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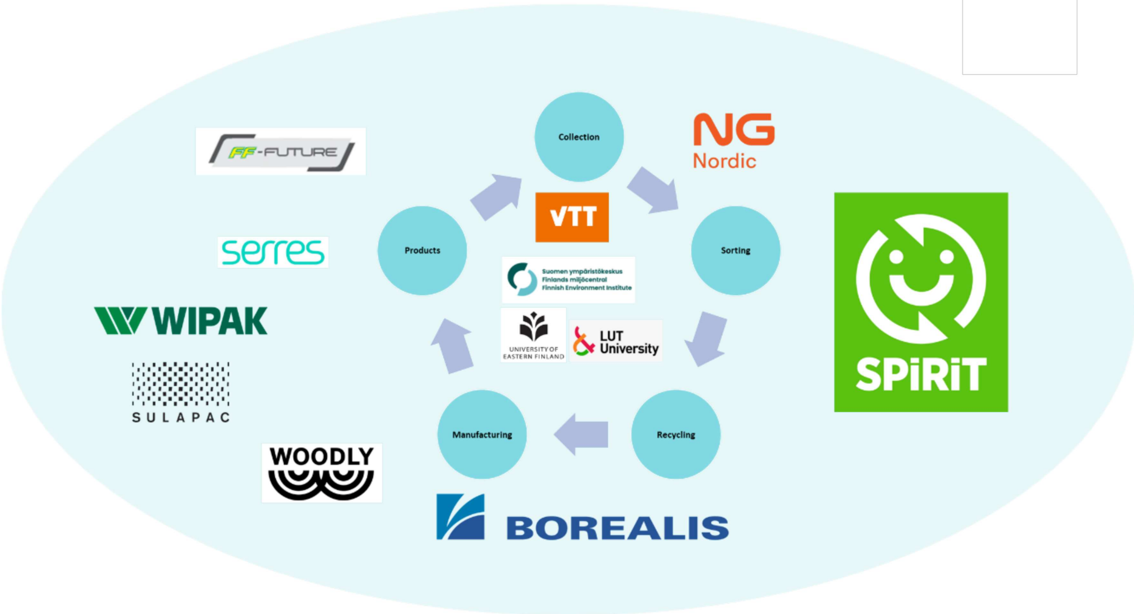

PlasticsCircularity

Creating business through circularity of plastic

Review of existing data-driven initiatives and their relevance on plastics circularity

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beyond the obvious

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Summary

This research report explores how data-driven solutions could be transforming the circularity of plastics, emphasizing the growing importance of digital tools, standards, and regulatory frameworks in enabling sustainable practices across the plastics value chain. The report begins by clarifying the concept of data in the circular economy, highlighting its role in transparency, traceability, and informed decision-making. It notes that data can range from broad annual recycling statistics to granular, real-time process measurements, and stresses that high-quality, well-managed data is becoming essential for compliance and competitiveness, especially as new EU regulations demand detailed product and material information.

The document reviews the current state of data-driven initiatives, such as Digital Product Passports (DPPs), which are being piloted in sectors like batteries and textiles. These passports compile lifecycle data to enhance transparency and support circular business models. The report also discusses advanced technologies that optimize polymer production and recycling, as well as machine vision and robotics for waste sorting.

A part of the report is dedicated to standards and certification systems, such as ISCC PLUS, which ensure traceability and sustainability in recycled plastics. Recent European standards now differentiate between sorted plastics and recyclates and introduce classifications like Data Quality Levels (DQL) for digital trading, paving the way for broader adoption of Digital Product Passports.

Cross-sectoral insights are provided, showing how data-driven circularity is being applied in electronics, food, and agriculture. The report highlights the evolution of data sharing technologies, the opportunities and challenges they present including privacy, security, interoperability and the regulatory landscape shaped by the EU Data Act, Data Governance Act, and Corporate Sustainability Reporting Directive (CSRD).

Ultimately, the report concludes that robust data frameworks and collaborative data ecosystems are foundational for advancing plastics circularity. Organizations that invest in these areas will be best positioned to meet regulatory requirements and market demands, driving the transition to a more circular and sustainable economy. However, their success depends on thoughtful implementation, harmonized standards, and a clear strategic purpose for data collection and processing.

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Preface

The transition to a circular economy for plastics is one of the most pressing challenges facing industry, policymakers, and society today. As environmental concerns and regulatory demands intensify, the need for robust, data-driven solutions has become increasingly clear. This report was prepared to provide a comprehensive overview of how digital tools, standards, and collaborative frameworks are shaping the future of plastics circularity. It brings together insights from recent research, practical case studies, and evolving European regulations to highlight the transformative potential of data in enabling transparency, traceability, and sustainability across the plastics value chain.

The work presented here is the result of collaboration among experts from VTT, Syke, and other partners in the PlasticsCircularity consortium. Our aim is to support stakeholders (manufacturers, recyclers, policymakers, and researchers) who are seeking to adopt innovative data-driven approaches and navigate the rapidly changing landscape of circular economy regulations. By reviewing existing initiatives and identifying key opportunities and challenges, we hope this report will serve as a valuable resource for organizations striving to meet both market and regulatory expectations.

We would like to thank all contributors and reviewers for their expertise and commitment to advancing sustainable practices in the plastics sector. We also acknowledge the support of the PlasticsCircularity consortium and the broader community working towards a more circular and resilient economy. It is our hope that the findings and recommendations in this report will inspire further collaboration and innovation, driving meaningful progress in plastics circularity.

Oulu, 4.2.2026

Tuomas Sormunen, Pauli Räsänen, Kiia Silvennoinen, Susanna Horn and Sari Järvinen

Contents

1. Introduction

The purpose of this report is to provide an overview of the potential of data-driven solutions to improve the circularity of plastic products and materials. For reference, the report also presents shortly data-driven initiatives (such as Digital Product Passport, DPP) from other market domains and describes the basics of data sharing technologies. The report is targeted at different actors in the plastics value chain interested in adopting data-driven solutions and data sharing technologies to their processes.

The term "data" can be understood in multiple ways, depending on context and purpose. At its core, data refers to raw facts or figures, numbers, words, or symbols collected through observation or measurement. However, data only becomes meaningful when it is organized and interpreted, transforming into information that can guide decisions or reveal patterns. In some contexts, data is quantitative, such as numerical measurements, while in others it is qualitative, capturing descriptions or opinions. The structure of data also varies. It may be neatly organized in tables and databases, or it may be unstructured, as in emails, images, or free-form text. Increasingly, organizations view data as a valuable asset, essential for innovation and strategic decision-making. Yet, the meaning of data is also shaped by its use: in science, it forms the basis for discovery; in business, it drives analytics and optimization; in legal contexts, it may represent sensitive personal information requiring careful management. Ultimately, data is not just a static resource but moves through a life cycle of collection, processing, analysis, and sharing, with its significance evolving at each stage. This diversity of perspectives highlights why data is such a powerful and versatile concept in today's world.

In the context of the circular economy, data encompasses a wide spectrum from high-level annual statistics, such as the total volumes of materials recycled each year, to highly granular, real-time measurements generated by manufacturing or recycling processes. For example, a recycling facility might collect time-series data with ten measurements per second, capturing detailed information about temperature, pressure, or material composition throughout the process. This diversity in data types enables both broad strategic planning and precise operational optimization, highlighting the essential role of data at every stage of the value chain to support progress toward higher circularity.

In PlasticsCircularity we have defined data in the following way: "*Data is in digital format, allowing it to be transmitted efficiently over communication channels. The methods used to collect data can vary widely, which in turn can influence the quality and reliability of the data itself. Data may take many forms (numerical values, text, positional information etc.) and is organized in a structured format that includes metadata descriptions to provide context and meaning. Importantly, data is always linked to real-world entities or phenomena, such as process parameters, resource usage, products, emissions, side products, waste, materials, end products, or specific events. The frequency with which data is collected depends on the intended use: in some cases, data is gathered in near real-time, while in others, it may be collected periodically, with a growing preference for more frequent updates rather than relying solely on annual figures.*"

Data is fundamental for advancing the circularity of materials and products because it enables transparency, traceability, and informed decision-making throughout the entire value chain. With accurate and timely data, organizations can track material flows, monitor product lifecycles, and identify inefficiencies or opportunities for reuse, recycling, and resource optimization. As the circular economy evolves, robust data frameworks are becoming essential, not only for internal optimization but also to comply with a rapidly changing regulatory landscape. Upcoming regulations in the EU will require companies to collect, manage, and share detailed product and material data, making high-quality data management a prerequisite for both compliance and competitiveness. Currently, EU is preparing a wide range of new regulations, incentives, and guidelines to promote circular economy (CE) and to improve data-based measurement, traceability and communication of sustainability.

Additionally, the International Organization for Standardization (ISO) is developing standardization systems related to both circularity and data-based traceability. While many of these systems are currently voluntary, there is a shift toward mandatory regulation. However, the goal is not to collect excessive amounts of data. Gathering, storing, and processing data comes with its own resource and environmental burden. Therefore, data collection should be limited to what is strictly necessary to ensure transparency and support informed decision-making.

As studied by Horn & Silvennoinen [1], in the plastics sector data and traceability are part of several regulations. For example, traceability is regulated within the EU in e.g. food contact materials [2], in which traceability means the ability to identify where different materials, substances or articles come from and where they go. Thus, traceability is used for health and safety compliance checking. Traceability is also included in EU-level regulations in batteries [3], in the EU Strategy for Sustainable and Circular Textiles [4] and in the Ecodesign for Sustainable Products Regulation (ESPR) [5]. The ESPR, for example, demands life cycle information to be available and easily accessible in form of a DPP and it is expected to significantly enhance end-to-end traceability of a product throughout its value chain. Traceability is also required in the proposed revision of the packaging and packaging waste directive (PPWD) [6] to ensure the minimum recycled material content. Outside the EU, there are other regional systems for traceability. For example, in the USA, traceability is regulated especially in the food sector [7]. In Australia, the Australian Traceability Framework provides a regional approach to enhancing traceability systems across various industries [8]. On a global scale, the GS1's Global Traceability Standard [9] provides a foundational methodology for organisations to design traceability systems tailored to their unique requirements and objectives.

The ESPR regulation proposal is linked to the DPP. The DPP is a tool proposed by the European Commission to compile life cycle data related to a product and to enable efficient information flow. Its purpose is to make the materials and sustainability aspects of a product more transparent to all actors in the value chain, including consumers, thereby promoting the implementation of the circular economy. In other words, it aims to support more sustainable production and circular economy-based business models through increased data availability, encourage informed consumer choices, and serve as a registry for product compliance. The DPP is intended to include, among other things, product identifiers, information about the substances contained in the product, its circular economy history, and its sustainability. It would also contain documentation regarding the product's compliance. The product passport is meant to be accessible to all actors in the value chain so that decisions can be made based on reliable data. However, not all information would be available to every actor, and access would be regulated according to product category. The DPP will first be implemented for three product groups, batteries, textiles, and construction products, after which it is expected to expand to other sectors.

