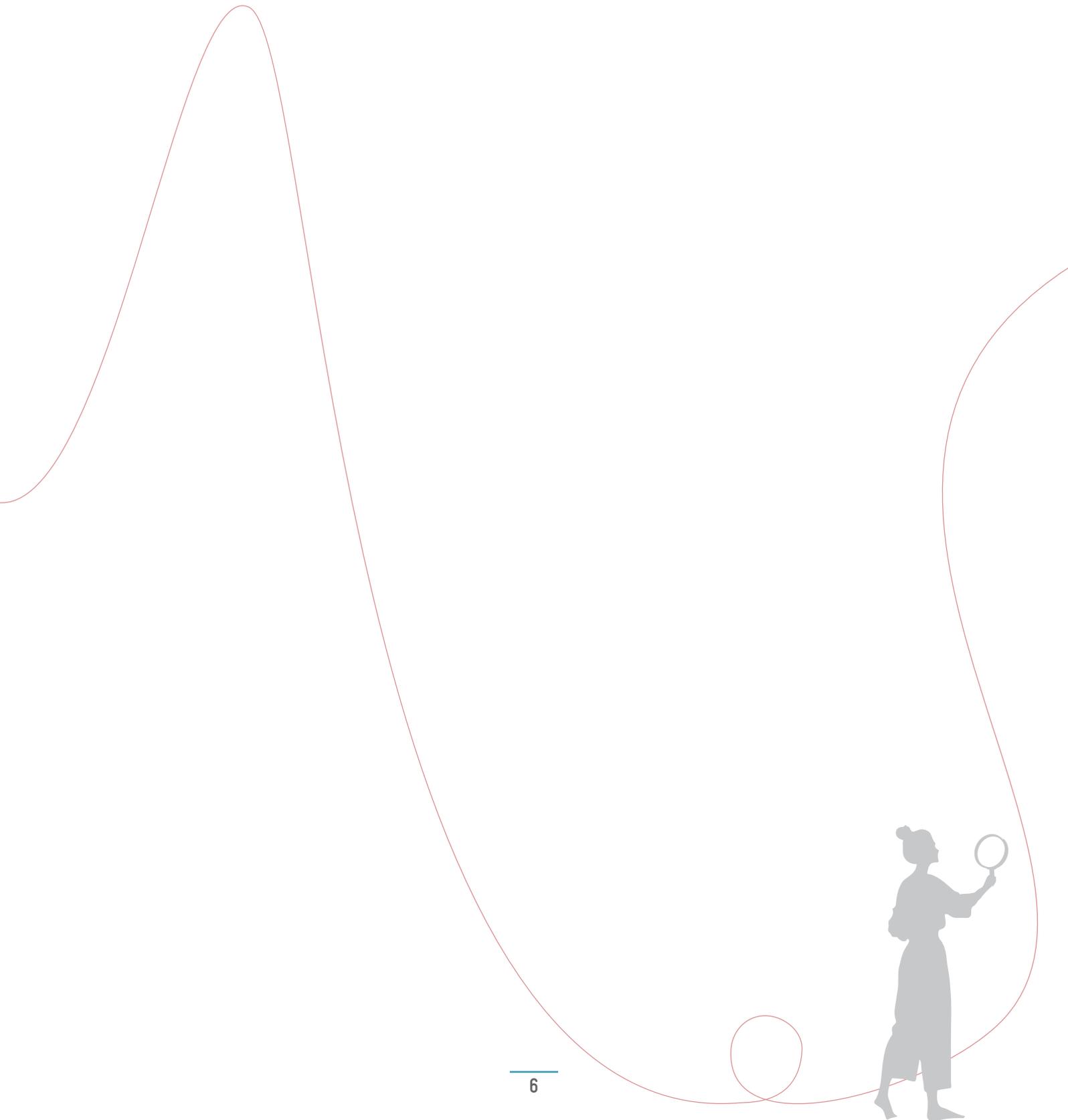


The implementation of these technologies faces significant hurdles, especially regarding a high capital intensity for sorting infrastructure and competition with cheap, subsidised virgin plastics that often make tracing investments unattractive without strong regulatory mandates like minimum recycling quotas. Beyond these general economic barriers, the report puts a specific focus on the Global South Perspective: There is a risk of a 'Circularity Divide', where high technology costs and specialised skill requirements exclude stakeholders in the Global South from international trade. In many regions, millions of livelihoods depend on the informal waste sector. High-tech, formal traceability solutions could potentially displace these workers if they are not intentionally integrated into the system's design.

In order to implement tracing technologies and at the same to contribute to true and comprehensive sustainability, the report recommends:

- **Leveling the playing field:** Internalising the environmental costs of fossil-based plastics to ensure recycled materials are price-competitive.
- **Upstream incentives:** Using tracing data to reward producers who design for recyclability through differentiated EPR (Extended Producer Responsibility) Fees.
- **Inclusive governance:** Developing global standards that are adaptable to local conditions and ensuring the informal sector is a partner in digital transitions.





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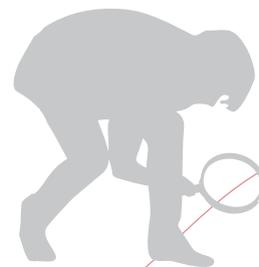
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Abbreviations

AI	Artificial Intelligence
BMUKN	German Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety
DPPs	Digital Product Passports
ELV	End-Of-Life Vehicles Regulation
EPR	Extended Producer Responsibility
ESPR	EU Regulation on Ecodesign for Sustainable Products
EU	European Union
NIR	near-infrared
NKWS	German Circular Economy strategy
PE	Polyethylene
PET	Polyethylene Terephthalate
PP	Polypropylene
PPWR	Packaging and Packaging Waste Regulation
SKU	stock keeping unit



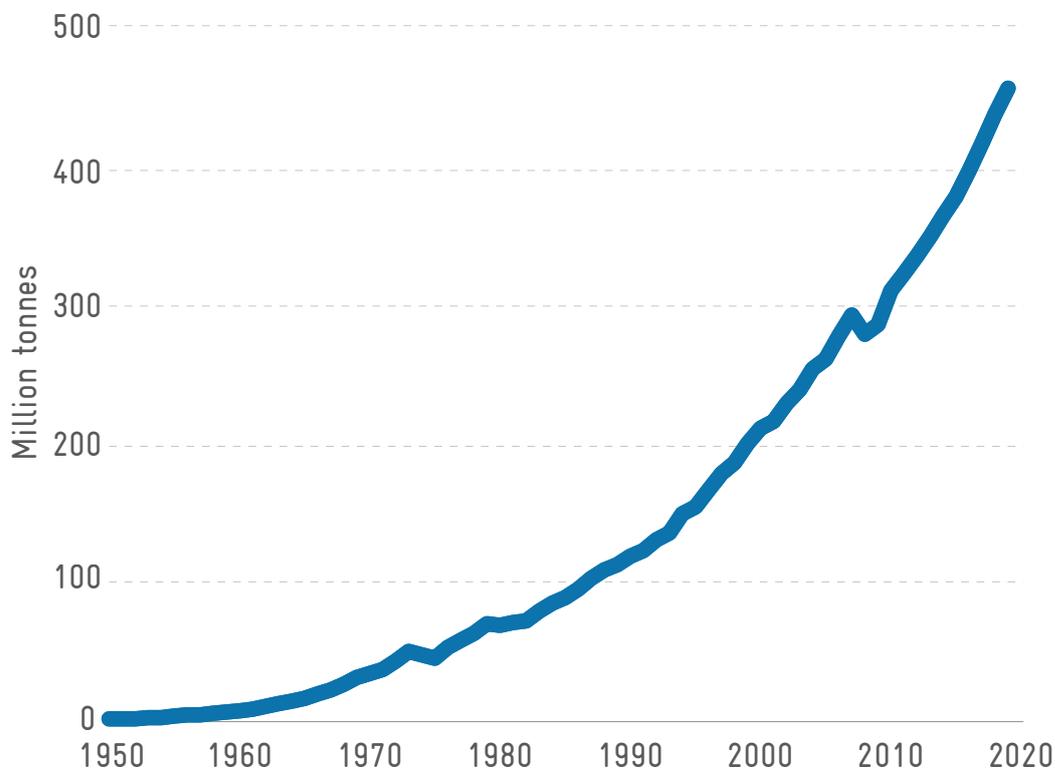
1 Introduction



1.1 The challenge of circular plastics

Within just a few decades, plastic has become an integral part of everyday life. Today, hardly any sector can be imagined without it – most notably the food system with its wide range of plastic packaging, but also mobility, construction, and modern medicine. Plastic’s main advantage lies in its versatility. Depending on the polymer type and the additives used, plastics can be extremely rigid or highly flexible; they can block or allow air exchange and UV radiation; and they can be manufactured in virtually any shape, size, or colour. One characteristic shared by all plastics is their exceptional durability. Combined with the availability of cheap oil as a feedstock, this has driven a continuous increase in global plastic production in recent decades (see Fig. 1). As a growing share of the world’s population moves to cities and adopts packaging-intensive consumption patterns similar to those of the Global North, even optimistic scenarios assume that global plastic consumption will at least double by 2060.¹

Figure 1 Global plastics production in recent decades, in tonnes



Source: Ritchie et al. 2023. Data source: Geyer et al. 2017; OECD 2022, OurWorldinData.org/plastic-pollution CC BY

¹ OECD 2022.

The very properties that make plastic attractive – low cost, versatility, and durability – become major challenges at the end of its life. Plastic waste poses a serious threat to ecosystems, particularly in countries of the Global South where waste management infrastructure is often insufficient to handle the volume of waste generated. These impacts are compounded by CO₂ emissions during production, largely due to the reliance on petroleum, the often poorly understood effects of potentially toxic additives, and the fragmentation of plastics into microplastics. Microplastics are now found even in remote regions such as Antarctica and increasingly accumulate in living organisms, including humans, with long-term health risks – such as genetic damage – still largely unknown. In this context, the regular ‘planetary health check’ clearly concludes that novel entities such as plastics have exceeded the so-called safe operating space.²

Plastic thus represents one of the central dilemmas of our time. Continuing current production and consumption patterns is incompatible with sustainability goals, yet completely eliminating plastic is equally unrealistic, given its essential role in critical applications such as medical care. Several Sustainable Development Goals – particularly those relevant to the Global South, such as poverty reduction and universal access to safe drinking water – cannot be achieved without plastic by 2030. Moreover, replacing plastic with alternative materials, such as aluminium packaging, could lead to even greater environmental burdens due to higher resource and energy demands. Improving plastic recycling is therefore crucial. Nevertheless, plastic is still predominantly used as a single-use material with extremely short lifespans, and only around 10 per cent is currently recycled.³

1.2 Intransparency as a key barrier to improved recycling

The largely linear use of plastics worldwide, combined with low recycling rates – even in countries with advanced waste management systems such as Germany – can be attributed to several factors. These include the failure to internalise environmental costs associated with fossil-based plastic production and, in some cases, direct or indirect subsidies, such as exemptions from energy taxes. As a result, recycled plastics are often uncompetitive with virgin materials, discouraging investment in improved collection, sorting, and recycling technologies.

One of the most significant barriers, however, is the lack of transparency throughout the plastics value chain. In many cases, it is difficult to determine where individual plastic products end up after being placed on the market. Consequently, it remains unclear where and how plastic waste is generated, who has used it for which purpose, or how often it has already been recycled. Yet this information is essential for accurately assessing the market potential of different plas-

² Potsdam-Institut für Klimafolgenforschung (PIK) 2025.

³ OECD 2022.

tic waste streams. When such data are unavailable or only accessible at prohibitively high costs, recyclers face significant economic risks. As a result, they often opt for disposal rather than recycling – through incineration or co-processing in cement plants in Germany, or landfilling in many countries outside the EU.

The OECD (2022) describes this problem in terms of transaction costs related to acquiring and verifying information. While data on material composition could, in principle, be obtained through laboratory analysis, the associated effort and cost often exceed those of using virgin materials, whose properties are well known and standardised. This lack of transparency therefore represents a key reason for the continued low use of recycled plastics. Uncertain information increases economic risk compared to homogeneous virgin materials, and recyclers frequently cannot achieve margins high enough to compensate for this risk. As a result, disposal remains the cheaper option in many regions.

A related transparency issue concerns the tracking of plastic waste under Extended Producer Responsibility (EPR) schemes. In principle, EPR requires producers to assume physical and financial responsibility for the end-of-life phase of plastic products, either by organising collection and recycling themselves or by commissioning authorised organisations, as mandated under regulations such as the EU Packaging Regulation. However, especially in the case of plastic waste exports – which are generally permitted only for recycling – there are repeated instances in which waste is not processed as intended. In such cases, it is often unclear who is responsible for plastic waste that ultimately ends up in landfills or the environment in countries of the Global South. This undermines producer responsibility and weakens the effectiveness of EPR systems.

1.3 Material tracing as an enabler for improved circularity

Against this backdrop, recent years have seen increasing debate on how to address the lack of transparency in plastics value chains. The EU Plastics Strategy already proposed the development of ‘smarter and more recyclable plastics’, alongside improved tracing and the removal of hazardous substances from recycled materials.⁴ Similarly, the European Commission’s Circular Economy Action Plan emphasises transparency, stating that digital technologies will play a key role in tracking, tracing, and mapping resource flows.⁵

Increasingly, regulation, particularly at the European Union level, put a strong emphasis to further develop the digital circular economy with the establishment of the necessary digital foundations. This is already very fundamentally incorporated in the strategies for the so-called Twin

⁴ European Commission, Directorate-General for Environment 2018.

⁵ European Commission 2020.

Transition (transformation to digitalisation and sustainability). Currently, the introduction of the Digital Product Passport is a focal point of these efforts – regulated in concrete details by the Ecodesign Regulation. This regulation, which was adopted in May 2024, will soon see numerous sectors delegate acts to introduce Digital Product Passports. Already by February 2027, the Battery Regulation will obligate producers to show product passports for certain battery types in electromobility and industrial applications, which puts pressure on the automotive industry, its suppliers and the chemical industry, among others. Digitalisation and the coupling of information flows on the one hand and material flows on the other also play a central role in the recently launched German Circular Economy strategy (NKWS). Interestingly, the NKWS already hints to the global implications of such strategies ('the Federal Government is cooperating closely with partner countries in the "Global South" to develop digital solutions and to establish product passports worldwide').⁶ This policy discourse mainly on the National and European level will have significant impacts also on stakeholders alongside globalised value chains – on the one hand allowing to demonstrate in a reliable way e.g. how plastic waste has been recycled and how this contributed to diversion from landfills; on the other hand, potentially excluding stakeholders without access to relevant technical infrastructures or data bases. It is thus unclear how increasing traceability would influence global trade relations. This publication aims to identify the influencing factors that will decide about the sustainability of such a technical innovation that now has to be embedded in specific socio-economic contexts.

The idea of tracing materials is one core element of a Circular Economy 4.0: Increasing the transparency of value chains by linking digital data and physical material flows enabling the analysis and ultimately optimisation of material flows and resource use. But despite the broad acknowledgement for the need of new digitally-based circular business models and the clear political will to support this, a prevailing challenge is still the absence of a universally accepted definition in literature, giving rise to a diffuse understanding of the subject – inter alia with regard to insufficient data on secondary materials and used products or the absence of temporal information essential for tracking transition dynamics.⁷

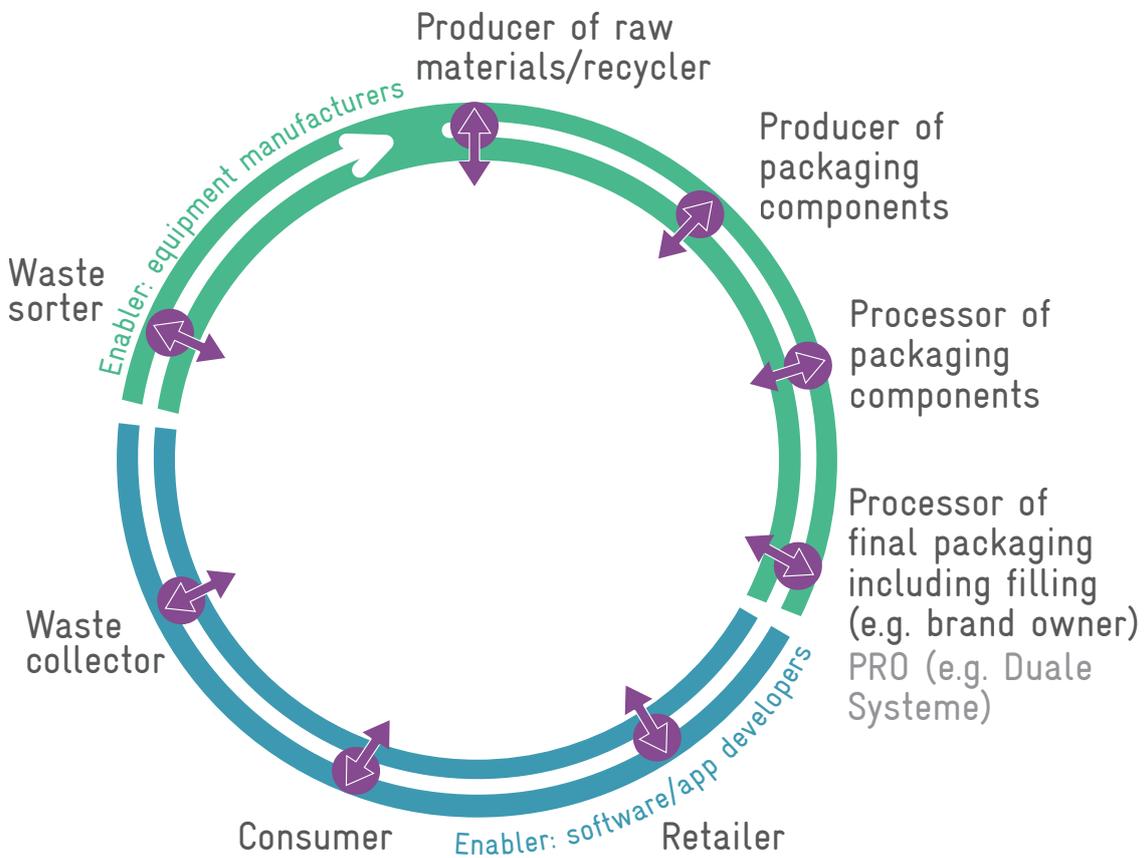
Against this background, the following publication aims to provide insights into one specific element of such a digital circular economy: The tracing of specific materials alongside the value chain focusing on the example of plastics and specifically plastic packaging. In this context, 'tracing' is understood as any technological concept that increases the level of information about the composition, the material quality or the final fate of plastic products. Tracing alone will clearly not be the final solution, but as illustrated in the following figure 2, it might be a key element that could enable new cooperation between different stakeholders in the context of a Circular Economy 4.0. The figure illustrates the complex interactions of different stakeholders taking part in the production as well as the use and recycling of plastic packaging. They have different

⁶ Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (BMUV) 2024.

⁷ Araujo et al. 2025.

roles, responsibilities and obligations in order to achieve and support circular processes for plastic packaging. Already here, it becomes clear that efficient circular processes between all stakeholders involved cannot happen unless data is structured and shared through a common business language.

Figure 2 Circular packaging value network



Source: GS1 Germany GmbH, 2023.

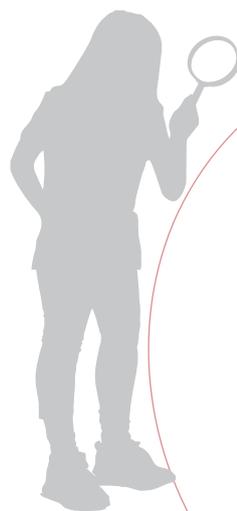
1.4 Objectives and structure of this publication

Against the background of this complex and dynamic development, the aim of this publication is to provide a practical classification of the potential of material tracing for plastics:

- What approaches to tracing already exist? How are they already used, for which plastic applications and/or purposes? What are their respective strengths and weaknesses, and what opportunities and risks do they present for future development?
- A specific focus will be on the perspective of stakeholders in the Global South: To what extent are they already involved in relevant processes today? How might they benefit from these developments or possibly suffer from being excluded from future business areas?

The scope of the analysis has been limited to tracing approaches that cover the full life cycle of plastic. Various tracing solutions that focus on the collection of plastic waste, monitoring of such activities or ensuring compliance with regulatory requirements are not part of this publication to allow a strong and clear focus on the guiding question of how tracing could contribute to a comprehensive circularity of plastics.

To this end, the following Chapter 2 develops a framework that explains the tracing concepts beyond the specific technology and describes the ecosystem conditions needed for tracing to actually function effectively. Chapter 3 builds on this by presenting selected tracing concepts and the business models based on them. Chapter 4 discusses the resulting opportunities and risks, particularly with regard to stakeholders in the Global South. The final Chapter 5 draws conclusions for the further development of necessary framework conditions, including in the context of the negotiations for a UN Plastics Treaty. The publication draws on literature review and interviews with experts from academia, the private sector and civil society.

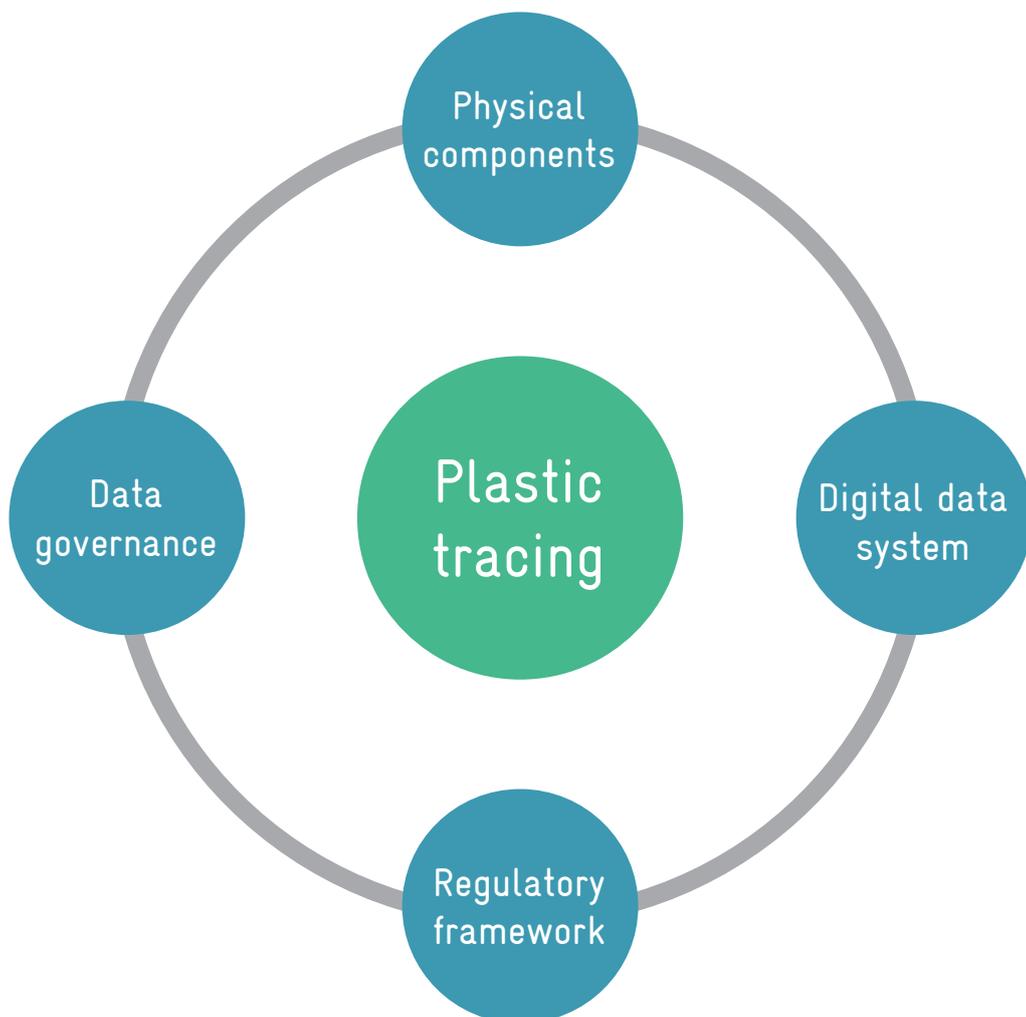


2 Analytical framework for material traceability



The analysis of different systems that enable traceability of plastics requires a clear definition of what exactly is meant by ‘traceability system’. Particularly from the perspective of the Global South, it is essential to consider not only the technological aspects, but also the broader conditions that determine whether such technologies can be meaningfully applied in practice. Following Gazeau et al. (2024), a distinction should therefore be made between physical and digital key components of the system (Chapter 2.1) and aspects of use (Chapter 2.2). This differentiation is therefore aimed less at comparing technical solutions, but rather at their efficient applicability for specific use cases – which are presented in the following Chapter 3.

Figure 3 Elements of a plastic tracing ecosystem



Source: Own Illustration, 2025.

2.1 Physical and digital key components of the system

As described above, the starting point for all systems for the traceability of plastics is the idea of transferring certain data along the value chain or making it accessible to various stakeholders, who could then use this as a basis to increase the circularity of the material. This immediately raises the question of what specific data should be collected. Potential information may include information on the manufacturing process or specific material qualities, but also on the distributor or actors responsible for proper disposal.

Building on this, the next step is to answer the question of what type of data carrier might be most suitable for the previously defined purpose. The spectrum ranges from physical imprints (watermarks, barcodes) to data carriers integrated into the material/product (RFID, markers) to purely digital systems. Closely related to this, in turn, is the specific question of the positioning of the data carrier – on the product surface, within the product, or similar. The efficiency of the respective solution always depends heavily on the respective product, which is then subject to various external conditions throughout its life cycle, such as moisture, contamination, or, as is usually the case with plastic packaging, compression in trash cans.

In addition to the data storage device itself, a technical infrastructure is also required that enables both the storing of data and its retrieval and use. Key factors in evaluating the system include the necessary investment, as well as the ongoing costs of operation and maintenance.