From the standardisation perspective, traceability is defined in the ISO 9000 series of standards focused on quality management as the ability to trace the history, deliveries, use, and location of a product or its materials and components using recorded, unique, batch-specific data [10]. However, it is increasingly associated with the need to make supply chains more transparent, sustainable, and responsible [11]. The European Commission has identified transparency and traceability as one of the priorities in promoting the sustainability of supply chains, and the corporate responsibility initiative UN Global Compact already in 2014 proposed that the definition of traceability in standards should be expanded to include sustainability perspectives, i.e., the ability to determine and trace the history, deliveries, use, and location of a product or its materials and components to support various sustainability claims [12].

This report provides an overview of the potential of data-driven solutions to improve the circularity of plastic products and materials. It begins by reviewing the current state of data initiatives and research in plastics circularity, including relevant standards and certification systems. The report then explores the concept of the DPP and its application in different sectors, such as batteries and textiles, before examining how data-driven approaches are being used in other domains than plastics circularity like electronics and agriculture. Further sections discuss the evolution of data sharing technologies, the opportunities and challenges they present, and the regulatory landscape shaping data management in the circular economy. Finally, the report highlights the essential role of data as an enabler for transparency, traceability, and informed decision-making throughout the plastics value chain, setting the stage for future developments in both industry practice and policy.

2. Data-driven initiatives and the current state of research in plastics circularity

Data-driven solutions for facilitating the circular plastics value chain is a research topic that has gained wide popularity recently, particularly in the EU due to incoming strict recycling requirements. Various review articles have been conducted in this domain [13], [14], [15], [16], but these reveal that studies have been mainly focusing on a single step of the value chain, i.e. the whole value chain optimization has not been done. The potential of digital solutions for facilitating full value chain optimization is recognized, e.g. in the context of DPPs [17], which is the topic of the next section, or blockchains [18]. Even though DPPs and blockchains have been widely explored from a technical perspective as enablers of value chain optimization, empirical studies on their practical implementation remain scarce. In this section, we outline data-enabled circularity use cases that have reached maturity, and which are seen as key parts in full value chain optimization.

Process analytical technology (PAT), such as Raman or near infrared (NIR) spectroscopy, together with machine learning can be used to infer polymer quality attributes, like melt flow index or intrinsic viscosity, in near real time. With these inferred values, advanced control systems can adjust various key parameters in real-time to stabilize product grades. The Raman and NIR probes are robust for inline polymerization monitoring and machine learning improves the predictive accuracy of these sensors for polyolefin production. The net effect is fewer off-spec batches, reduced lab-analysis latency, and smoother, faster grade transitions across campaigns. Companies such as Endress+Hauser [19] and Metrohm [20] provide such solutions.

DPPs assign each item a unique identity that carries grade, additives, post-consumer recycled content (PCR) percentage, and batch information, retrievable via QR (Quick Response) code, NFC (Near Field Communication) tags or digital watermarks. Proven pilots show that DPPs improve recyclability instructions, enable supply chain verification, and streamline audits of recycled content. Data-hubs based on the Electronic Product Code Information Services-standard and supply chain pilots from the company R-Cycle, along with watermark implementations from Digimarc, illustrate practical routes to scale. According to the actors, the result is end-to-end transparency that benefits compliance teams, recyclers, and customers alike [21], [22], [23].

Digital twins of extrusion equipment combine physics and data to recommend energy-optimal settings for temperatures, screw speeds, and pressure while maintaining cycle time and quality. It has been shown that digital twins can reduce energy consumption and improve efficiency by stabilizing processes. These models can also be linked to energy price signals and production planning to shift energy-intensive steps to cheaper slots. Plants can achieve lower energy consumption (per produced weight), less scrap, and fewer troubleshooting stoppages [24], [25].

Machine vision fused with robotics has recently gained popularity in waste sorting lines, particularly for construction and demolition waste as well as increasingly for packaging plastics. In the former case, traditional pneumatic air separators cannot fulfil actuation due to heavy particle weights – companies such as ZenRobotics [26] and Waste Robotics [27] provide solutions for this case. In the latter case, quality control has often been done with manual sorting at the end of the sorting line.

Companies such as EverestLabs [28] and RecycleEye [29] in addition to ZenRobotics [26] provide solutions for packaging waste, replacing the often-used manual sorting by human.

With this foundation, we can now examine how these data-driven approaches are being formalized through new tools and regulatory mechanisms.

2.1 Standards and certification systems: enabling data-driven circularity

A variety of standards exists currently to deal with plastic waste. In addition, certification systems allow for a certified method to include plastic recyclates into new products. In this section, we investigate these.

2.1.1 Certification systems

Certification systems for plastics from recycled feedstock are many:

- International Sustainability and Carbon Certification (ISCC)
- RecyClass
- Ocean Bound Plastic Certification Program
- Global Recycle Standard (more related to textiles)
- CERTILOOP

As an example, we outline the features of ISCC PLUS, which is arguably the most commonly used scheme for recycled plastics.

ISCC PLUS [30] is an internationally recognized voluntary certification system designed by ISCC to ensure the sustainability, traceability, and responsible management of supply chains involving agricultural, forestry, waste, residue, non-bio renewables, and recycled carbon materials, including waste plastics. The system is applicable to markets not regulated by the EU Renewable Energy Directive (RED II), such as chemicals, food, feed, and energy, and is harmonized with ISCC EU (another certification system) for streamlined certification. ISCC PLUS emphasizes ecological and social sustainability, greenhouse gas (GHG) emission savings (voluntary), and robust traceability throughout the supply chain, with independent third-party audits ensuring compliance.

Waste plastics are a central focus within ISCC PLUS, which supports the circular economy by certifying the recycling and recovery of post-consumer and pre-consumer plastic waste. The system defines post-consumer material as plastics discarded by end-users, while pre-consumer material refers to waste generated during manufacturing processes. Both types can be certified if they meet ISCC's criteria, including evidence that the material is genuinely waste and not intentionally produced for recycling. The certification process requires documentation, traceability, and compliance with national regulations.

ISCC PLUS recognizes both mechanical and chemical recycling as valid pathways for processing waste plastics. The system encourages proper design of collection and sorting schemes to ensure high-quality recyclable fractions and mandates that recycling operations minimize environmental and social costs.

A key feature of ISCC PLUS is its rigorous chain of custody requirements, ensuring traceability of waste plastics from their point of origin through recycling and into new products. The system allows for physical segregation, mass balance, and controlled blending as chain of custody methods. Mass balance, in particular, enables the blending or mixing of sustainable and non-sustainable materials (i.e., in the case of plastics, recycled and virgin, respectively) while maintaining bookkeeping to ensure that the certified output does not exceed the certified input. This approach is critical for recycled plastics, where physical separation is often impractical; physical separation implies fully separate processing lines that do not allow for virgin material to be blended. Controlled blending, meanwhile, relies on constant blend percentage of virgin and non-virgin material, which is not feasible due to varying availability and quality of non-virgin material. Thus, mass balance is seen as a paramount alternative.

Under the mass balance approach, the sustainability characteristics (such as raw material category, GHG emissions, and waste status) remain assigned to batches of material on a bookkeeping basis, even though the physical properties of the mixture may be lost. Most importantly, mass balance allows for differing blend percentage of virgin and non-virgin material in plastic processing in a single processing line. The key requirement is that the total amount of sustainable material withdrawn from the system cannot exceed the amount of sustainable material added, adjusted by conversion factors that account for processing losses. Mass balances must be site-specific, material-specific, and period-specific (with a maximum period of three months), and all relevant documentation must be available for audit. This system ensures that sustainability claims are credible and verifiable, supporting transparency and integrity in supply chains for certified materials. Even though mass balance allows for flexibility in terms of recycled content availability variation, the content of recycled material in an individual product cannot be verified upon this scheme, somewhat limiting it.

As traceability is a key requirement in the ISCC PLUS certification, rigorous book-keeping is needed for each actor. An example of this is given in Figure 1. All actors in the value chain are expected to comply with ISCC PLUS reporting (self-declaration and sustainability declarations), sharing this information along with the material/product to the next actor. Thus, full value-chain traceability is obtained, with the last actor being confident in their sustainability claims (e.g. recycled material content). Since all actors are certified, the system allows for interchanging actors, e.g. recycled material providers, if a need occurs. This enables a lean procedure when supply chain changes occur.

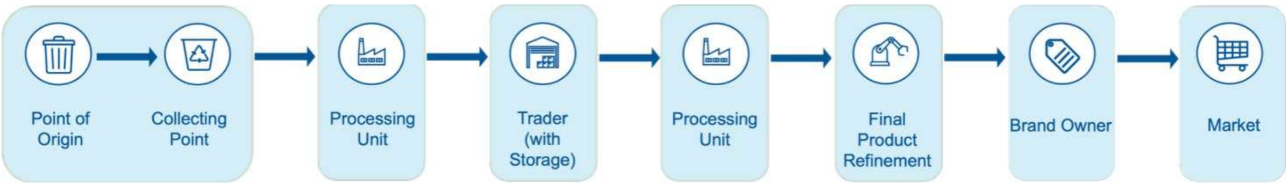

Figure 1. Example figure of a value chain in ISCC PLUS. Adapted from [31].

2.1.2 Standards

Recently, progress on European Standards (EN) regarding recycling of plastic waste has been done. This was ushered by a European Commission standardization request in 2022, which prompted standardization work by a committee directly related to plastics, namely CEN/TC 249 [32]. The standardization request contained revisions to 11 old standards as well as new deliverables to 10 different areas [33]. The deadline for the deliverables was in August 2025, so the standards have already been published. In this section, we outline the ones relevant for data-enabled circularity.

The revision request consisted of revising the previous standards on characterization of plastics wastes:

- EN 15347:2007 Plastics – Recycled plastics – Characterisation of plastics wastes
- EN 15342:2006 Plastics – Recycled plastics – Characterisation of polystyrene (PS) recyclates
- EN 15344:2021 Plastics – Recycled Plastics – Characterisation of polyethylene (PE) recyclates

- EN 15345:2007 Plastics – Recycled Plastics – Characterisation of polypropylene (PP) recyclates
- EN 15346:2014 Plastics – Recycled Plastics – Characterisation of poly(vinyl chloride) (PVC) recyclates
- EN 15348:2014 Plastics – Recycled plastics – Characterisation of poly(ethylene terephthalate) (PET) recyclates

As can be seen, these standards concerned recycled plastics. New standards were developed for sorted plastics, and they replaced EN 15347:

- General characterisation [34]
- Sorted PE [35]
- Sorted PP [36]
- Sorted PET [37]
- Sorted PVC [38]
- Sorted PS [39]

This revision makes a clear difference between characterization of sorted plastics and plastic recyclates. Indeed, no EN standard existed for sorted plastics previously.