2.2 Key elements for the usage of traceability systems

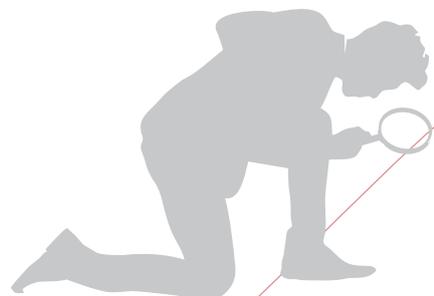
With regard to the actual use of the respective systems, additional questions arise that are much more focused on the ecosystem in which they are deployed. Treick et al. (2021) differentiated those ecosystems according to which specific circularity R-strategies the tracing system should be used for – from traditional waste management (recovery, recycling) to lifespan extension strategies such as repair or remanufacturing to more systemic approaches like reduce or refuse.

A second central aspect for the integrated assessment of such technical systems is the question of data governance, which can be designed very differently in all its facets. Right at the beginning, this concerns the question of who will be involved in the decision-making process for establishing a traceability system and who will ultimately make the decisions here, including on the selection of the specific technical components. During the operation of a system, a decision must then be made as to who is responsible for the selection and quality assurance of the data that is to be stored or used for traceability. Closely related to this is the question of how and by whom this data is kept up to date and, if necessary, at what intervals it is updated. Access to such data and thus the possibility of traceability of a material also largely defines the design of the under-

lying business model – which service require payments, and conversely, who bears the associated costs for development, operation and maintenance?

Considering the current status of plastic waste recycling in countries of the Global South, the question that particularly needs to be addressed is whether and how the informal sector and its interests can or will be included in the design of such a system. In addition to the costs to be borne, the question of the necessary skills specifically for using the data plays an important role. The consideration of open access criteria can be seen as a guideline here, as can the interoperability of systems.

All of the factors mentioned here are significantly influenced by the regulatory framework, which governs the establishment and use of plastics tracing systems from the local to the international level, or finances them through dedicated funding instruments. This, in particular, determines the extent to which actors in the Global South are either supported in their activities by the implementation of such systems – or potentially forced out of the market.



3 Proof of concept – existing good practices



Given the market potential associated with transparency along the plastics value chains and the increasing public attention, various approaches for implementation have emerged in recent years. Two very different approaches are presented below, both of which are considered global best practice examples for contributing to the circular economy through data transfer – on the one hand, the concept of ‘digital product passports’ and on the other hand the concept of attaching data to physical components. Both target different groups, have different functionalities, and are therefore based on different business models. Nevertheless, the comparison can help to better classify opportunities and risks, especially from the perspective of the Global South.

3.1 Physical tracking via markers or tracers

Physical tracking can be implemented either through an optical identifier (a marker) or by adding material to the polymer matrix or surface (a so-called tracer). The information embedded in the marker or tracer needs to be retrieved, identified, and compared with a database in order to decide how the lifetime of the plastic material can be further prolonged or treated.⁸ Over the last years, various systems of physical tracking for plastic products have been developed and tested to address the lacking transparency of the value chain. The following sections present two such systems based on tracer and (water-)marks.

One of the available tracing technologies for plastic products has been developed by the German company Polysecure and is based on the use of tiny amounts of fluorescent additives (tracers) on or in objects that glow in a specific colour after suitable stimulation (see the following figure 4). This signal can be assigned to a tracer sorting code which specifies the respective sorting fraction. In this way plastic waste can be separated into distinct fractions that can also be recycled separately to achieve higher quality and sorting rates (e.g. PE non-food vs. PE food packaging).⁹ The resulting process comprises three main steps at a single stage: singulation of the material to be sorted, combined detection and storage in fractions.

⁸ Rumetshofer et al. 2023.

⁹ Moesslein et al. 2023.

Figure 4 Detection of tracers in flakes of construction materials



Source: Polysecure GmbH, n. d.

The use of fluorescent tracers makes it possible to identify a material-independent separation characteristic, allowing sorting into relevant, specification-compliant fractions aligned with the ideal recycling path – independent from the main type of plastic that is currently used as the

starting point for sorting (e.g. PET, PP, ...) or the look of the product. This ability of sorting lines to differentiate and separate highly specific subfractions into pure types creates the basis for high-quality recyclability. The tracer materials are rare earth compounds that glow with a characteristic 'colour' under special excitation conditions. This highlights that additional resource requirements for better sorting always have to be balanced with the potentials of improved circularity, especially when using non-recyclable materials like the rare earths used here in tiny amounts. The emitted fluorescent signal is ideally suited to quickly and reliably identify and sort packaging and other materials that move quickly and chaotically, are deformed and contaminated, and come in a wide variety of printed and unprinted versions. Based on the combination of various tracer materials, Polysecure has developed a sorting code system that helps make packaging and other materials potentially circular and recyclable because they can be sorted precisely and reliably.

The key requirements in the development of the tracers were maximum efficiency and biocompatibility of the materials used. Significant progress has already been made during the development process towards reliable detection also at lower tracer concentrations. Furthermore, the company's previous toxicological studies and migration tests indicate that approval for use in food contact applications could be expected.¹⁰ Tracers can be applied to packaging, for example, using conventional printing processes or via labels, and then washed off or removed with the printing ink during the recycling process. Alternatively, the tracers can also be dispersed in the plastic as a permanent dopant. Moesslein et al. (2023) have shown that the tracers survive multiple extrusion cycles and other stresses without negatively affecting the properties of the plastic itself. As a component of the plastic, they could be used by producers and distributors to ensure the quality of recyclates and compounds.

With regard to optimising the technology, the focus was particularly on demonstrating a closed recycling loop on an industrial scale for food packaging based on mono-polyethylene (PE). To enable appropriate reuse as a food contact material, EU Regulation 282/20082, among others, stipulates a purity requirement of >99% for the sorted PE food packaging fraction from the post-consumer waste stream. This criterion cannot be derived from the material properties of the packaging itself, so Polysecure's tracers are used as an additional sorting criterion for specific marking and sorting. To enable tracer detection for older near-infrared (NIR) sorting systems, recognising different materials not based on secondary properties as colour, transparency or density, but detecting absorption of NIR radiation which is a primary property of the material, Polysecure has also developed a technology called 'TBS-light' that can be integrated at lower costs into existing NIR sorters to enable tracer detection. This eliminates the need for costly new cameras, additional computing power, or strong light or excitation fields – nevertheless the system still costs approximately €10,000 per meter of bandwidth.

¹⁰ Moesslein et al. 2023.

3.2 Digital watermarks

An alternative approach to allow a comprehensive tracing of plastic waste are so called ‘digital watermarks’. These specific watermarks are imperceptible codes of the size of a post stamp covering a significant surface of a packaging. These digital codes can be either integrated into the artwork of a package (2D) or onto the 3D surface of the pack by mold modifications.¹¹ These codes can be detected and decoded by high-resolution cameras in the sorting line. The identified code can be compared with a database, and thus detailed information about the material composition can be obtained. This allows a very differentiated and accurate sorting of packaging: e.g., product specific sorting for rejection of specific products (e.g. silicon cartridges) and even dividing streams into food/non-food or further into detergent/cosmetic grades. Like tracers, digital watermarks not only allow advanced detection but also advanced sorting by using the full dataset of the packaging including origin, age, additives, time of manufacturing, information about the packaged material itself or the specific content of recycle.

There are two technologies: On the one hand, digital watermarks for print consist of repeated tiles, whose pieces can be combined together to provide a barcode, that are applied by the encoder in a mosaic manner, as seen in figure 5. This process does not require any special inks or printing processes. On the other hand, digital watermarks for molds are the result of micro-topological variations in the substrate of the mold, creating signal tiles.¹²

Figure 5 Digital watermarks

Human eye

Digital watermarks are subtle marks printed all over packaging but are invisible to the human eye.



High-resolution camera

These watermarks can be detected by high-resolution cameras on a conveyor belt at a rate of 3m/s.

They carry information – like material type and use – that greatly increases the accuracy and speed of sorting plastic packaging.

Source: Digital Watermarks Initiative HolyGrail 2.0, n. d.

¹¹ Digital Watermarks Initiative HolyGrail 2.0, n. d.
¹² AIM 2024.

These optical barcodes in the form of digital watermarks can carry a wide range of attributes, such as manufacturer, stock keeping unit (SKU), type of material used, composition for multi-layered objects, or food versus non-food usage. One of their most valuable advantages is the infinite number of codes that can be assigned to a digital watermark. Furthermore, digital watermarks don't require chemicals to be added to the packaging when they are applied or embossed, contrary to nonpermanent markers/tracers such as described above. The idea is that once the packaging coded with digital watermarks has been used and disposed of by consumers and entered into a waste sorting facility, the digital watermark can be detected and decoded by a high-resolution camera on the sorting line. Based on the transferred attributes, for instance, whether the packaging is for food or non-food, the system is able to sort the packaging in corresponding streams. This results in better and more granular sorting streams, and consequently in higher-quality recyclates benefiting the complete packaging value chain.

The technical viability of digital watermarks for accurate sorting of packaging waste as well as the economic viability of the technology at large is currently further assessed in the multi-stakeholder cross-value chain project 'Holy Grail 2.0.' Under the lead of AIM (European Brands Association) and with the support from the Alliance to End Plastic Waste, this project started in September 2020 and involves more than 160 companies and organisations. It aims to bring the technology to semi-industrial and industrial scaled level. The basic idea is to open up new recycling streams, effectively overcoming limitations of current NIR sorting technologies and driving a true circular economy for packaging. Digital watermarks can connect packaging material and packaging with all information needed for a digital passport. With these features, HolyGrail 2.0 goes beyond other sorting technologies, which solely use optical shape detection or pure material detection by NIR. It does not need extra installations except a high-resolution camera which is installed with a growing number of sorting machines anyway. The initiative follows the pioneering project HolyGrail 1.0 (2016–2019), which was facilitated by the Ellen MacArthur Foundation and brought together different stakeholders from the packaging value chain. At the end of HolyGrail 1.0, the branded consumer goods industry decided to develop a platform to take the initiative to the next stage.¹³

Intelligent sorting by digital watermarks requires accurate and up-to-date information on a whole range of essential attributes of the packaging. Identification of packaging components and finished products through global, open, and unique identifiers (transported and provided by the watermarks) is key to allow technologies to be connected or integrated and to ensure scalability and interoperability. This holds the potential to become the basic language for data capture, data storage, and data sharing. The information about essential attributes for sorting/recycling must be stored in a powerful cloud-based database platform to enable a secure and continuous exchange of master data with the sorting equipment. It is also important to apply fundamental information systems security principles to ensure confidentiality and integrity of data. For these

¹³ AIM 2024.

kind of challenges, HolyGrail 2.0 offers the potential for a standard for data governance that of course has to be supported by opening the technology to digital watermark providers and readers. In order to go beyond pilot projects to an actual broad application, the consortium now aims to develop ‘landing strips’ from national markets like Belgium, the Netherlands, Germany, and Denmark. Ideally, a successful demonstration of the technical and economic viability of the technology would inspire more countries and waste management operators to implement this new sorting technology.

In a future outlook, HolyGrail 2.0 aims to enable a closed loop return of packaging and packaging material for individual manufacturers for their own reuse or recycling. Even if today’s economic conditions do not yet favour individually closed loops, advances in automation and logistics technologies can change the economics. This could incentivise additional investments into the recyclability, durability or reusability of packaging materials. Digital watermarking also needs to be continuously benchmarked with other upcoming technologies like object recognition, in particular when these technologies are connected with artificial intelligence. In such an integrated system, digital watermarks could potentially provide much more benefits than for sorting/recycling. They could offer added value during the full life cycle of a package: from full details on composition along the supply chain over quality control in producing plants to fast checkouts at retailers and consumer engagement (in store/at home). Especially in the field of consumer engagement, digital watermarks have huge potential. While today, many packages have leveraged the QR code because it has native scanning ability with current cell phone technology, in the future, there is the potential to leverage digital watermarks in the same way.¹⁴ By doing so, it is possible to extend consumer interaction with the product digitally, providing added multimedia information. For example, one can envision how scanning the package via its digital watermark in the future could link to information (a video or web content) indicating how to recycle the item. There is also value for governments, as digital watermarks would allow for the first time to quantify very precisely collection, sorting, and recycling rates with a granularity down to levels of single stock keeping units (SKUs). With this improved transparency, governments would be in a much better position to meet the ambitious national recycling targets, e.g. as targeted by modulation of EPR fees.

3.3 Advantages and disadvantages of tracers and watermarks

Technologies like physical tracers or digital watermarks offer significant opportunities to improve the sorting of plastic waste: They provide additional information about the composition of specific waste streams as well as about single plastic products and their material characteristics. Such information allows steering defined plastic waste fractions to higher quality recycling processes that otherwise would be incinerated or landfilled. The two general approaches present-

¹⁴ AIM 2024.

ed above differ with regard to the quality requirements of the waste material input: Recognising watermarks might be easier if the waste is not too contaminated and the surface of the material can be analysed; on the other hand, the use of tracers requires additional resources and changes to permanently add new substances that cannot be removed by mechanical recycling processes.

Both options require the installation of additional technical infrastructure to sorting processes and thus of course investments that might be challenging especially for developing countries. In return, both options offer extended business models if the waste can be sorted into fractions of higher purity and quality that can be sold for higher prices. However, such investments might exceed the financial capacities of many stakeholders in this value chain. Comparing the two approaches, the necessary additional costs for adding markers to the material might be higher, at the same time the necessary investment costs for the sorting infrastructure lower. In both cases, the necessary skills for using the technology are relatively low and should not represent a barrier e.g. for stakeholders in the Global South. The existence of competing systems should also prevent the emergence of monopolies or other market-hindering phenomena. From a circular economy point of view, it is mainly an ‘end-of-pipe’ approach. It focuses on the treatment of waste with limited potentials to improve the circularity or recyclability of products. Its key advantage lies in creating incentives to increase the share of plastic waste that is recycled instead of land-filled.

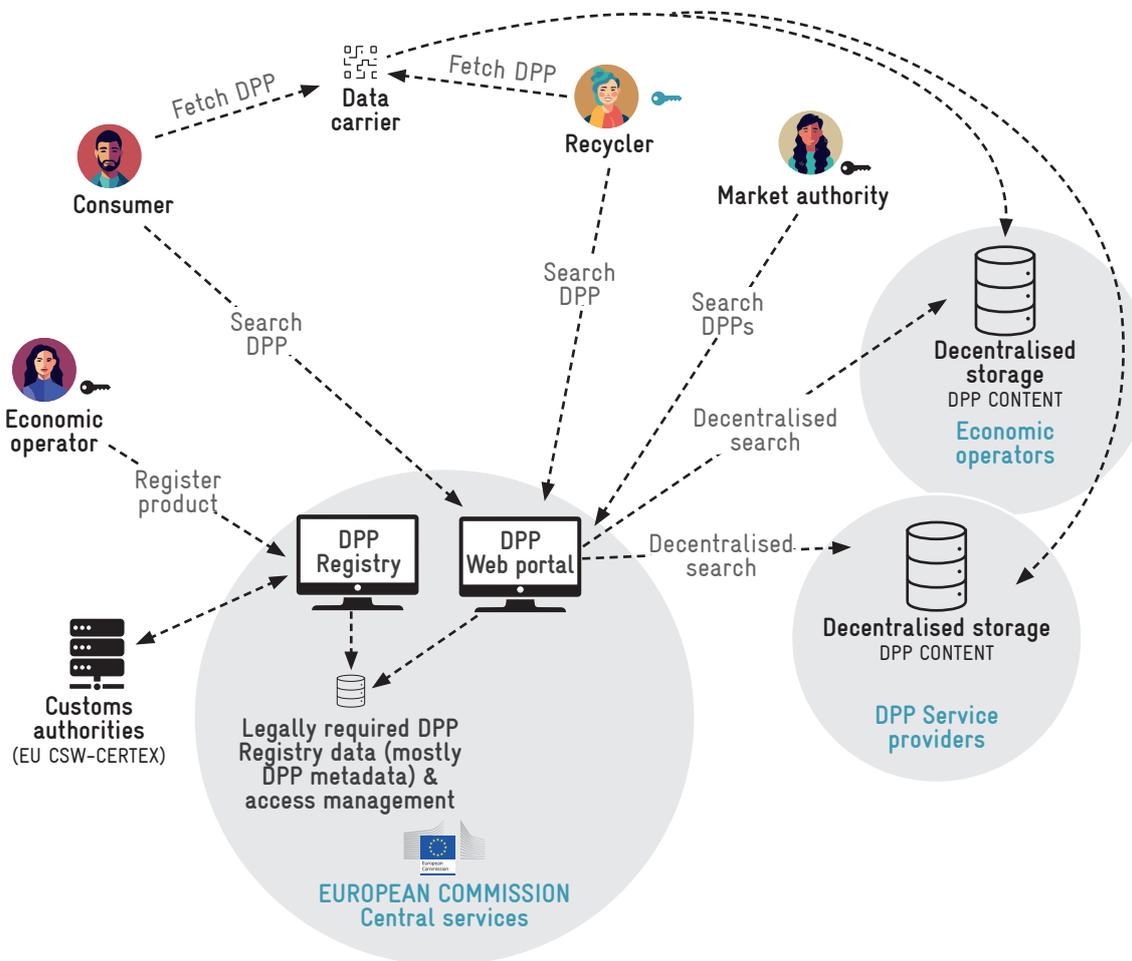
3.4 Digital product passports for plastic packaging

A third, conceptually even more ambitious and comprehensive approach to tracing materials such as plastics is the establishment of Digital Product Passports (DPPs). DPPs are still in development but are expected to play a key role in facilitating innovative circular approaches by enabling the exchange of information on the sustainability parameters of products, such as their carbon footprint and recyclability, across value chains. A DPP is a product-specific, electronically accessible dataset. The dataset is permanently linked to the product via a unique product identifier and is intended to be based on open, interoperable standards.¹⁵ This means that every product with a DPP will carry a unique code through which it can be identified. Product specific data can be provided to the DPP user upon request. The identifier is placed on the product with a so-called data carrier which can come in different forms like watermarks, RFID chips or QR codes. The applicable data carriers will depend on product specific regulation. The standardised and machine-readable information is provided by the economic operator bringing a product to the market and stored by this operator or a service provider on decentralised servers. The DPP data under current designs will not be stored directly on the data carrier, see also figure 6 for illustration.

¹⁵ The European Parliament and the Council of the European Union 2024.

The DPP serves as a central information point for the circular economy by providing comprehensive data on the entire life cycle of a product. This includes, for example, information on materials used, hazardous substances, the ecological footprint, as well as repair and dismantling instructions or disposal guidelines.¹⁶ By adhering to open-data principles, the DPP facilitates cross-sectoral data exchange and enhances cooperation between businesses, consumers, and authorities.¹⁷

Figure 6 The DPP System as envisioned by the European Commission



Source: adapted from GS1, 2025.

16 Alcayaga et al. 2024.
17 European Commission 2025.

3.4.1 Background and functions of the DPP

At present, the development of DPP is spear-headed by the European Union. Hence, in the following, the EU's current plans are being referred to illustrate the ongoing development. DPP development beyond EU borders is currently only emerging. Further below we introduce an approach under development by the Japanese company NEC. Based on the EU Regulation on Ecodesign for Sustainable Products (ESPR), issued as Regulation (EU) 2024/1781, the DPP aims to establish a framework for managing information requirements.¹⁸ A central promise of the DPP is to increase transparency along supply and value chains as well as towards the general public. This makes the DPP a digital instrument for the electronic registration, processing, and dissemination of product-specific information. By harmonising information requirements, the DPP contributes to creating a level playing field for manufacturers within the European Union. The passport provides access to product-specific data. It provides relevant information to the specified actors in the production and consumption process as well as to authorities along the full lifecycle including end-of-life treatment. It includes essential information such as product composition, potentially hazardous substances, reparability and durability indicators, dismantling instructions or disposal guidelines, as the CO₂ footprint.

However, while the DPP is framed by the ESPR, supporting delegated acts regulating DPP content and functioning are still to be created. These delegated acts will provide rules and guidance for sectors and products falling under the ESPR (starting with textiles, tyres, furniture on the product level, and iron and steel as well as aluminium on the material level). There will also be technical and circularity-related delegated acts, for example determining the nature of identifiers and cross-cutting rules regarding reparability. Technical standardisation for the underlying system (the 'DPP-System') are being created until the end of 2025 and come into effect in spring 2026.

Access to the DPP will be differentiated by stakeholder groups on a need to know-basis. Consumers receive e.g. user-friendly information to support sustainable purchasing decisions, while market surveillance and customs authorities can access specific data to verify regulatory compliance and carry out targeted inspections. Economic actors such as manufacturers, importers, distributors, or recycling companies will likewise benefit from the facilitated exchange of information, which strengthens resource circulation and enables new business models. The DPP ensures that authorities can efficiently match products with their unique identifiers and the data stored in the European registry. This simplifies the enforcement of existing regulations and provides a higher degree of legal certainty. At the same time, the DPP can serve as an information tool for policy makers, with the data collected informing the further development of future regulatory measures.¹⁹

¹⁸ The European Parliament and the Council of the European Union 2024.

¹⁹ Alcayaga et al. 2024.

The scope of the DPP according to the ESPR is broad. The regulation stipulates that the DPP generally applies to a wide range of physical goods placed on the market or put into service within the European Union. This also includes components and intermediate products, as well as digital content that is an integral part of a physical product. However, certain areas are excluded, such as food and feed, pharmaceuticals, veterinary products, and living plants, animals, and microorganisms. An exemption is also valid for all products regulated under other regulations or directives. However, such other regulations already foresee DPPs for products, e.g. for specific batteries, cars or construction products. The latest edition of the European Single Market Strategy suggests an extension of the scope of the establishment of DPPs to basically all products on the EU market. Consequentially, this would mean the adaption or translation of the rules set by the ESPR for DPPs to most sectors in the EU.²⁰

3.4.2 DPP and Artificial Intelligence

DPPs are not linked to artificial intelligence (AI) by necessity. At present, the creation, transfer and reading of DPP should be possible without using AI. However, three potential applications are likely to emerge:

1. Automated Data Synthesis: Populating a DPP may require gathering complex technical specifications across global supply chains. AI could automate this ‘data harvesting’ by extracting information from company databases, industrial sensors and design files, significantly reducing the administrative burden.

2. Integrity and Interoperability: To ensure trust, AI might serve as a digital auditor for data validation or plausibility checks. It could be used to cross-reference data to spot inaccuracies or ‘greenwashing’, while also acting as a universal translator and harmonising semantics between different industries so information flows seamlessly.

3. Data Analytics: The true value of the DPP may lie in aggregated data. AI could analyse millions of passports to provide systemic insights, such as scrutinising global material streams, offering a powerful tool for resource optimisation and more effective regulatory oversight. Looking further ahead, these insights might also catalyse data-driven design refinements and improve decision-making processes for improved recovery of materials at a product’s end-of-life.

3.4.3 DPP implementation in the plastics sector

At present there are no regulations pertaining to the plastics sector specifically, or a specific type of plastics. However, several regulations will or might involve direct obligation to provide input

²⁰ European Commission 2025.

on plastic content for specific products, but this is as of yet a matter of speculation since delegated acts regulating DPP are not yet published.

Two product groups under the ESPR that are directly related to plastics are textiles (garments) and tyres. It is to be expected that both groups will have to declare the plastics content. In terms of tracing and tracking, tyre DPPs may also record lifecycle data, so that product-specific tracing is possible. Further DPP-relevant regulations in the EU are inter alia the Packaging and Packaging Waste Regulation (PPWR) and the End-of-Life Vehicles Regulation (ELV).

The PPWR itself does not prescribe a DPP for plastics packaging per se, but proposes that for products obliged to have a DPP, information regarding the product's packaging should be included. A hypothetical example could relate to the packaging used for garments under the textile DPP. While this does not mean tracing and tracking for any specific form of packaging, a different perspective may be taken for reusable transport packaging which also receives specific attention under the PPWR. Companies providing such packaging such as pallets made of plastic may want to provide them with a DPP, and in fact many of such goods can already be digitally identified and are being managed in various kinds of cycles. Another motivation of providing information to a DPP under this regulation may come from future obligations for a minimum recycle quota in plastics packaging which the PPWR foresees. DPP can be used to document and validate the recycle content of the packaging products concerned.

Similar rules apply to the ELV Regulation which is currently under negotiation in an advanced draft. The ELV foresees a Circular Vehicle Passport, which can serve to document the planned use of recycle plastics content in future cars. In a phased approach starting from the regulation's introduction, the ELV Regulation currently prescribes 15% of recycled content in a new car by year 6 after enforcement, 20% by year 8, and 25% by year 10. It is not yet clear when the ELV will finally enter into force, but it is reasonable to expect a decision within 2026.

As stated above, delegated acts do not yet exist. It is not possible to state what the exact information content of DPPs will be and these may vary from product to product and from polymer to polymer. However, for some products and materials preparatory work commissioned by the European Union and executed by the Joint Research Centre (JRC) may already provide some hints as they suggest informational requirements.²¹ For plastics and polymers, the following requirements are listed:

- Life cycle water consumption
- Level of life cycle emissions to water
- Possible release of non-biodegradable microplastics
- Level of life cycle emissions to air
- Content of sustainable renewable materials

²¹ Faraca, G. et al. 2024.

- Sourcing of raw materials from certified sustainable practices
- Recycled content
- Carbon footprint
- Share of energy consumption from low carbon sources
- Life cycle energy consumption

It should be noted that this list refers only to environmentally related indicators. Suggestions made for other product groups, e.g. for batteries, already hint to more encompassing datasets that include a range of information that is more aligned with the full ESPR information demand:

- General battery and manufacturer information
- Compliance, labelling, certifications
- CO2 footprint of batteries
- Due diligence in the supply chain
- Battery materials and composition
- Circular economy and resource efficiency
- Performance and durability

3.4.4 Current approaches towards a DPP for plastics

As the regulation is still emerging, DPPs for plastics so far mostly exist in the form of plans, prototypes or small-scale approaches. In the following we present such approaches.