The standards for sorted plastics [34] outline required characteristics that have to be given about each batch (e.g. main polymer, origin), as well as enumerates some optional characteristics (e.g. percentage of different non-polymer materials present in the batch). In addition, the standard includes detailed methodology on how to acquire this information, i.e. how to sample the batch, and how to analyse the material composition therein.

Similar characteristics are available in the standard for recyclates. E.g. for PE recyclates [40], mandatory characteristics include e.g. form and density, while optional characteristics include impurities and other thermomechanical characteristics. Here also detailed method for determination of contaminants and density are given. To note is that a new standard was developed for acrylonitrile butadiene styrene (ABS) recyclates [41] that follows the same logic; previously, no standard for ABS existed.

Moreover, a totally new series of standards was developed [42]. This lays out the recommendations for specifications of different recycled plastic materials for different use cases, e.g. moulding and extrusion. This is intended to facilitate the market of recycled plastics, as the converter can specify their needs with the standard, which the recycled material supplier can then comply with. The series includes standards for PE, PP, PET, PVC, PS and ABS.

Finally, the new standard EN 18065 [43] outlines a classification of recycled plastics based on Data Quality Levels (DQL) that are intended for digital trading. The standard provides a classification scheme, DQL1 – DQL4, which contain information, properties and optional characteristics of each batch of recyclate, with increasing number of details based on the DQL level. Moreover, the already-existing standard EN 15343 [44] concerns “plastics recycling traceability and assessment of conformity and recycled content”. This standard is often included in certifications as a voluntary feature such as in ISCC [30].

Another example of relevant standard includes Greenhouse Gas Protocol (GHG) assessment reporting requirements. The GHG Protocol [65] is the globally recognized methodology for measuring and reporting GHG emissions.

The standards may well pave the way for DPP for recycled plastic feedstocks, which will be covered next.

3. Digital Product Passports: concepts and sectoral applications

A DPP is a structured digital record that contains detailed information about a product's entire life cycle, from raw material sourcing and manufacturing to usage, recycling, and other end-of-life options. It is designed to enhance transparency, traceability, and sustainability across supply chains, enabling stakeholders to make informed decisions and comply with evolving regulations.

DPP has recently gained momentum particularly in Europe due to the initiatives by the European Commission. The *Ecodesign for Sustainable Production Regulation* [5], enforced in 2024, is designed to promote sustainable design of physical products in general. Different domains have their own particular initiatives, e.g. the EU strategy for sustainable and circular textiles [4], the new EU battery regulation [45], as well as the new EU construction products regulation [46].

DPP for batteries is arguably the most well-known of the current applications, and it is also the one that has seen most development in recent years. Indeed, the battery regulation states that by the beginning of 2026, all electric vehicle batteries must have their own unique digital battery passport in the European Union market. This has ushered in conceptualizing the requirements of such a passport, including what data fields to include in the passport, who has access to the data and in what format. This development is not exclusive to the battery DPP, but rather such conceptualization is on-going in all other domains as well.

The information gathered in the DPP allow for different use cases for different actors, for example [17]:

- Customer: sustainable procurement, product lifetime extension and end-of-life trajectories
- Service provider: condition-based maintenance
- Manufacturer: selecting and employing value-retention strategies at product level
- Supplier: remanufacture of components
- Third-party recycling company: retaining material value with reversible losses

The data sources enlisted in the article that allow for such use cases are related to:

- Usage and maintenance, e.g. running hours and location
- Product identification, e.g. serial number and country of origin
- Products and materials, e.g. number of life cycles and recycled content
- Guidelines and manuals, e.g. installation guidelines and safety instructions
- Supply chain and reverse logistics, e.g. component suppliers and recycling partners
- Environmental impacts, e.g. carbon footprint
- Compliance, e.g. regulations and labour conditions

Of course, each DPP must choose and conceptualize their own data fields to allow for domain-specific scenarios and use cases for promoting sustainability. We explore some examples in the following sections.

3.1 Battery DPP

The EU battery passport is the first DPP initiative to have reached maturity. It will be mandatory from February 2027 for three main categories: electric vehicle batteries, light means of transport batteries (such as e-bikes and e-scooters), and industrial batteries with a capacity above 2 kWh. Portable and SLI (starting, lighting, ignition) batteries are out of scope. Industrial batteries are further divided into sub-categories, including stationary energy storage systems and batteries for industrial activities, communication infrastructure, and energy storage. The regulation also covers repurposed batteries, such as former electric vehicle batteries used in industrial applications, though this will assumedly be less common. [3]

The battery passport contains a comprehensive set of data, up to 90 attributes, organized into seven clusters: 1) general battery and manufacturer information, 2) compliance, labels, and certifications, 3) carbon footprint, 4) supply chain due diligence, 5) materials and composition, 6) circularity and resource efficiency, and 7) performance and durability. Data is further classified as static (unchanging or rarely changing) or dynamic (updated over the battery's life). Access to data is controlled by defined groups: the general public, authorities, and persons with legitimate interest. Examples of data fields include battery ID, manufacturing details, carbon footprint per lifecycle stage, due diligence reports, hazardous substances, dismantling manuals, recycled content shares, performance metrics (e.g. capacity, power, resistance), and event logs (e.g. deep discharge events). [47]

The battery passport is designed to create transparency and unlock value for businesses, authorities, and consumers. Seven direct use cases are enabled by mandatory data: 1) reliable ESG data communication, 2) informed purchasing decisions, 3) eased servicing, 4) precise risk assessment for transport, 5) more efficient recycling, 6) simplified residual value determination, and 7) streamlined trade of used/waste batteries. Five additional potential use cases could be realized if the passport is integrated with traceability systems and data aggregation: increased end-of-life collection, efficient data exchange, industry benchmarking, accurate market overview, and informed policy design. Quantified benefits include cost reductions (e.g., 10–20% in recycling), increased secondary material availability, improved safety, and reduced environmental impact (e.g., up to 20% of electric vehicle battery material demand met by recovered materials by 2045). [48]

The battery passport improves the value chain by enabling upstream, downstream, and roundstream benefits. Upstream, it fosters competition and innovation through transparent ESG profiling and supply chain visibility. Downstream, it optimizes end-of-life management, supports efficient recycling, and enables better allocation of batteries for reuse, remanufacture, or repurposing. Roundstream (system-wide), the aggregation of passport data allows for benchmarking, market analysis, and policy development, driving a more circular, resource-efficient, and resilient battery ecosystem. The passport also supports digitalization, enabling automated data flows and integration with other DPPs in the future. [48]

Even though the battery passport specification has been completed and released as a standard [49], several uncertainties remain. The EU Battery Regulation will be supplemented by multiple delegated and implementing acts to clarify methodologies (e.g., for carbon footprint, recycled content, performance thresholds, and data access). Technical challenges include harmonizing standards, ensuring data security, and managing large data volumes. SMEs may face higher relative implementation costs. Open questions include how to handle dynamic data updates, integrate voluntary data attributes, aggregate data across passports, and manage access rights. The passport is expected to serve as a blueprint for other DPPs in sectors like textiles, electronics, and vehicles, with learnings from its deployment informing broader EU policy and industry practice. [47], [48]

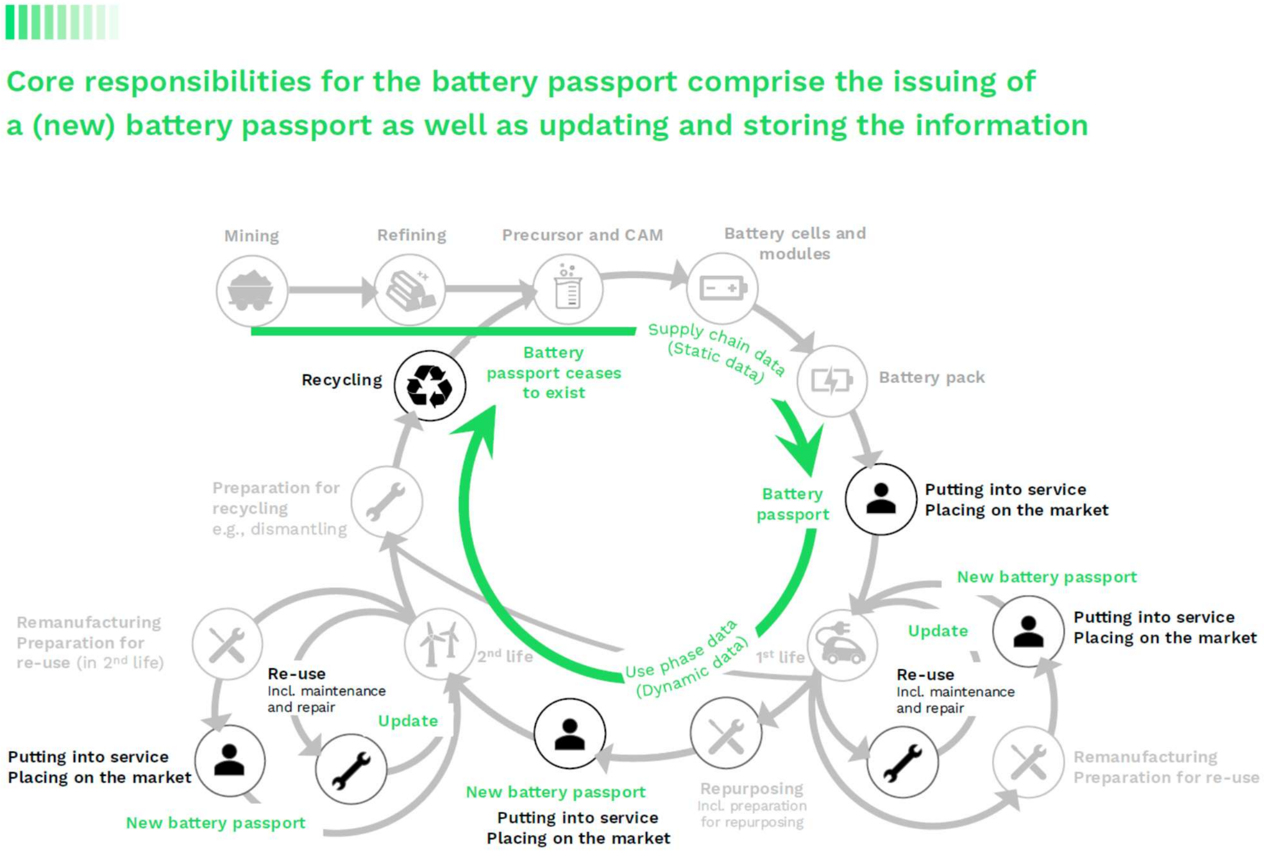

Figure 2. Illustration of the battery passport model. Adapted from [47].