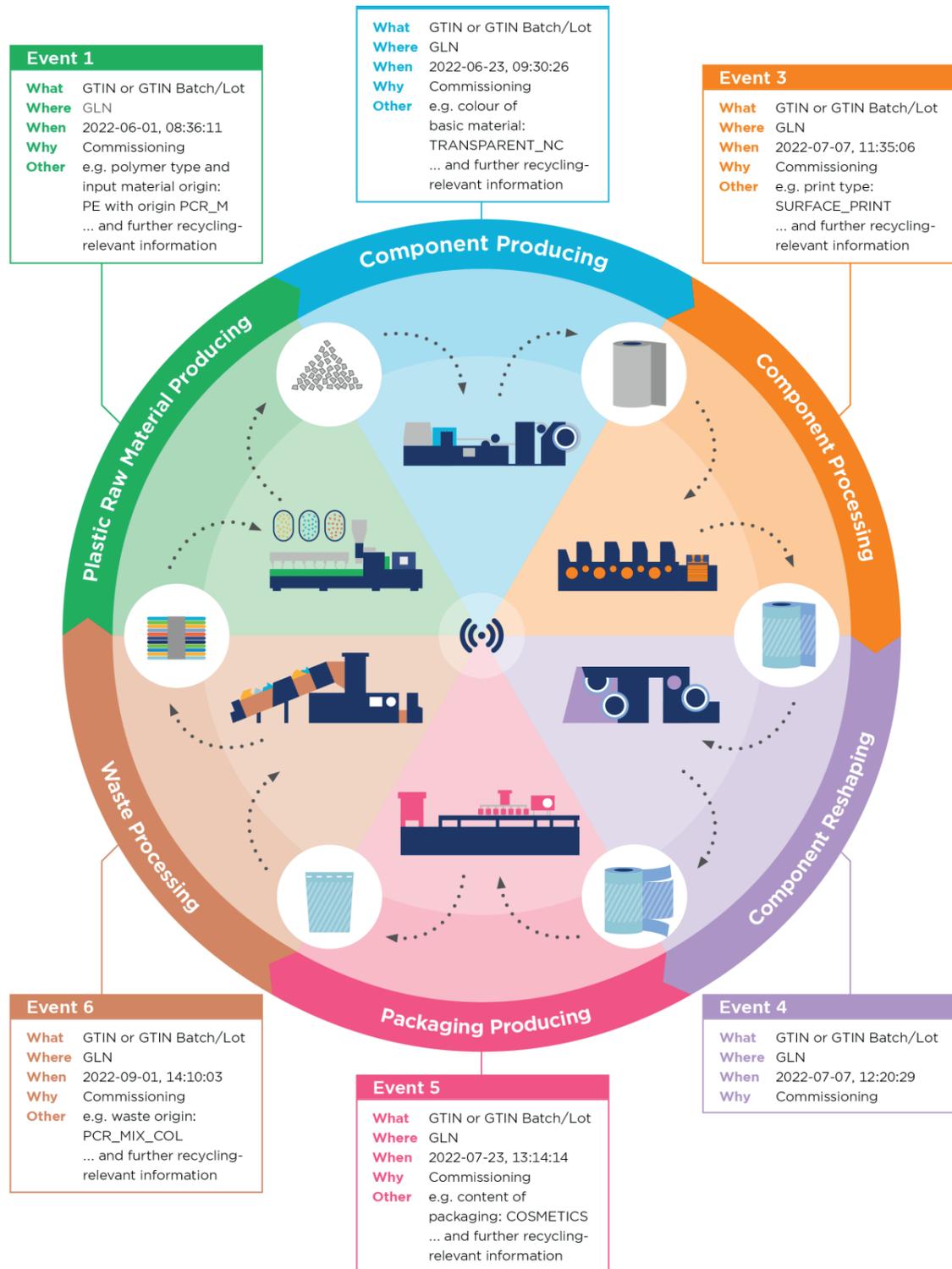
R-CYCLE

The initiative R-Cycle²² created an approach for DPPs for plastics packaging based on GS1-Standards. GS1 stands for Global Standards One, a globally operating, non-for-profit organisation, which develops standards for product identification and data exchange. GS1 standards are used to a high extent in retail. In the project PDS4CircularPlastics (Processes and data sharing approach for enabling circular plastics value networks) the initiative developed an application recommendation that describes the recycling-relevant process steps in plastics production and presents the required attributes for data transfer along the value chain. The following figure 7 illustrates the various approaches of the concept, based on integrated ‘events’. According to the initiative’s information, R-Cycle provides its own interoperable data infrastructure as a software service. Production, processing, sorting and recycling data can be integrated across the lifecycle.

Figure 7 indicates how the system data is handled and updated in the digital space throughout the material’s lifetime, and that this data can be used for recycling, but also given to research and analysis for development of improvements, or to a matching platform for sales.

²² R-Cycle, n.d.

Figure 7 The PDS4CircularPlastics framework



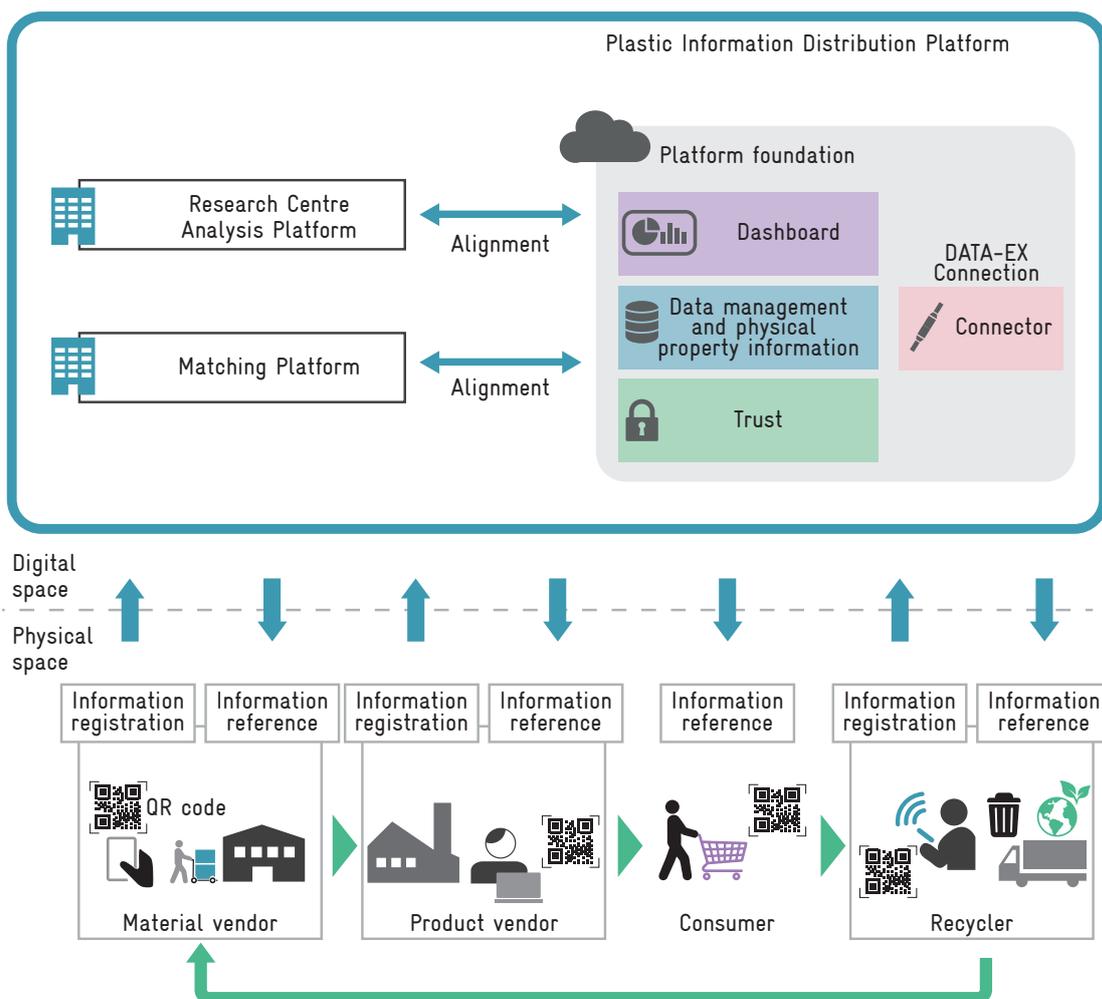
Source: GS1 Germany GmbH, 2023.

NEC

The Japanese company NEC has devised a prototypic ‘plastics information distribution platform’ to trace and manage the lifecycle of plastics as a R&D project.²³ The goal is a platform system to manage and visualise evidence of the material life cycle on a dashboard. The tracked stages include material development, product manufacturing, distribution, collection, and sorting.

Figure 8 indicates how the system data is handled and updated in the digital space throughout the material’s lifetime, and that this data can be used for recycling, but also given to research and analysis for development of improvements, or to a matching platform for sales.

Figure 8 NEC concept for a plastics tracing platform



Source: adapted and translated from NEC Corporation, 2024.

CIRPASS-2

The CIRPASS-2²⁴ project creates DPP in 13 pilot projects for different industries some of which involve plastics. Most notably, they focus on tyres, mattresses and textiles, but also electronic appliances and construction products. Funded by the European Union, it is one of the currently leading projects of DPP development worldwide. Among its chief goals is the deployment and validation of DPP for future scaling and in real-life conditions. Within the project, several different approaches to creating a DPP are tested. Next to the already mentioned GS1 technologies, other tested technologies include the Industry 4.0-linked Asset Administration Shell, a virtual ‘container’ for data that is stackable and hence able to create digital twins and DPP. CIRPASS-2 also hosts the Circular Data platform listing a host of currently existing DPP initiatives.

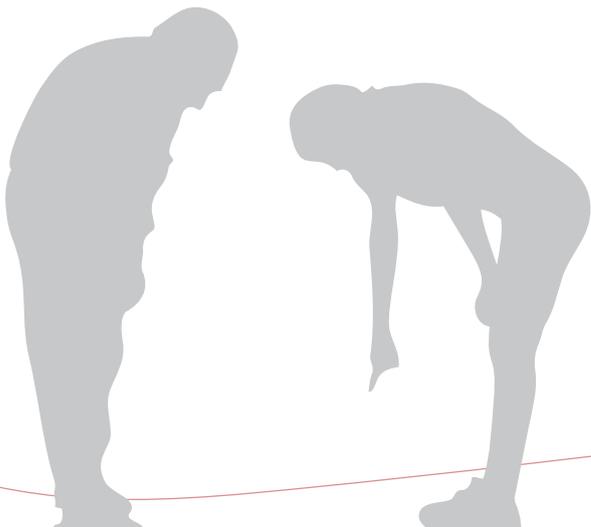
3.4.5 Advantages and Disadvantages of Digital Product Passports

DPPs offer several significant benefits for tracing and tracking plastics. Firstly, they facilitate robust data management as they possess the capability to hold, combine, and provide large amounts of information. This allows for a comprehensive history of the plastic product, detailing its composition, prior use, and end-of-life options. Secondly, they offer technological flexibility and accessibility: DPPs are not restricted to a single technology, meaning that several technological solutions are possible and combinable, promoting innovation. Furthermore, they can be created using existing means, lowering the barrier to entry for many companies. The ability to work decentralised also enhances data security and resilience. Finally, the concept benefits from growing global momentum, receiving increasing attention worldwide, with reliable systems emerging and gaining traction in major regulatory jurisdictions.²⁵ This suggests a future where they become a standard requirement for market access in many industries and economies. Hence, for tracing and tracking within and beyond value chains, DPPs can foster a more distinct and more informed selection of material e.g. with regard to attributes like recyclability or climate impact. They can also inform where a certain material or item of packaging is geographically but also in its lifecycle allowing for estimations of availability e.g. for use or recycling. It is important to state here that such chances will depend on the specific sort of plastics packaging. Not all types will lend themselves to the same form of effort due to economic and technical reasons. Insights gained through a prolonged use of DPP may then also influence market and product design so that packaging offered becomes more adapted to circular and sustainable requirements. Lastly, the more intricate insights provided by DPP may help to automatise and speed up administrative processes also on the side of the government and inform political decision making for the circular economy.

²⁴ CIRPASS-2, n.d.

²⁵ Alcayaga et al. 2024

However, despite their potential, the implementation and usability of DPPs for plastics faces several critical hurdles. A major concern is complexity and data overload: Depending on their established goals, DPP systems can be overly complex, and there is a risk of the system becoming data heavy and overshooting the actual needs of actors in the cycle. Collecting and managing excessive data can create unnecessary costs and complexity without adding commensurate value to recycling or reuse processes. Furthermore, there is a challenge related to speed and accessibility for end-of-life processes. A key disadvantage is that DPPs can be less suitable for applications like recycling when data cannot be accessed very quickly. Sorting facilities require near-instantaneous material identification, and slow or cumbersome data retrieval undermines the efficiency gains intended by the DPP. Lastly, a significant challenge is posed by standardisation and interoperability risks. As mentioned above, the necessary standardisation is still ongoing. This lack of established, universal rules means that it is currently unclear if emerging systems will be interoperable across different companies, countries, or technology platforms. A fragmentation could severely limit the overall effectiveness of DPPs in global plastic value chains.