3.2 Textile DPP

The European Union is exploring the introduction of DPP for textiles as part of its broader strategy for sustainable and circular textiles. The DPP aims to enhance traceability, transparency, and circularity throughout the textile value chain, providing detailed information about products from production to end-of-life. This initiative is seen as a key enabler for the transition from a linear to a circular economy in the textile sector, aligning with both regulatory requirements and growing consumer demand for transparency and sustainability.

Several prominent initiatives are shaping the development of textile DPPs, each with unique approaches and objectives. Notable European initiatives include EON [50], BCome [51], circular.fashion [52] and CIRPASS (which also explored DPP for batteries) [53]. These projects are driven by a mix of industry, brand, and national interests, and are designed to enhance transparency, traceability, and sustainability across textile supply chains. For example, BCome focuses on responsible supply chains and transparency, while circular.fashion emphasizes recycled fabrics and circular business models. CIRPASS, supported by the European Commission, aims to establish cross-sectoral standards (common rules for electrical and electronics as well as battery sectors), whereas initiatives like EON leverage blockchain to ensure secure, transparent data sharing and traceability. The initiatives differ in technical architecture, data openness, and functional scope. While all of them aim for transparency and sustainability, their approaches to data granularity, interoperability, and user accessibility differ, reflecting varying priorities and technological strategies.

The DPP is designed to serve multiple use cases across the textile life cycle. For consumers, it provides accessible information to make informed purchasing decisions and manage the textiles at end-of-life. For textile companies, it centralizes data to improve resource management, supply chain transparency, and compliance with regulations. The DPP also supports circularity by facilitating repair, resale and recycling of garments and other textiles, as well as tracking after-sales activities. Authorities and certification bodies can use the DPP for market surveillance and regulatory compliance, while recyclers and sorters benefit from detailed material information to optimize recycling processes. Overall, the DPP is envisioned as a tool to inform, authenticate, and differentiate textile products, supporting both sustainability and competitiveness.

Looking ahead, the future of DPPs in textiles is promising but faces some challenges. The sector is moving toward harmonized standards, especially with the European Commission's push for cross-sectoral DPPs under initiatives like CIRPASS. Key challenges include achieving interoperability across platforms, ensuring data security and privacy, managing the complexity of global supply chains, and balancing proprietary interests with the need for open, standardized data. Additionally, the successful adoption of DPPs will depend on stakeholder collaboration, technological integration, and the ability to provide value to all participants, from manufacturers to consumers and end-of-life operators. The ongoing evolution of regulations and technology will continue to shape the landscape, with the ultimate goal of fostering a more sustainable and transparent textile industry. [54]

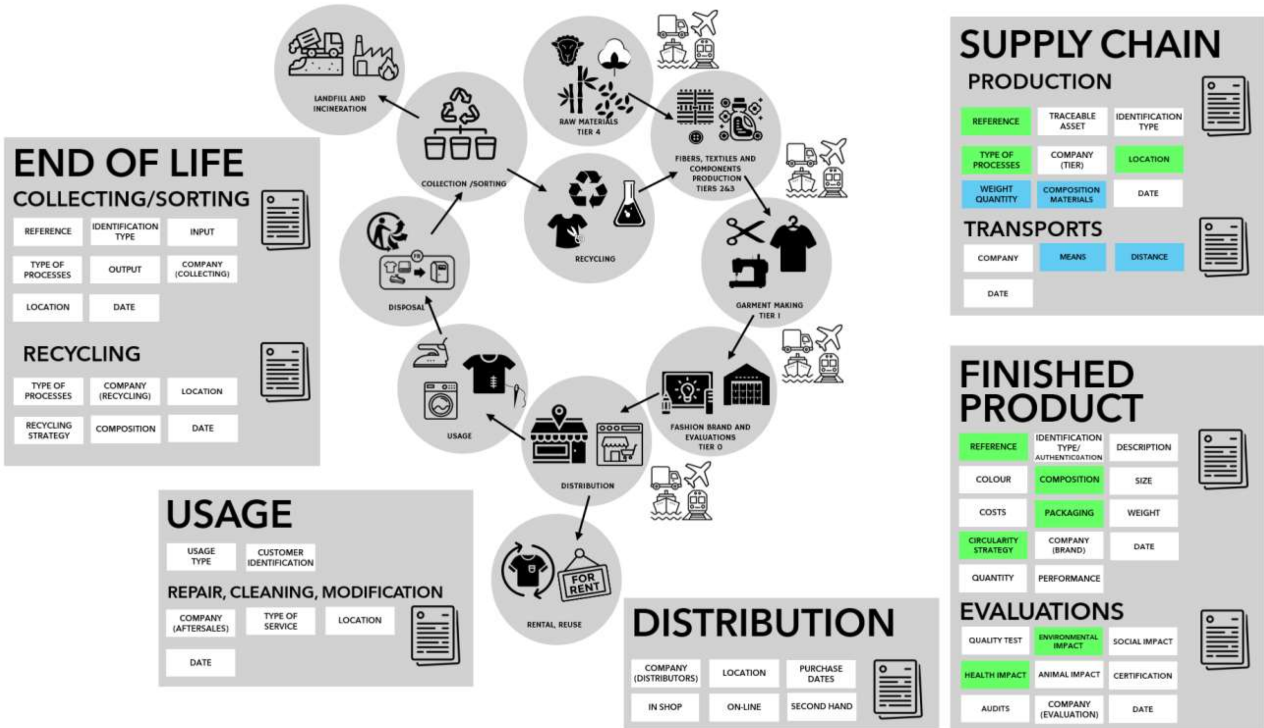

Figure 3. Illustration of a general textile DPP. Adapted from Figure 9 in [54].

4. Cross-sectoral insights: data-driven circularity in electronics, food and agriculture

DPPs are one way to facilitate circularity through providing intricate knowledge on what the product is, what it is made of, and how it should be recycled. However, since DPP by itself is just a carrier of information, further infrastructure is needed to optimize the value chain. In the following sections, we outline examples of how data-driven circularity and digital solutions are used to enhance the circularity in two different sectors, 1) electronics and electronics waste and 2) food and agriculture. DPPs in these sectors are recognized as key enablers of a more efficient value chain, but a lot of different solutions outside DPPs are also used or visioned.

4.1 Electronics and electrical waste

The rapid proliferation of electronic devices, driven by technological innovation and consumer demand, has led to a dramatic increase in electronic waste (e-waste) worldwide. In 2022 alone, 62 million tonnes of e-waste were generated, with projections indicating a rise to 82 million tonnes by 2030. This surge is not only an environmental concern but also a resource management challenge, as electronics contain valuable and often scarce materials. The traditional linear "take-make-dispose" model is increasingly unsustainable, prompting a global shift toward circular economy principles that prioritize resource optimization, waste minimization, and long-term sustainability. Data-driven and digital solutions to facilitate the circularity in this domain has been recognized. Some examples of academical work related to the topic are given below, based on recent review articles [55], [56], [57].

A key use case for envisioned for digital solutions in the sector is the implementation of advanced tracking systems and reverse logistics platforms. Technologies such as the Internet of Things (IoT), blockchain, and big data analytics can be used to monitor the movement of electronic products throughout their life cycle, from production to end-of-life. These systems enable real-time data collection on product usage, location, and condition, which supports efficient take-back schemes, enhances transparency, and helps prevent illegal dumping or informal recycling. For example, digital platforms can facilitate the coordination between manufacturers, consumers, and recyclers, ensuring that e-waste is collected and processed through formal channels.

Data-driven automation is transforming the sorting of e-waste. Machine learning and robotics are being applied to identify, separate, and dismantle complex electronic devices, improving the recovery rates of the significant amounts of valuable and critical materials present in the devices. Automated systems could analyze product composition and optimize disassembly sequences, reducing labor costs and exposure to hazardous substances. These technologies can support the extraction of secondary raw materials, which can be reintroduced into manufacturing processes, thus closing the material loop and reducing reliance on virgin resources.

Digital tools can also be used to engage consumers and ensure compliance with extended producer responsibility (EPR) policies. Mobile applications and online platforms can educate users about proper disposal methods, incentivize returns through rewards or discounts, and provide information on the environmental impact of e-waste. Furthermore, data analytics can support policymakers and companies in monitoring collection rates, identifying gaps in infrastructure, and evaluating the effectiveness of recycling programs. These insights are crucial for designing targeted interventions and improving the overall efficiency of e-waste management systems.

4.2 Food and agriculture

The global food and agriculture sector faces multiple challenges, including population growth, resource scarcity, environmental degradation, and the urgent need for sustainable food systems. Again, linear models of production and consumption are increasingly unsustainable, prompting a shift toward circular economy principles, where waste is minimized, resources are reused, and value is retained throughout the supply chain. Central to this transformation is the adoption of data-driven approaches, leveraging digital technologies to optimize resource use, enhance productivity, and close material loops in agri-food systems. Below are some examples of use cases [58], [59], [60].

A central use case for data-driven and digital solutions in agriculture is the precise management of critical resources such as soil and water. Big data analytics, IoT sensors, and wireless sensor networks (WSNs) are used to monitor soil nutrient levels, pH, and moisture in real time, enabling tailored fertilizer recommendations and irrigation scheduling. For example, machine learning models process sensor data to optimize fertilizer application and maintain soil fertility, while IoT-based systems and WSNs support efficient water use by predicting water needs and automating irrigation, even in water-scarce regions. These technologies are deployed in both open-air and controlled environments (e.g., greenhouses, hydroponics, aquaponics), supporting sustainable intensification and reducing resource waste.

Digital solutions enable continuous monitoring of crop growth and animal health, supporting yield prediction and quality assurance. Smart farming systems integrate data from climate sensors, remote sensing (satellite and drone imagery), and on-farm devices to forecast yields, detect plant diseases, and assess crop quality. Machine learning and deep learning models are widely used for these tasks, such as predicting tomato or wheat yields using multi-source data or identifying diseases and pests from image data. In livestock and aquaculture, sensor networks and computer vision track animal behaviour, health, and environmental conditions, enabling early intervention and improved welfare.

Autonomous robotic systems, including unmanned ground vehicles (UGVs) and drones (UAVs), are increasingly used for automating repetitive and labour-intensive tasks. These robots perform seeding, spraying, weeding, harvesting, and even pollination, often guided by AI-based perception systems that process sensor and image data. For example, drones equipped with multispectral cameras monitor crop health and guide targeted pesticide application, while ground robots use computer vision for weed detection and mechanical removal. Such automation not only increases efficiency and reduces labour costs but also supports precision agriculture by minimizing input use and environmental impact.

Data-driven solutions extend beyond the farm gate to optimize agri-food supply chains. Big data platforms and blockchain technologies are used to enhance traceability, ensuring food safety and transparency from production to consumer. These systems track product origin, monitor storage and transport conditions, and enable rapid response to contamination or recalls. Additionally, analytics are applied to identify sources of food waste throughout the supply chain, from farm to retail, supporting targeted interventions to reduce losses and improve sustainability. Retailers and producers use consumer data and social media analytics to adjust supply, reduce overproduction, and better match market demand.
A recurring theme is the integration of diverse data sources (climate, soil, crop, animal, market, and genomic data) into decision support systems that aid farmers, managers, and policymakers. These systems leverage cloud computing, edge/fog computing, and AI to provide actionable recommendations for resource allocation, risk management, and operational planning. However, the

review articles also highlight challenges such as data interoperability, standardization, cybersecurity, high initial costs, and the need for user-friendly interfaces. Most advanced solutions remain at the prototype stage, with further research needed to address technical and socio-economic barriers and to scale up adoption, especially in complex or resource-limited settings.

5. Data sharing technologies: background, opportunities, challenges, and regulation

Data sharing is the practice of making data available to other individuals, organizations, or systems for analysis, collaboration, or reuse [61]. It enables improved transparency, efficiency, and innovation by allowing authorized parties to access, utilize, distill and elevate shared data into more valuable and actionable insights. That is, data sharing leverages a common data pool to transform shared data into meaningful information, deeper knowledge, and practical wisdom, thereby advancing collective intelligence.

Data sharing has evolved from simple transfers between computers to a complex ecosystem that fuels the modern digital economy. While the fundamental concept of sharing information to accelerate progress has existed for centuries, digital, cloud and data space technologies have made it more efficient and widespread than ever. This section outlines the historical context, current state, and the key challenges and opportunities in data sharing.

5.1 Background of data sharing

The history of data sharing is rooted in the human need to disseminate information. Early forms included cave paintings and the development of written language. The Gutenberg printing press marked a revolution, allowing for the mass reproduction of texts and accelerating the spread of knowledge. With the advent of modern data sciences in the digitalized world, a repeating phrase has become ”the value is in data” that has been demonstrated with the power of data reuse in the fostering artificial intelligence (AI) context.

The digital era and digital data sharing has begun since invention of a computer. The digital era began with the World Wide Web (www) in the late 1980s, enabling data transfer through standardized protocols like Hypertext Transfer Protocol (HTTP). The 1990s and 2000s saw the rise of websites as repositories of data, followed by the development of Application Programming Interfaces (APIs) around the late 2000s, which allowed for programmatic, real-time sharing of data between businesses. This has laid the foundation for the Big Data and Internet-of-Things revolutions (see Figure 4) followed by the current hypergrowth in AI evolution and deployment.

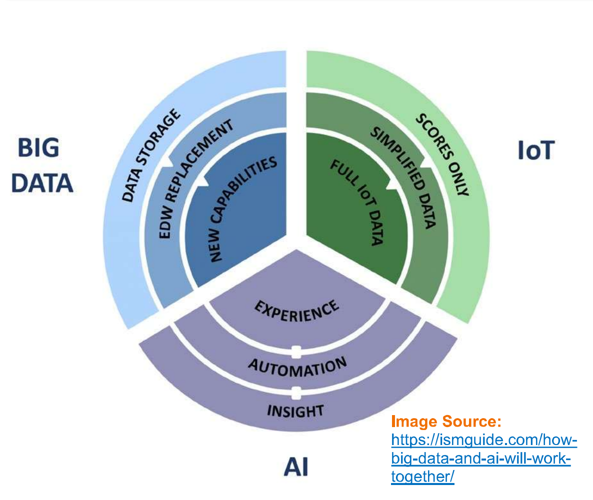

Figure 4. Data sharing for mutually beneficial purposes in Big Data, IoT and AI contexts. Adapted from [62].

5.2 Opportunities and challenges

Data sharing promotes innovation. It accelerates research, enables collaborative problem-solving, and drives the development of new data-driven products and services by allowing organizations and researchers to access, combine, and analyse diverse datasets. It also enables large-scale research projects, like those focused on global climate change and resource-scarce societal challenges, that require data from multiple sources. Ultimately, it empowers collective intelligence and supports the development of more effective solutions to complex challenges supporting long-term resilience for all communities.

Data sharing is an enabler for cost reduction and improved efficiency. It enhances collaboration, reduces duplication of effort, and supports evidence-based decision-making. By pooling resources and data, organizations can develop more efficient processes, especially in areas like circular economy, supply chain management and fraud detection.

Having said “the value is in data”, data itself has become a valuable asset. The rise of data marketplaces and platforms allows organizations to monetize their data holdings. By improving data transparency and availability, data sharing fosters trust (e.g., in material origin traceability), drives operational efficiency, and unlocks new opportunities for value creation across sectors together with new business models.

While the benefits of data sharing are clear, significant challenges must be addressed for it to reach its full potential. One of the fundamental data sharing obstacles focuses on privacy and security. Sharing sensitive information introduces risks of data breaches and unauthorized access. Navigating, understanding, applying and complying successfully with complex and evolving regulations like General Data Protection Regulation (GDPR) [63] and California Consumer Privacy Act (CCPA) [64] is a major hurdle in legal, administrative and technical perspectives all together. Shared data might become a tool that discloses business critical information either directly or nowadays more worryingly indirectly in the accumulated semi-hidden form embedded in AI data models.

Data sharing introduces a new legal and ethical complexity layer. Determining data ownership, ensuring proper consent, and establishing fair value distribution for shared data can be a legal and contractual stipulation minefield. Things get even more complicated when scrutinizing ownership, usage tracing and economic benefits of the results inferred from the shared data. The responsible use of data and derived outcomes must be formally established to maximize collective advantage benefitting every partner fairly.

A tangible real-life data sharing challenge is in technical barriers. Though an organization might have good capabilities and resources in digitalized data-driven systems, the established infrastructures can still be inadequate for data sharing purposes due to, for example, non-standardized data formats and poor data quality. Ensuring that data is well-documented and contextualized properly is crucial to its usability. In short, technical shortcomings frequently hinder the seamless exchange of data. The last but not the least obstacle is in organizational and cultural resistance. A lack of trust, fear of losing a competitive advantage, and the cost of as well as resources required for preparing data for sharing act as a straightforward justification in a strong "no go" decision in data sharing.

Data collection, storage, and processing have significant environmental implications, primarily due to the energy demands of data centres and the life cycle of digital infrastructure. Globally, data centres consumed an estimated 415 terawatt hours (TWh) of electricity in 2024 (ca. 1.5% of total global electricity use) and this figure is projected to more than double by 2030, reaching up to 945 TWh, driven by AI and cloud computing growth [86]. In addition to energy consumption, the production and disposal of hardware involve resource extraction and e-waste generation, further increasing the environmental burdens of digital data-based systems (see e.g. [87]). In addition to energy, large amounts of water are also required to operate data centres, both directly for liquid cooling and indirectly to produce electricity, For example, data centres are among the top-ten water consuming industrial or commercial industries in the USA [88]. These statistics highlight the importance of minimizing unnecessary data collection and adopting efficient cooling and energy strategies to reduce environmental impacts.

To enable organizations to leverage the potential value of their data and take advantage of it, all the parties involved, including data producers, owners and consumers, must have a strong reciprocal rationale for data sharing. To solve the trustor–trustee dilemma, all the contributing parties must commit to transparency on data usage and results deployment in a verifiable way to establish mutual trust[1] and trustworthiness[2]. These require a clear consensus of coverage of costs and risks, benefits (both financial and non-financial) and legal requirements to leverage the data economy and larger societal goals.

Organizations that embrace a data-sharing culture will be better positioned to adapt to change, outperform competitors, and create sustainable long-term growth.

5.3 Data sharing and regulation

In addition to profound mutual business interests, there is an increasing number of regulations enforcing data sharing. Starting in 2025, the European Union requires large organizations through the Corporate Sustainability Reporting Directive (CSRD) [66] to report Scope 1, 2, and 3 emissions (see Figure 5) using the European Sustainability Reporting Standards (ESRS), which are harmonized with the GHG Protocol. The CSRD requires organizations to disclose detailed, standardized sustainability data, including environmental, social, and governance (ESG) metrics. In turn, this creates a demand for high-quality, interoperable, and machine-readable data across organization value chains. The CSRD itself places strong emphasis on data integrity, governance, and digitalization. This implies that the organizations must utilize robust data management systems

[1] **Trust** as defined in the standard ISO/IEC 25002:2024: Degree to which a user or other stakeholder has confidence that a product or system will behave as intended.
[2] **Trustworthiness** as defined in the standard ISO/IEC TR 24028:2020: Ability to meet stakeholders' expectations in a verifiable way.

to ensure accuracy, traceability, and auditability of ESG data promoting cross-functional collaboration to meet the reporting obligations. In turn, these requirements push towards data sharing technologies and automation, including e.g. cloud platforms, analytics and AI, to streamline data collection and reporting processes.

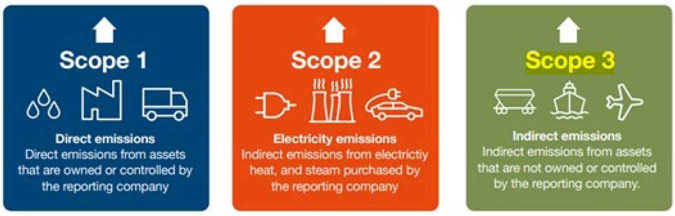

Figure 5. Scope 1, 2, and 3 emissions in GHG assessment. Adapted from Figure 5 on page 11 in [67].

Though the CSRD is distinct, it is interconnected strongly to other EU regulations, including the EU Data Act [68] and EU Data Governance Act (DGA) [69], [70] (see Table 1).

Table 1. Data sharing interconnection between Data Act, Data Governance Act and CSRD

EU Directive	Role	Link to CSRD
Data Act	Ensures access, portability, and interoperability of data	Supports technical infrastructure for ESG data collection and sharing
Data Governance Act	Builds trust and ethical frameworks for data use	Enables secure, voluntary, and public-good use of sustainability data
CSRD	Mandates ESG data disclosure	Relies on robust data governance and digital tools to meet reporting standards

The Data Act provides the technical and legal infrastructure to support the data flows needed for CSRD reporting. It complements CSRD by facilitating access to data across sectors and stakeholders, including public authorities, which may use sustainability data for policymaking and enforcement. Secondly, it promotes interoperability of data formats and systems, which is crucial for CSRD compliance, especially when integrating ESG data from multiple sources, including but not limited to suppliers and subsidiaries. Thirdly, it supports data sharing obligations required in sustainability reporting, especially in sectors like energy, transport, and manufacturing where IoT and sensor data are relevant data sources for environmental metrics acquisition.

The DGA supports governance, trust, and ethical use of data, which are essential for credible and transparent CSRD disclosures. It establishes frameworks for data altruism, data intermediaries, and public sector data reuse. All these support sustainability goals of CSRD. Firstly, data altruism mechanisms encourage voluntary sharing of ESG-related data for public good, research, or benchmarking. Secondly, trusted data intermediaries enable organizations to manage and share sensitive sustainability data securely and in compliance with CSRD. Thirdly, public sector reuse of data, including environmental impact data, enhances transparency and comparability in sustainability reporting.