3.5 Overview over the different approaches

The following table aims to summarise the key characteristics of the three different technological approaches presented in this chapter. It highlights that all three systems have specific strengths and weaknesses – with an increasing complexity and especially number of stakeholders that need to be involved.

Table 1 Key characteristics of the three technological approaches

	Physical tracers	Watermarks	Digital Product Passports
Contribution to the circularity of plastics	Significantly improved sorting of plastic waste, also for heavily polluted waste fractions	Significantly improved sorting of plastic waste	Contribution to circular business models and circular product requirements throughout value networks
Complexity of the system	Modular system that can be implemented by various stakeholder	Coordinated system with higher functionality	Highly complex system with cross-industry requirements and need for global coordination
Cost effectiveness	Moderate investment costs, low operational costs	Significant investment costs, lower operational costs	Massive investment agenda with high potentials for increased competitiveness of circular business models
Status of implementation	In use, inter alia for fraud prevention	Pilot implementation	Regulatory framework under development
Application	Different plastic waste streams, e.g. packaging and waste of electrical and electronical equipment (WEEE)	Packaging	Very broad range of applications, e.g. textiles, packaging, tyres
Data carrier	Tracers included in the material	Watermarks printed on the material	Decentralised data-based system, data carriers are being determined per sector/product group
Strength	Robustness, e.g. with regard to pollution	Strong network of supporting actors	Comprehensive approach, combing different data sets

Source: Own Elaboration, 2025.

4 Challenges and barriers of plastic tracing



The implementation of the technical approaches selected here for improved traceability of plastic flows has considerable potential to transform the currently predominantly linear handling of plastic towards a circular economy. However, there are various challenges and barriers that need to be addressed for truly circular and sustainable solutions.

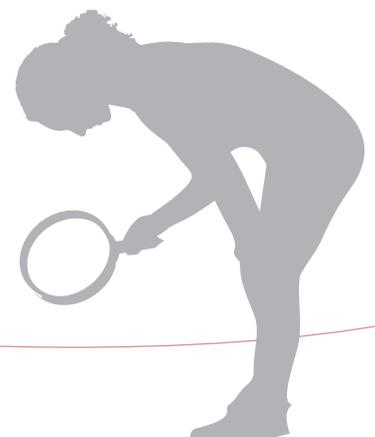
4.1 Plastic recycling – ecologically beneficial, but no excuse for excessive use of plastic

By providing information – be it via markers, watermarks, or DPPs – it becomes possible to automatically sort plastic waste into different waste fractions, which can then be recycled for higher-quality purposes. The key advantage lies in the supplementation of information on the composition of plastic waste, such as colour or plastic type, which can currently be recorded either manually by workers or automatically via NIR detection systems. Given the complexity of plastic packaging, especially with multilayer designs or combinations of different materials, such tracing systems offer the possibility of routing individual packaging to the optimal recycling process.

In particular by identifying materials of such high quality that they can also come into contact with food, they could make it possible to replace significantly more primary plastic with recycled materials in this area in the future. Currently, almost exclusively material from deposit return systems can be used for food applications.

Various life cycle analyses illustrate the positive environmental effects that could be achieved through the increased use of recycled material.²⁶ High quality recycled materials have a significantly lower carbon footprint compared to virgin material. However, also the recycling process itself causes environmental impacts – recycled plastic is by far not climate neutral. The environmental benefits of recycling processes could be further increased when using renewable energies, e.g. from photovoltaics. Nevertheless, high quality recycled materials have a significantly lower carbon footprint compared to virgin material.

²⁶ Saleem et al. 2023.



Even the technical optimisation of plastic cycles through the use of tracing technologies must therefore not call into question the principle of the waste hierarchy: plastic should only be used where it contributes to sustainability goals; the avoidance of plastic waste should continue to be the top priority. The additional energy expenditure for tracing does not call these advantages into question. However, even 100% recycling, based on perfect sorting of waste, would still be associated with high energy consumption – an aspect that would have to be taken into account, especially in many countries in the Global South with difficult supply of renewable energy.

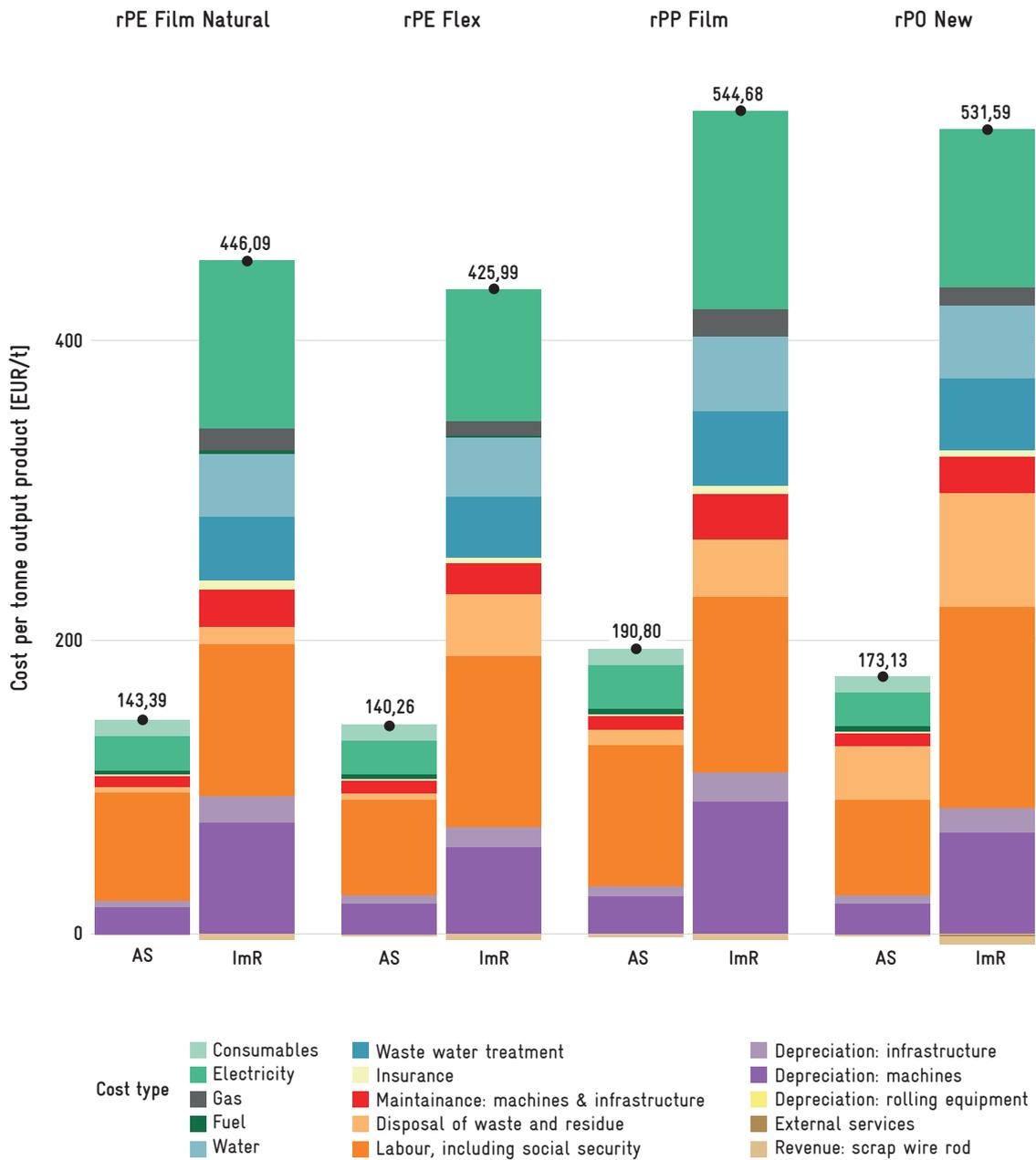
4.2 Plastic tracing – ecological business model with high capital intensity

The approaches presented here for material tracing of plastic waste are all characterised by the use of highly complex technology and thus correspondingly high investment requirements. The actual relevant costs arise less from the labelling of the material, be it through tracers, watermarks, or the use of barcodes (e.g., costs for marker material are estimated in the range of 20–50 US dollars per ton of plastic in the literature²⁷); the decisive bottleneck is the technical components required to actually read such data carriers during the sorting process and of course for setting up globally standardised data sets of high accuracy and reliability.

The plastics recycling business model, which would justify such investments, can only work if there is a market for high-quality recycled plastic. However, given the competition with cheap primary plastic (based, among other things, on externalised environmental costs and additional subsidies), this market is currently under considerable pressure, so that many plastics recyclers are very reluctant to invest in additional facilities or components required for tracing. Therefore, ambitious regulatory requirements for the recycling of plastic waste are needed, e.g. through mandatory recycling quotas, as defined in Europe by the Packaging Directive. If companies are forced to meet corresponding targets as part of EPR, then even recycling processes that are significantly more expensive than waste incineration or landfilling otherwise common in the Global South will be worthwhile. Figure 9 shows that the operational costs for recycling plastic waste – depending on the type – are between €565 and €735 per tonne, differentiated here according to the stages of pre-sorting (AS) and recycling (ImR).

²⁷ Howard et al. 2024.

Figure 9 Operational cost structure for recycling of plastic waste



Source: Van Camp et al., 2024.

Considering these significant costs and necessary investments and the prices of virgin plastic types that are already available at costs of €600 and below, material tracing can contribute to achieving higher revenues through better recycled material qualities that could be sold at higher prices. Without the information provided by tracing, the average quality of plastic waste would not set sufficient incentives to sort and recycle this waste stream at all.

In the vast majority of countries in the Global South, regulatory requirements are not yet high enough to actually justify such investments. A future driver, however, could be minimum recycling quotas, i.e. the obligation of those placing for example packaging on the market to use a minimum amount of recycled plastics in production. However, it must be considered that such quotas can lead to significant shortages of recyclates such as they are currently emerging, particularly on the European market, which would then have to be compensated for through imports. This could possibly also promote tracing outside the OECD countries if the recycled material could subsequently be sold to European buyers at correspondingly high prices – strengthening the potential for benefits from international recyclate trade, also for recyclers from the Global South.

4.3 Material Tracing – Game changer with risks for an open market structure

The advantages of the tracing approaches presented here only become apparent through scaling: The necessary effort for coding data, developing interfaces, etc., only pays off once a minimum market share is achieved. Unlike traditional plastics recycling, this approach is about network effects: The more companies agree on a specific system, the greater the economic benefits for each individual. Accordingly, it is to be expected that ultimately only a very limited number of tracing systems will be able to establish themselves on the market. On the one hand, such a ‘uniform system’ would offer significant opportunities for truly transparently depicting the fate of plastic waste. The idea of manufacturer-specific sorting could represent a game changer, for example, for concepts of ecologically differentiated license fees within the framework of Extended Producer Responsibility systems – thus making investments in improved recyclability a truly viable business model for manufacturers and distributors of, for example, packaging.

These advantages of a global system for tracing plastics are offset, particularly from the perspective of the Global South, by the risk of being largely excluded from the necessary development of standards and norms. For example, with the DPP, only a very limited number of globally operating companies are ambitiously developing corresponding systems – the perspective of the Global South is effectively not represented in such rounds. As part of a data-driven business model, the use of these systems will most probably be offered only for the payment of fees – the lower the initial hardware costs, the higher the costs of using the software and the underlying da-