As a summary, data sharing is a common denominator in many regulatory contexts nowadays. For example, the EU CSRD requires data sharing and aligns with both the EU Data Act pushing for interoperability and the EU DGA focusing on trustworthy data ecosystems.

5.4 State-of-the-art of data sharing technologies

Today, data sharing is a cornerstone of business operations and research. The modern data sharing landscape is defined by the following technologies and concepts:

- *Cloud-based data marketplaces*, such as Snowflake, Databricks, and Amazon Web Services (AWS), offer data-sharing-as-a-service (DSaaS), enabling organizations to easily buy, sell, and share curated data feeds without the need for complex Extract, Transform, and Load (ETL) processes.
- *Privacy-enhancing technologies*, including for example homomorphic encryption, secure multiparty computation and data masking, allow organizations to analyze encrypted data without decryption, addressing key privacy and security concerns.
- *Data clean rooms* provide secure, neutral environments where multiple parties can jointly analyze data without exposing their raw datasets. This is especially valuable for collaborative analytics and fraud detection.
- *Decentralized architectures*, such as data mesh, treat data as a product and empower business units to manage and share their data independently, improving accessibility and ownership compared to the traditional centralized data warehouses or lakes.
- *AI systems*, especially proliferating Large Language Models (LLMs), are drivers for the growing demand for high-quality shared data. For AI systems to generate dependable and meaningful inferences, it is imperative that they are trained and operated using data that is both accurate and trustworthy. The quality, quantity and reliability of the underlying data have a direct influence on the validity of the conclusions drawn by these systems. That is, inadequate, inaccurate or untrustworthy data can propagate errors throughout the inference process impairing the credibility of the system's outputs ultimately.

Table 2 summarizes examples on data sharing approaches utilized in the industry world. These vary from manual file transfer procedures to more automated interfaces and service platforms. The evolving data sharing landscape is defined by a shift towards more decentralized, secure, and collaborative data ecosystems. While traditional methods like data warehouses and APIs are still widely used, the focus is moving to new frameworks that prioritize data sovereignty and trust. Data space technologies are the leading-edge innovation in this field. They are decentralized, governed environments that enable secure and trustworthy data transactions between multiple participants. Unlike centralized data platforms, data spaces do not aggregate data into a single location. Instead, they provide a set of common rules, standards, and technical building blocks that allow data providers to maintain control over their data while making it available for use under specific, agreed-upon conditions.

Table 2. Contemporary data sharing approaches.

Method	Main use	Pros	Cons
PDF / Excel files, email, FTP[3]	Manual data transfer; task-based	Simple; widely used and supported	Inefficient; time consuming; copy-paste in/out systems
APIs, EDI[4]	Applications, systems and software in general	Near real-time; high maturity	Need to agree separately (rigid) point-to-point data sources
Data platforms, ERP, MES[5]**, WMS**[6]**, etc.**	For a specific purpose; Platform-as-a-Service (PaaS) / System-as-a-Service (SaaS) deployments	High maturity, data centricity, analytics	Data overseas; big organizations dictate data sharing rules; fragmented security schemes; expensive
Data lakes, data warehouses	Merge collections of databases under company IT	High maturity, high security; enables wider (cloud) analytics	Not for many-to-many data sharing networks
Proprietary collaboration platforms	Supply chain mgt; uniform communication; order & offer tracing, etc.	Network-based data sharing; fit-for-the-purpose; analytics and optimization	Centralized; potential lock-in; new vertical integration is a challenge
Data spaces (open)	Many-to-many over multiple organizations; data for reuse; EU data economy model	Data economy enabler, no lock-in, sovereignty, interoperable, multiple verticals, traceable, governance, value sharing, low barrier	Emerging maturity; requires trust and clearing houses; IT-competence needed; incomplete cybersecurity audits; EU-oriented; EU Data Act biased

Data spaces are built on four key pillars:

- *Governance*: A framework of legal, administrative, and contractual rules that defines the rights and obligations of participants.
- *Trust*: Mechanisms like decentralized identity management and verifiable credentials to ensure that participants and their data are trustworthy.
- *Interoperability*: The ability for different systems and datasets to communicate and exchange information seamlessly.
- *Data Sovereignty*: A core principle that ensures data owners can control who accesses their data and under what conditions.

[3] File Transfer Protocol (FTP)
[4] Electronic Data Interchange (EDI)
[5] Manufacturing Execution System (MES)
[6] Warehouse Management System (WMS)

While data spaces offer a promising model for a data-driven economy, their real-life implementation is complex due to several *key challenges* as follows:

- *Interoperability* is a major technical hurdle in data spaces. Data from different organizations often use disparate formats, standards, and protocols. Without a common language, connecting these systems is difficult and costly, leading to fragmented data ecosystems.
- *Trust and data sovereignty* still involve open questions at a detailed level in real life. Organizations are hesitant to share valuable data if they can't control its usage in fully transparent manner. Establishing trust among participants and ensuring that data providers maintain full sovereignty over their data is a fundamental requirement. The target is in defining who can access it and for what purpose.
- *Governance* based on a clear, fair, and legally sound framework is essential. In addition to the technical methodology aspects, it includes defining rules for data access, intellectual property, liability, and dispute resolution. However, formulating mutually acceptable governance rules is usually a lengthy process. Without the governance rules, data spaces cannot function as a reliable marketplace.
- *Scalability* has been a limiting issue in real world data spaces. As data spaces grow, they must be able to handle a high volume of transactions and a large number of participants without compromising performance or security. Each new connection point is a potential vulnerability, and ensuring a robust security posture across a decentralized network is a complex task.
- *Lack of standardization* has slowed down wide deployment of data spaces. The developing field of data spaces has seen various initiatives and projects, including for example International Data Spaces (IDS), but a lack of a unified standard has hindered broad adoption and cross-sector collaboration. Even many cutting-edge organizations are waiting for established standards and appropriate commercial tools, platforms and services before initiating small-scale data spaces experiments or committing to operational environment deployments seriously.

With respect to better guidance on principles in a fair data economy, including models for legal, business, governance, technical and ethical aspects, national Finnish organizations SITRA [71] and Business Finland [72], [73] have published rulebooks for creators and users of data spaces.

The European Commission has also identified and acknowledged the data spaces challenges depicted above. To address these, the European Commission has commenced an open-source initiative, called Smart Middleware Platform (SIMPL), that is discussed next. The targeted SIMPL-based solutions are aligned with the emerging standard ISO/IEC 20151 [74] which defines the foundational concepts and essential characteristics of dataspaces, helps organizations distinguish data spaces from other data-sharing models, and sets a foundation for interoperability across implementations. Figure 6 illustrates how ISO/IEC 20151 associates with the EU Data Act and EU Data Governance Act regulations.

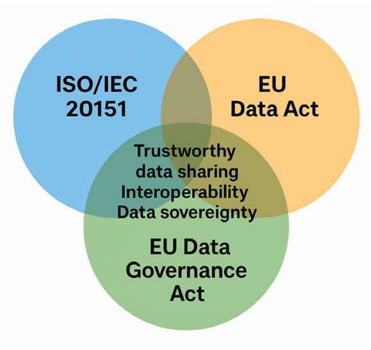

Figure 6. Interconnection between ISO/IEC 20151, EU Data Act and EU Data Governance Act.

5.5 Smart Middleware Platform (SIMPL)

The SIMPL project [75] is a part of the EU Data Strategy, which aims to create a single market for data to boost innovation, competitiveness, sovereignty and the creation of new data-driven services. SIMPL is an open-source middleware platform designed to enable seamless, secure, and interoperable data sharing across diverse sectors and data spaces (see Figure 7). It acts as an intermediate software layer (a "digital backbone") that connects applications, databases, and infrastructures, and supports heterogenous cloud-to-edge continuum in computing environments. It targets lowering technical and legal barriers in deploying data spaces in general.

SIMPL aims to solve the key data spaces challenges as follows:

- *To achieve a solid standard or recommendation acceptance*, SIMPL is a collection of open-source software components designed to make data spaces easier to build and operate. As an open-source platform, it ensures transparency, flexibility, and adaptability. Its modular architecture allows for easy customization and integration with various systems, supporting scalability and continuous improvement.
- *To promote interoperability*, SIMPL facilitates the integration and co-operation of heterogeneous data services, allowing organizations, governments, and researchers to share and access data securely while maintaining control over their own data. By providing a common technical stack, SIMPL helps to harmonize various data space initiatives and promote interoperability by ensuring that different systems can communicate effectively. This is similar to how an operating system provides a consistent environment for different applications.
- *To enhance trust and data sovereignty*, SIMPL provides the technical building blocks for enforcing data usage policies through smart contracts and automated control mechanisms. This allows data providers to programmatically define and enforce the conditions under which their data can be used, ensuring they maintain control and sovereignty even after the data is shared.
- *To build a common foundation for governance*, SIMPL provides a reference architecture and technical capabilities that support a variety of governance frameworks. Though SIMPL does not define the governance model itself, it includes tools for identity management and policy enforcement, which are crucial for any data space to function under a clear set of rules. It facilitates onboarding, cataloging, and contract management between data providers and consumers. As a result, data owners have technical means to retain full control over access, usage, and sharing conditions, ensuring compliance with EU regulations such as GDPR and the Data Governance Act.
- *To promote scalability and flexibility*, SIMPL's modular, open-source nature means that it can be adapted to the specific needs of different application domains and scaled to accommodate a growing number of participants and data flows. The platform is being developed to be "cloud-to-edge federated," allowing for seamless data exchange across diverse computing environments.

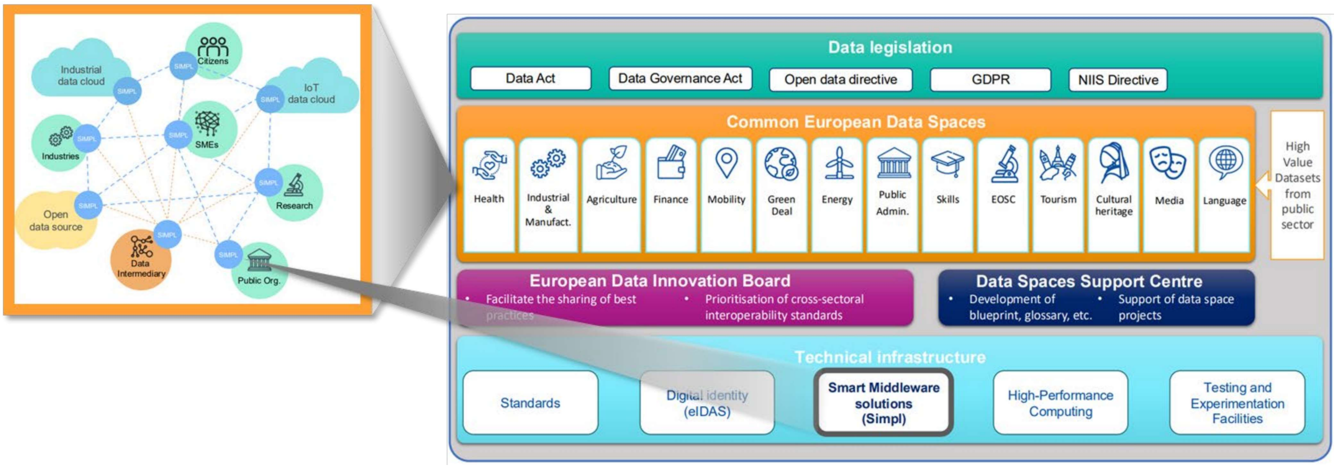

Figure 7. SIMPL in common European data spaces stack. Adapted from pages 4-5 in [76].