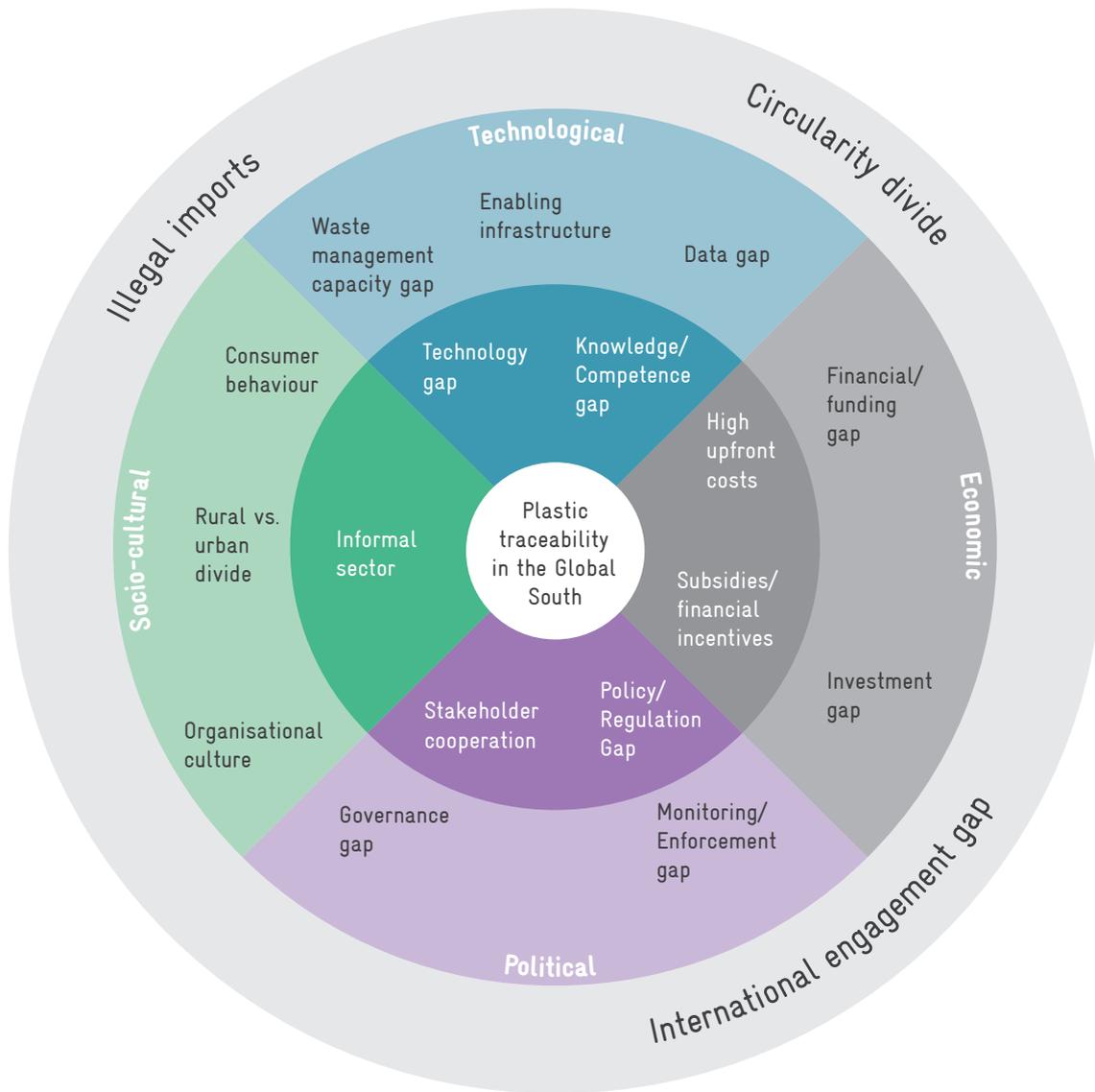
ta bases might get – with unforeseeable consequences for actors in the recycling sector, but especially the informal waste management sector in the Global South.

However, the full implementation of the approaches presented here could lead to a fundamental change in the livelihoods of the millions of people in the informal waste sector, who make their living primarily from the collection and sorting of plastic waste – associated with both opportunities and risks: On the one hand, complete transparency regarding the whereabouts of plastic waste would increase the visibility of this sector – one of the central demands of their representatives. It would (finally) become clear how important these actors are in limiting the consequences of our current handling of plastic waste. On the other hand, it is of course also conceivable that the improved sortability of plastic waste could lead to a form of cherry picking, in which the informal sector is deprived of precisely those waste fractions that previously enabled them to make a living. At the same time, it is foreseeable that the investments required to use such tracing approaches themselves can hardly be met by all actors in the Global South – neither in the professional recycling market that has developed in recent years, nor, of course, in the informal sector. This ambiguity and unpredictability of how tracing will ultimately change the global recycling market once again highlights the design task for the associated ecosystems: It is not the technology itself, but its use, the participatory development of regulations and access to knowledge that ultimately determine the extent to which these will contribute to sustainability in a comprehensive sense.

4.4 The Global South perspective – beyond a Euro-centric view on circular plastics

The literature review and interviews for this publication show that relevant actors from the Global South have so far not been adequately included in the design and development of plastic traceability approaches. An analysis of potential challenges around plastic traceability for actors from the Global South suggests that multiple interconnected economic, political, technological, and socio-cultural factors, both inherent to traceability systems and structurally embedded in developing countries, impede plastic traceability, along with systemic global factors. It is to be noted that some of those also apply to countries from the Global North, and not all aspects apply to all countries from the Global South equally. This simplified distinction aims to increase the visibility of an underrepresented perspective that would be necessary to include in traceability discussions. Figure 10 provides an overview of these challenges. The inner circle represents specific traceability challenges, while the middle one lists structural challenges, and the outer one systemic global challenges.

Figure 10: Overview of the challenges of Plastic Traceability in the Global South



Source: Own Illustration, 2025.

Technological challenges

Given the central role of physical and digital technologies in implementing plastic traceability, technological challenges represent a major constraint in the Global South. One of the primary barriers is the significant gap in waste management capacity.²⁸ In addition to inadequate waste management infrastructure, researchers highlight the absence of centralised waste systems and the fluidity and fragmentation of the recycling industry as key concerns. Without functioning collection and recycling infrastructure, traceability systems add little practical value, since

28 Oyintola and Kolade 2023.

materials cannot be effectively recovered or reintegrated into the economy. Furthermore, structural limitations in enabling infrastructure, such as connectivity, energy access, and information technology facilities, further hinder the adoption of crucial and innovative technologies.²⁹ Additionally, the widespread data gap that characterises many Global South countries poses further obstacles to implementing sustainability strategies, as data availability and knowledge are prerequisites for effective waste management systems.

In the specific context of plastic traceability, these technological challenges are exemplified by the significant knowledge and technology gaps in many Global South countries. Even where enabling technologies exist, these regions often face a severe skills gap and inadequate technical expertise to implement or use them effectively.³⁰ This issue is particularly pronounced when implementing complex tracing technologies which require specialised skills. Moreover, limited access to technology in many regions further exacerbates the challenges of adopting traceability systems.

Economic Challenges

A major obstacle to adopting and implementing traceability in the Global South is the significant lack of circular investments and limited access to available funding. Between 2018 and 2023, only 5 billion US dollar – just 2.6% of the total 190 billion US dollar invested in plastic circularity – was allocated to digital solutions, which are essential for enhancing plastic traceability.³¹ Moreover, despite emerging markets being the largest contributors to plastic pollution, they received only 6% of total investments, underscoring the urgent need for increased funding in these regions. Beyond insufficient investment, limited financial support and inadequate funding represent major economic barriers to implementing traceability systems.³² Private stakeholders especially in the Global South often struggle to access financial resources, while public investment in essential infrastructure, such as waste management, remains inadequate. This challenge is further exacerbated by severe deficiencies in public resource management, including widespread corruption in many Global South countries, making the financial landscape even more unfavourable for the adoption of traceability systems.

These financial constraints pose significant challenges to sustainability initiatives in general but are particularly problematic for plastic traceability due to the high up-front costs involved.³³ Implementing traceability systems requires expensive new machinery and advanced software, such as blockchain technology in the case of DPPs.³⁴ These costs are burdensome for all stakeholders but especially for small and medium enterprises (SMEs) in the Global South, where the lack

29 Pisa and McCurdy 2019.

30 Hira et al. 2022.

31 The Circulate Initiative 2024.

32 Debnath et al. 2023.

33 Gazeau et al. 2024.

34 Dasaklis et al. 2024.

of sufficient subsidies and financial incentives makes adoption even more prohibitive. Additionally, in regions like Sub-Saharan Africa, where waste management is perceived as a high-risk sector, the combination of high costs and investment uncertainty further exacerbates the economic challenges of implementing plastic traceability systems. Especially countries in the Global South with high amounts of plastic waste imports face the challenge of highly heterogenous plastic waste sources including countries that might use different forms of plastic tracing.

Political challenges

As stated by Muirhead and Porter (2019), plastic traceability is part of, and dependent on, the broader transition from state-centric, hierarchical governance to more networked and horizontal forms of governance. This shift requires complex interactions among multiple public and private stakeholders. In the Global South, severe governance challenges in some countries – evident from a glance at the Global Governance Index³⁵ – pose structural constraints to implementing sustainability strategies such as traceability. In Sub-Saharan Africa, this challenge is further exacerbated by the misalignment between public participation and policy commitment, underscoring the need to improve governance dynamics to support sustainability transitions. Beyond governance issues, another major political obstacle is the policy monitoring and enforcement gap in many Global South countries. As several authors highlight, even where strong regulations exist, their effective implementation and enforcement remain a significant challenge.³⁶

A key political challenge specific to plastic traceability is the lack of stakeholder coordination especially in the Global South due to weak governance structures. Research from various contexts has shown that stakeholders along the value chain often operate in isolation, or ‘in silos’, severely limiting plastic traceability applications.³⁷ Effective traceability requires collaboration and alignment to ensure smooth information flow and data interoperability. Furthermore, the lack of clear and harmonised standards for data collection, reporting, and monitoring poses an additional obstacle, as fragmented or missing standards hinder interoperability and discourage private sector investment. Given the complexity of governance structures in systems like DPPs, stakeholder collaboration is particularly crucial. Finally, governments play a vital role in guiding traceability efforts, but ongoing regulatory uncertainty further threatens stakeholder coordination and engagement.³⁸

Socio-cultural challenges

Alongside techno-economic and political factors, socio-cultural and demographic aspects are also crucial when assessing the challenges to plastic traceability. In this context, consumer behaviour and social norms play a significant role in the implementation of sustainability strategies. In reference to the Global South, several authors highlight the need to improve public awareness

35 World Bank 2025.

36 Brinkmann et al. 2022.

37 Sivakumar et al. 2018.

38 WEF 2025.

and education in these areas, alongside addressing persistent socio-cultural dynamics, including the stigmatisation of waste workers, as they continue to challenge effective implementation.³⁹ Low levels of public awareness, coupled with the fact that waste is often perceived as having little or no value, contribute to widespread littering and undermine both traceability efforts and circular economy strategies. However, in the social dimension, the dominance of the informal waste sector is arguably both the most crucial challenge and potentially valuable resource at the same time in the context of plastic traceability. Worldwide, an estimated 14.2 million people are active in the informal waste sector, which provides an important source of livelihood and plays a key role in waste collection.⁴⁰ However, structural and technical limitations, compounded by technology-based formal traceability solutions, may severely impact the informal sector and could potentially drive many workers out of business. This presents a significant challenge to the scalability of plastic traceability solutions. Therefore, as emphasised by several authors, it is crucial not only to recognise the informal sector's role and potential in waste management but also to integrate them into the governance process.⁴¹ Furthermore, the informal waste sector may be a source of important innovative solutions and should be included in the design of such systems to leverage their knowledge and ensure an inclusive design from the start.⁴² However, when plastics are littered or remain outside collection systems due to a lack of awareness or perceived low value, they bypass both formal and informal recycling channels and leave no starting point for traceability.

Systemic challenges

Further exacerbating the already significant challenges faced by the Global South in implementing plastic traceability are systemic issues linked to negative global dynamics. One key factor to address is the so-called 'Circularity Divide,' as global inequities severely hinder access to circular technologies and services for actors in the Global South due to a lack of financial resources and technical skill sets.⁴³ Furthermore, while stakeholders in the Global North are making strides in improving sustainability standards and requirements, the inability of businesses in the Global South to meet these standards could present significant barriers to trading recycled materials in-ter alia with larger companies in the Global North, further deepening the North-South divide. In this context, it is important to note that the impact of such standards varies depending on each country's specific trade balance and economic configuration. Another critical issue related to power asymmetry is the lack of an inclusive perspective when determining and assessing the feasibility of plastic traceability solutions. Additionally, there is a pressing need to adapt global standards, such as the Global Traceability Standard (GS1), to suit local conditions and challenges.

39 Voronkova et al. 2023.

40 International Alliance of Waste Pickers 2023.

41 Tsakona and Nøklebye 2024.

42 Sharma and Dahlastrand 2023.

43 Barrie et al. 2022.

5 Learnings and outlook



Against the background of the discussed strengths and weaknesses of existing best practice examples, especially with regard to the resulting opportunities and risks for stakeholders in the Global South, the following conclusions summarise what will be needed in the future to implement approaches to ‘plastic tracing’ as part of a circular economy for plastics that takes all dimensions of sustainability into account.

1. Considering the current intransparency especially of global plastic flows, tracing systems could become a key lever for more circularity. Key potential advantages relate to a) improved sorting, b) improved accountability of companies and c) recognition of relevant stakeholders.

The various implementation examples, as different as they are in their concrete approaches, overall illustrate the need to link material and information flows even more closely in the future. The current lack of transparency along the entire value chain means that necessary investments in circular structures for the production and use of plastics are not being made – even though the necessity and magnitude of this task cannot be postponed any further. An estimated 15.4 trillion US Dollar in private sector investments and 1.5 trillion US Dollar in public expenditure are needed between 2025 and 2040 to reduce annual mismanaged plastic volumes by 90% relative to 2019 levels.⁴⁴ However, investments of this magnitude will only be made if they are accompanied by appropriate de-risking measures and a positive cost-benefit analysis, in particular in the countries of the Global South. Tracing could make a significant contribution to this, as it enables both the precise distribution of responsibilities and the specific whereabouts of materials to be traced more precisely. Tracing should be seen as a building block of a comprehensive digitalisation of the circular economy – the significantly complex structure of collection, recycling and reuse in the form of recycled material, compared to the linear alternative of using primary plastic, will hardly be able to become competitive quickly enough without digital structures for data coordination and, above all, data validation.