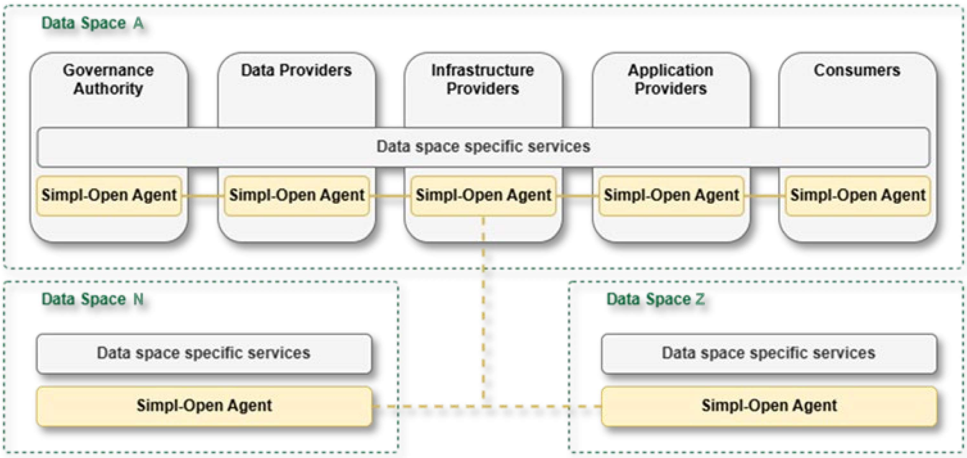

Figure 8. A high-level example on interoperability between data spaces using SIMPL. Adapted from page 3 in [77].

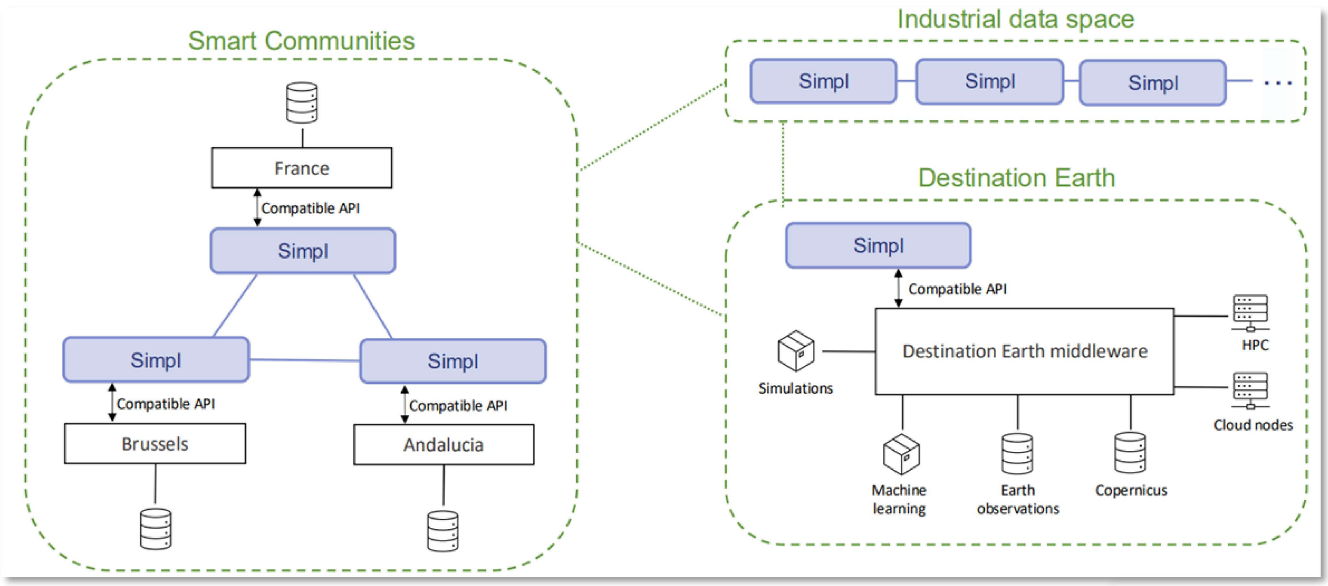

Figure 9. A high-level example on interoperability between various application domains using SIMPL. Adapted from page 9 in [76].

5.6 Examples of data spaces

Aligned with the European data strategy, the European Commission is funding the concept of Common European Data Spaces in 14 application domains/sectors, including Green Deal / Circular Economy, to harness the value of data for the benefit of the European economy and society (see Figure 10). These data spaces include both IDS-based (like GREAT and AD4GD[7]) and non-IDS-based (like Common European Data Space for cultural Heritage - Europeana) solutions.

Agriculture	AgriDataSpace, Divine, CrackSense, ScaleAgData, AgDataValue, 4Growth, Dig4Live
Cultural Heritage	Common European Data Space for Cultural Heritage, Eureka3D, 5Dculture, DE-BIAS, AI4Culture, XRCulture, 3DBigDataSpace, RCtoDC, Lip3D
Energy	IntNET, OMEGA-X, EDDIE, Enershare, Synergies, Data cellar
Finance	Procurement under the Digital Europe programme (under development)
Green deal	GREAT, AD4GD, B-Cubed, FAIRiCUBE, USAGE, **Smart cities and communities** DS4SSCC DS4SSCC-DEP (under development) SAGE (Sustainable Green Europe Data Space
Health	**European Health Data Space:** MyHealth@EU HealthData@EU Pilot Joint Action Towards the European Health Data Space – TEHDAS **Cancer images:** EUCAIM **Genomics:** GDI
Language	European language data space
Manufacturing	Data Space 4.0 SM4RTENANCE UNDERPIN
Media	TEMS
Mobility	PrepDSpace4Mobility deployEMDS
Public administration	European Legal Data Space OOTS - Once Only Technical System Public procurement: PPDS
Research and Innovation	The European Open Science Cloud (EOSC), Skills4EOSC, EOSC Focus, FAIR-IMPACT, RDA TIGER, FAIRCORE4EOSC, AI4EOSC, EuroScienceGateway, FAIR-EASE, RAISE, SciLake, EOSC4Cancer, GraspOS, CRAFT-OA, AquaINFRA, Blue-Cloud 2026, OSCARS, EVERSE, OSTrails, EOSC Beyond, EOSC-ENTRUST, SIESTA, TITAN
Skills	DS4Skills EDGE-Skills (under development)
Tourism	Deploytour DATES (past preparatory action)

Figure 10. EU-funded Common European Data Spaces. Adapted from [78].

With respect to IDS-based approaches as illustrated in Figure 11, there are 10 data space initiatives in various development phases in circular economy context, and two of these, including Dataspace Lab and Green Deal Dataspace, are already in the operational state.

[7] GREAT aims to establish the Green Deal Data Space, and AD4GD integrates to the Green Deal Data Space.

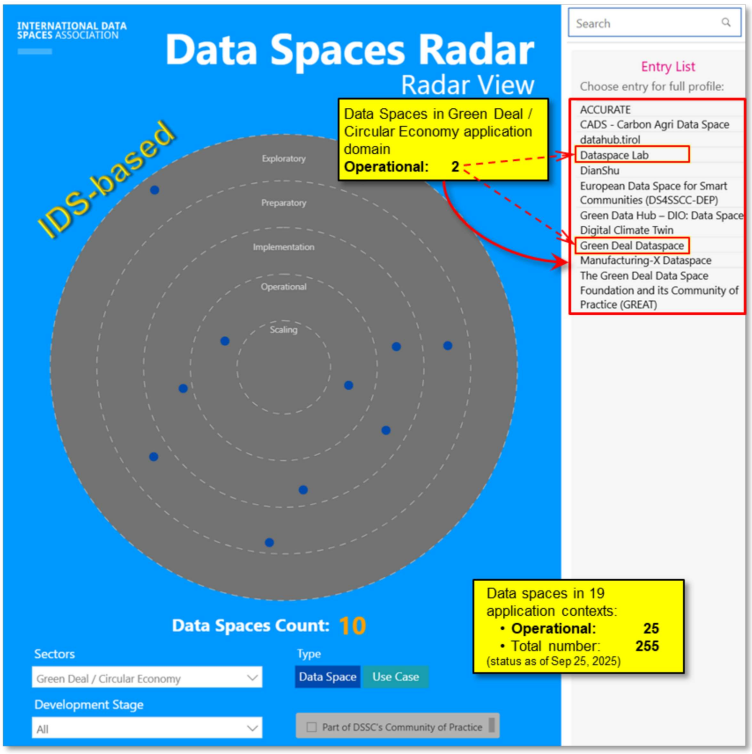

Figure 11. Existing IDS-based data spaces in Green Deal / Circular Economy. Adapted from [79].

With robust data sharing technologies in place, data becomes a true enabler for circular strategies.

6. Practical viewpoints on traceability

As stated already in the previous sections of this report, traceability is widely recognized as a key enabler for implementing circular economy principles in complex value chains such as plastics. In this section, the focus shifts from theory to practice: how value chain actors perceive the role of data and traceability in implementing circular solutions, such as reuse, recycling, rethinking, and reducing. Traceability is seen from a generic viewpoint, as any kind of information or data increasing the transparency within the value chain of plastics. These viewpoints, collected by Horn and Silvennoinen [1] highlight what the transition from a linear to a circular model demands in terms of information flows and digital tools within and across companies. The interviewed actors comprise plastic value chain companies in Finland and Europe, such as raw material manufacturers, packaging companies, brand owners and recyclers. In addition, public sector actors and NGOs in the field were interviewed.

6.1 General viewpoints on plastic value chain, traceability and circular economy

The plastics value chain is seen by actors as highly challenging, given its extensive length and fragmented structure, in comparison to many other value chains. The plastic value chain starts with the production of fossil- or bio-based raw materials and continues through multiple processing stages. Plastics are incorporated into a substantial range of products, making the production and use phases highly diverse, before ending in waste management activities such as recycling, incineration, or landfill. The complexity of the materials flows is increased by the variety of functional requirements associated with different product types, e.g. packaging for food, toys, or cleaning supplies, or medicinal products, which often necessitate multi-material solutions that are difficult to recycle [82].