Tracing technologies have so far been used primarily to improve the sorting of plastic waste, particularly with regard to quality standards that could enable the reuse of recycled plastic in food contact products. Avoiding downcycling, in which high-quality plastic is subsequently only used for lower-value applications due to a lack of information about its previous use, is an important contribution to circularity and therefore also contributes to climate protection. However, the far more relevant lever would be incentives that also have an upstream impact on product design or the distribution model. Tracing should be used to ensure that actors who invest in improved recyclability of their plastic products either gain physical access to this material or, in the sense of ecologically differentiated license fees in EPR systems, pay lower fees for placing it on the market. Such systems already exist in the packaging sector. Tracing in the sense of individual traceability to the distributor could help develop circular product design into a true business model.

⁴⁴ The Circulate Initiative & International Finance Corporation 2024.

In addition to such a positive incentive, tracing should of course also be used to oblige the responsible party to take back illegal exports, even from abroad, and to pay appropriate fines. In both cases, this requires access by public authorities to data collected or made accessible through tracing. Further research will be needed to better understand the concrete pros and cons of specific tracing technologies, especially when implemented in the Global South.

2. Supporting tracing options alone will not be sufficient to stop the current plastic crisis.

Tracing plastic materials will only become a viable business model if virgin plastic – due to cheap virgin oil – doesn't remain the more cost-efficient option (neglecting the externalised environmental as well as socio-economic costs).

Despite all the optimism about how tracing could enable new circular business models in the handling of plastics, it should nevertheless be clearly communicated that even a completely transparent and/or digitalised plastics value chain will not be sufficient as long as there is no real level playing field with the use of primary, fossil-based plastic – as long as the price of oil does not reflect the actual environmental costs, but rather passing them on to the general public. Technology for the recycling of plastics will remain limited to a niche market, artificially created, for example, through instruments such as minimum recycling quotas. However, there is no genuine, original demand for plastic recyclates as a substitute, but only when their price is lower than for new materials. As soon as this price relationship reverses again, the enormous price elasticity becomes apparent – the demand for recycled material drops practically to zero. In such a scenario, it is hardly conceivable that private actors would invest in new recycling capacities to the necessary extent.

Expanding minimum recycling quotas could be an effective tool for establishing corresponding green lead markets. From the perspective of the Global South, however, it would have to be ensured that the requirements for the recycled material used are based on quality criteria, not on the question of the waste's origin. Otherwise, a policy instrument that is highly sensible from an ecological perspective could be used to seal off a market in a protectionist manner. Of course, it should also not be allowed to allow manufacturers to fulfil such obligations by importing inferior recycled material.

3. From a perspective of stakeholders in the Global South, tracing could have various effects – highlighting that it is not about the technology but the ecosystem in which it is used. Tracing could create significant business opportunities. At the same time, it could also exclude partners in the Global South – especially with regard to necessary investments, access to data, operating costs or digital skills.

In the discussion about material tracing and further digitalisation, a stronger consideration of the perspective of the Global South is absolutely necessary. As described, material tracing offers the potential to lead to a disruptive transformation towards circular plastics. Disruptive change

is absolutely necessary, as has been described above – ‘business as usual’ cannot be an option given the extent of the global pollution caused by plastic waste. At the same time, much greater attention must be paid to who will be the winners and who will be the losers in such a restructuring of a global value chain for plastics. The tracing options presented clearly illustrate where the risks of effectively excluding individual groups of actors from such a value chain could lie, given the necessary investments, ongoing costs, or necessary technical skills could lie. This can have potentially catastrophic socio-economic consequences for countries from the Global South, e.g. if the recycling industry in the Global South as an important economic sector with high employment rates would become dependent on the access to data bases run by companies in OECD countries. Such risks should not be used as an excuse to ignore the current lack of transparency in the value chain – as described, inaction is not an option; however, the debate must also pay greater attention to how actors in the Global South can be supported and empowered so that they too can benefit from the use of such technologies. The key starting point here is not the respective technology itself, but the associated ecosystem, including the regulatory framework. Especially in settings with weak waste management infrastructures, it should be carefully considered how to prioritise public investments and where tracing can already provide relevant returns on investments.

Against this backdrop, it is especially important to support actors in the Global South in integrating tracing systems into their waste management infrastructure systems and to provide access to investment loans or direct financial support for this purpose. A focus should also be placed on supporting the acquisition of digital skills, so that, for example, recycling companies in countries where significant quantities of plastic waste from OECD countries are still exported can also benefit from tracing approaches.

4. Especially the informal waste management sector – an often overlooked but important element of the current plastic recycling chain – would require specific support in order to be able to benefit from tracing systems. Companies could also be willing to pay a premium if plastic waste has been diverted from a landfill in the Global South instead of from for example waste incineration in Europe.

The informal sector in particular has so far neither been considered nor integrated in any way in the discussion about approaches to digitising the recycling value chain, or specifically in the context of plastic tracing. Stakeholders need targeted support to even formulate this perspective: tracing as an approach to making this work visible in the first place – but also the risks if waste sorting in the future might only be possible with capital-intensive equipment.

One concrete approach could be to use tracing to document the special sustainability value of this activity, especially when plastic waste can still be recycled in countries of the Global South, where waste management infrastructure is often inadequate. Tracing could then create a trustworthy basis for the corresponding recyclate to justify a premium on the usual price – because

the alternative here would not have been high-quality incineration, but rather the potentially unregulated landfill, with correspondingly significantly higher environmental impacts. Considering that the (future) demand for high quality recycled plastic based on mandatory recycled content quota could exceed recycling capacities in the European Union, tracing could play an even more relevant role for trade relations between the Global South and economic regions like Europe. Right now, there are also tendencies to protect the recycling markets in the Global South by only considering secondary plastics that has actually been recycled in Europe – and for this purpose using tracing technologies to explicitly hinder free trade in order to ensure the economic wellbeing of the domestic recycling sector.

5. The market is currently evolving extremely dynamically. There is a risk of a future oligopolistic or even monopolistic structure that would amplify the risks for the Global South. It would be important that relevant stakeholders reflect or at least acknowledge the perspective of the Global South in the highly important standard setting processes. Policy makers should put a stronger emphasis on open innovation systems that focus rather on performance and results than on specific technologies.

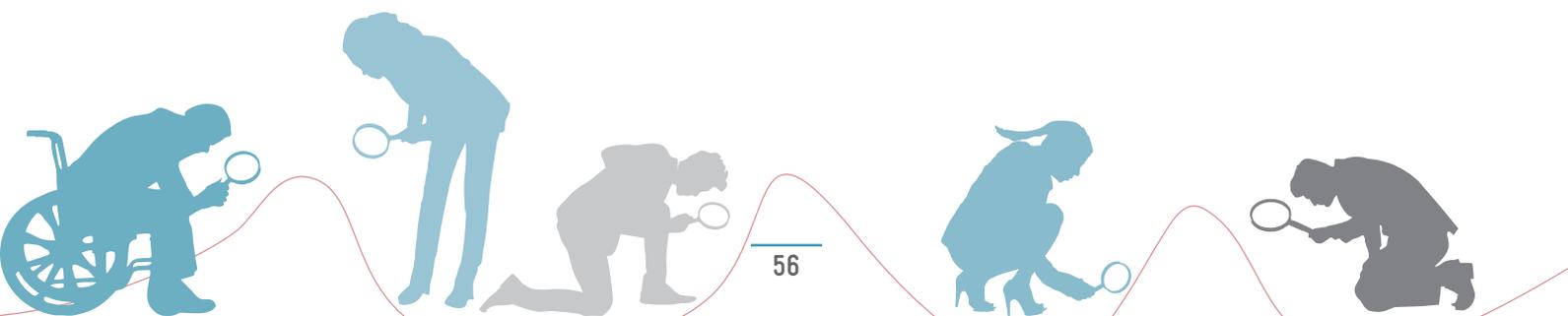
All approaches to establishing tracing in the plastics sector will require the definition of standards and norms as a necessary step if a new level of quality cooperation along the value chain is to be achieved. The business models that enable private investment in such tracing systems are based on such standards and norms – they are therefore a central and necessary component of tracing. However, it is all the more important to ensure participatory structures in the development of such standards as soon as public funds are also used for this purpose, for example, in research and development or through public loans.

Secondly, from the point of view of the regulatory framework, attention should be paid to the highest possible interoperability between different technologies – machines that can, for example, recognise watermarks should also be able to read tracer-based markers and vice versa. Here, the principle of open innovation should be followed, which focuses on opening up the innovation process of companies and scientific institutions to external actors. The goal is improved access to information on needs and solutions through the combination of internal and external resources and skills. With a view to cooperation between science and industry, opening up the innovation process to external groups of actors for the purpose of faster and better development of new products, services and processes is perceived as a promising approach – especially for processes of sustainable digitalisation. Otherwise, there is a high risk that the innovative digitalisation of the recycling industry, which is desired and necessary on the one hand, will exclude key players in the Global South from these processes and thus also from markets on the other – especially without a necessary debate on the interlinkages between just transition and access to data.

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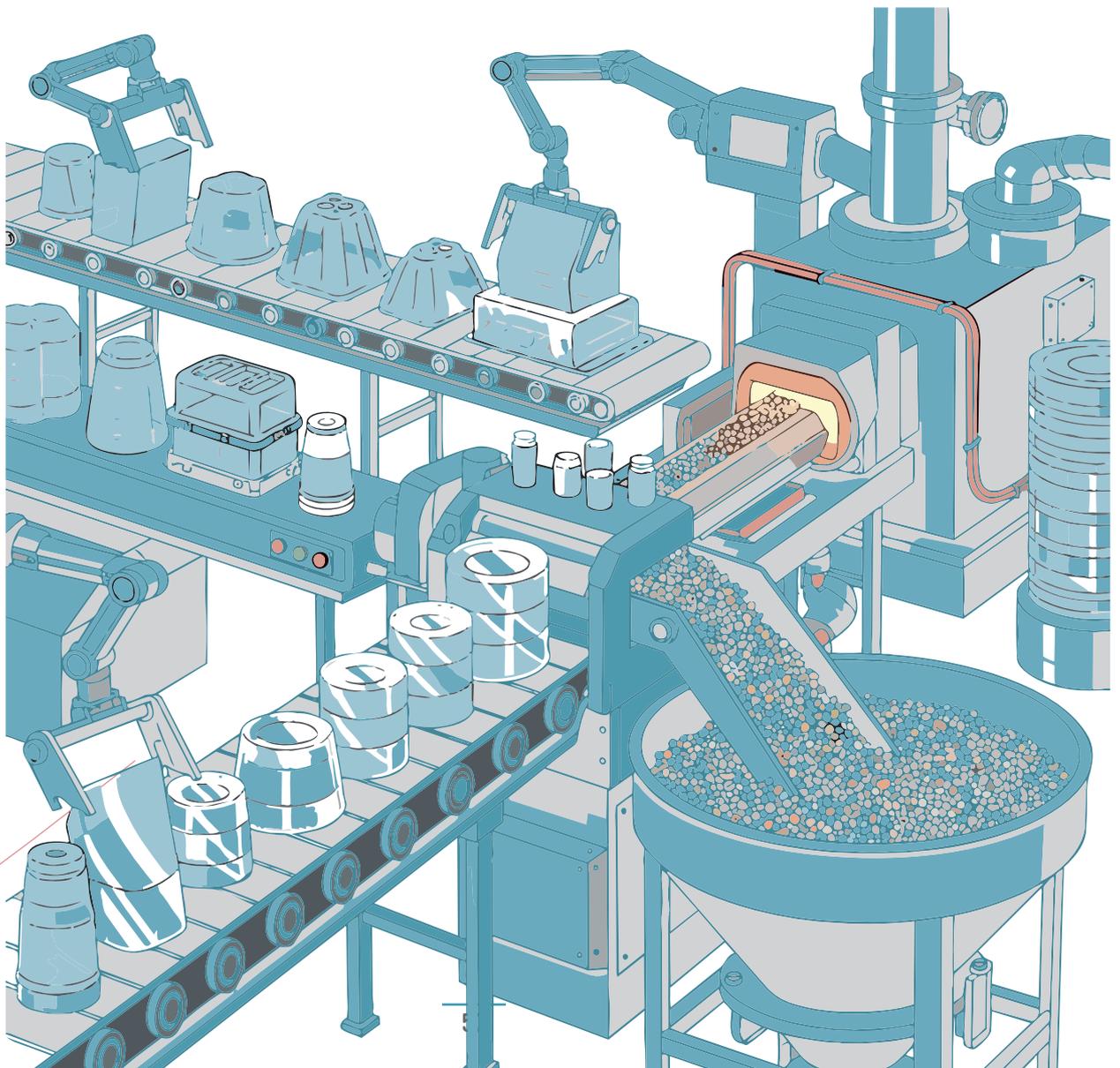
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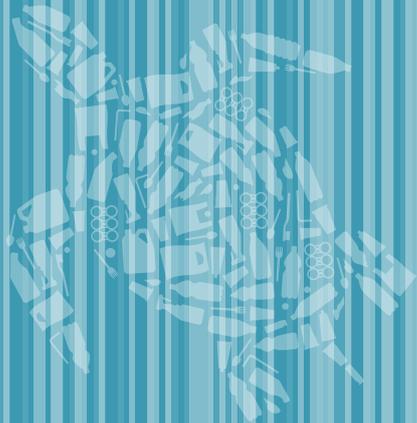
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