According to the interviews carried out by Horn and Silvennoinen [1], improved traceability across the plastic value chain enables, in general, organizations to monitor material and energy flows, identify environmental trade-offs, and support sustainability claims with data-driven evidence. For the actors, this means decisions on practical CE solutions (e.g., reuse, recycle, rethink, reduce) can, at best, rely on accurate and accessible data, such as material origin, composition, and environmental performance, which follows products through all life cycle stages. For example, manufacturers need information about raw material content and safety characteristics, while recyclers require chemical composition data to optimize their processes. Without such visibility, suboptimal decisions can occur, for example reducing carbon footprint in one stage while increasing it elsewhere.

The interviews reveal that, at current, most efforts in the plastics (especially packaging) sector remain recycling-oriented, with particular attention on improving the efficiency and quality of mechanical and chemical recycling. While reuse models and material reduction efforts, they are generally less widespread. Producers noted that the efforts for material reduction (“rethink”) has reached its limits as lighter designs often compromise recyclability and durability, creating new challenges.

6.2 Drivers for a data-enabled circular economy

From the perspective of plastics value chain actors, implementing circular solutions requires understanding the practical drivers that influence the transition from a linear to a circular economy. These drivers reflect both the opportunities that circular economy offers and the current barriers that limit progress. In this section, each driver is discussed in terms of its motivating factors, existing challenges, and the role of data and traceability in addressing these issues. Traceability emerges as a cross-cutting enabler, providing the transparency and information needed to validate environmental benefits, ensure compliance, support design decisions, and build trust throughout the value chain.

Growing *environmental concerns* are a major driver for circular economy solutions, as circularity is widely seen as a way to reduce environmental impacts. However, recycling processes themselves still have significant environmental footprints, as the output from mechanical recycling may have lower quality, and chemical recycling producing virgin-grade output, remains resource-intensive and energy-demanding. Traceability plays a critical role here by providing data to validate environmental gains, assess material qualities, and optimize recycling processes to minimize environmental impacts. Value chain actors see traceable life cycle data (e.g., environmental footprints, material contents and sourcing) as essential for guiding sustainable design and preventing unintended trade-offs. For instance, reducing the environmental impact of packaging material must not come at the cost of increased food waste due to compromised product protection.

Consumers also play a significant role in driving the transition. There is an apparent rising demand for circular products, especially among consumer-facing brands, as consumers increasingly value and demand recycled material content, recyclability, and lower carbon footprints. Nevertheless, also some consumer resistance is visible, particularly in contexts such as food packaging or hygiene products, where safety concerns about recycled content may appear. Traceability can help overcome these challenges by providing reliable data on material safety and contamination risks, supporting valid carbon footprint calculations across the value chain, and ensuring that marketing claims about recycled content are based on real data. Consumer benefits of traceability include enhanced trust and greater product transparency. Being able to communicate credible information about recycled content, safety, and environmental performance is seen to improve brand value.

Regulatory frameworks are among the most influential drivers for circular economy. EU initiatives such as the Green Deal, Single-Use Plastics Directive, PPWD, CSRD, and ESPR impose requirements for transparency and circularity. These regulations increasingly demand life cycle traceability of supply chains, including product-level data through mechanisms like the DPP. Traceability is therefore essential for compliance and for meeting the growing expectations of regulatory authorities. Detailed traceability may be necessary to meet emerging EU requirements on substantiating environmental claims and providing product-level impact data.

Technological development and design have significant potential to enable circular economy through developing innovative products, processing technologies and packaging solutions. However, current limitations include insufficient capacities for chemical recycling, poor recyclability of materials, and the lack of reuse solutions. Traceability is closely linked to these challenges, as better analytical tools and data systems are needed to understand the composition of waste flows and support technological improvements. Traceability can also support better product design by providing data on product performance during use and end-of-life phases.

Geographical factors also shape circular economy drivers. Restrictions on waste exports by third countries push for more local recycling solutions. At the same time, differences between countries in collection infrastructure, recycling practices, definitions of recyclability, and regulatory frameworks create inconsistencies. These inconsistencies create challenges for companies operating across multiple markets, and affect extended producer responsibility schemes, taxes, standards, and data collection. Traceability can help harmonize these systems by enabling consistent data collection and reporting across regions, supporting more uniform circular economy practices.

Quality and safety considerations are critical drivers, especially in sectors such as food and hygiene. While chemically recycled materials can achieve high quality, mechanical recyclates often fall short, and post-consumer waste streams may contain contaminants, odours, or hygiene risks. Currently, there is insufficient data on the composition of waste flows and potential contaminants. Traceability addresses these gaps by documenting material contents and identifying risks, ensuring that recycled materials meet safety and quality standards for demanding applications. This is particularly important in food contact packaging, medical plastics, or other high-quality applications, where the presence of contaminants poses significant risks. By documenting recycled content and tracking sources, companies can reduce uncertainty and reliance on extensive testing.

6.3 Practical implementation challenges

Plastics value chain actors agree that while traceability holds strong potential to enable circular economy strategies, its value depends on purpose-driven implementation. In practice, this means that data should not be collected merely for compliance but actively used to support outcomes such as improved recyclability, safer secondary materials, regulatory compliance, reuse models, and more efficient collaboration across the supply chain. The value chain actors emphasized that when traceability systems are designed only to meet regulatory requirements, they fail to deliver broader environmental or economic benefits, such as optimizing recycling processes or supporting reuse models. Aligning traceability with circular economy objectives is therefore seen also as a critical starting point for motivating practical implementation.

Currently, the implementation of such traceability or data collection varies significantly, according to the value chain actors. Most companies exchange only limited technical and safety data, such as material specifications and safety data sheets, while broader circularity and sustainability indicators, such as carbon footprint or material content, are inconsistently tracked or shared. A major challenge is that the data provided can be untimely, aggregated at an average level rather than batch-specific, or poorly documented, making it difficult to verify and apply in decision-making. In many cases, datasets lack clarity on calculation methods or system boundaries, which reduces comparability.

These problems are increased by the absence of standardized reporting formats across suppliers. While some stakeholders also raised concerns about misleading claims or greenwashing, a common problem lies in incomplete, outdated, or non-transparent data that limits the practical utility of traceability systems.

Confidentiality concerns and technological fragmentation further complicate implementation. Suppliers are often reluctant to disclose detailed information due to competitive concerns, and even when data is shared, it may be fragmented across different systems and formats, limiting interoperability. Existing technological solutions, such as barcodes, RFID, blockchain, and cloud-based platforms, differ widely in scope and functionality. Many systems focus on identification and storage rather than defining what data is essential for circular economy purposes. Blockchain can safeguard data integrity by preventing post-collection alterations, but it cannot address inaccuracies or biases introduced during data entry. Interviewed actors highlighted that without interoperability and clarity on data requirements, traceability systems risk becoming inefficient and unreliable.

Resource constraints were also repeatedly mentioned, particularly for small and medium-sized enterprises (SMEs), which often lack the financial and technical capacity to implement advanced traceability solutions. Actors expressed concern that without targeted support or simplified approaches, these companies risk being excluded from emerging traceability frameworks. At the same time, the maturity and scope of traceability systems differ significantly across sectors. Industries such as food, medicine, and hygiene packaging already have well-established traceability systems focused on safety, but environmental and social traceability remains underdeveloped. Expanding the scope to include sustainability indicators will require significant investments and alignment with evolving regulatory frameworks, such as the DPP.

Finally, actors emphasized that ensuring the quality and comparability of sustainability data is critical across all these challenges. Current methodologies vary widely, making it difficult to benchmark or verify claims. Improving analytical technologies to identify contaminants and integrating standardized reporting practices will be essential for building trust and maximizing the utility of traceability systems. Without these improvements, traceability risks becoming a compliance exercise rather than a strategic enabler of circular economy objectives.

6.4 The role of data initiatives

Emerging data initiatives are widely regarded as key enablers for improving traceability and supporting circular economy objectives. Among these, the DPP was mentioned as an approach to consolidate product-level information, such as material composition, environmental impact, and compliance data, into a standardized, accessible format across the value chain. This can help recyclers optimize processes, assist manufacturers in making informed design decisions, and enable brands to substantiate sustainability claims. However, a more concrete understanding about what information should be traced is still evolving, and practical implementation remains a challenge.

Public-sector actors regarded ongoing data initiatives as providing solutions to many of the previously discussed drivers and challenges. From their perspective, harmonized regulations, standardized verification mechanisms, and interoperable technologies will create the necessary foundation for transparency and comparability across value chains. They emphasize that initiatives like DPPs can consolidate product-level data on material composition, environmental impact, and compliance, making it accessible throughout the supply chain. This, in turn, is expected to support recyclers in optimizing processes, manufacturers in design decisions, and brands in substantiating sustainability claims.

Private-sector actors, however, remained more cautious. While companies acknowledge the potential of digital tools such as DPPs and blockchain for improving traceability and oversight of material and waste streams, contamination levels, and compliance, they also highlight significant concerns. A significant concern is the costs and resource requirement associated with implementing robust data collection systems, as well as the time and uncertainty involved in aligning these systems with operational realities. Several companies pointed out a perceived trade-off: investing heavily in comprehensive, standardized data initiatives may not always deliver the most efficient environmental improvements. In some cases, more flexible and innovative solutions could achieve circularity goals faster and at lower cost. This view highlights the need for clarity on the strategic purpose of traceability; for traceability to efficiently enable CE, companies must understand its purpose, align it with operational goals, and use it to generate strategic value, not simply comply with external demands. Across all discussions, interviewed actors agreed that the success of data initiatives will depend on balancing regulatory expectations with practical feasibility, ensuring that traceability systems are not only technically robust but also economically viable and strategically aligned with circular economy objectives.

7. Conclusions

In conclusion, this report has highlighted the pivotal role that data could play in advancing the circularity of plastics and other materials. By examining the current landscape of data-driven initiatives, standards, and regulatory developments, it becomes clear that high-quality, accessible data is envisioned to be the foundation for transparency, traceability, and informed decision-making across the entire value chain. Specially the public authorities believe on the role of data as an enabler. In recent years, the concept of the DPP has emerged as a central pillar in the data-driven movement toward a more circular plastics economy. The DPP is envisioned as a structured digital record that accompanies a product throughout its entire lifecycle, capturing essential information about its material composition, recycled content, environmental impacts, and compliance status. By making this data accessible to all relevant stakeholders from manufacturers and recyclers to regulators and consumers the DPP promises to transform how transparency and traceability are achieved across the plastics value chain.

The relevance of such data-driven initiatives on plastics circularity is multifaceted. On one hand, DPPs directly address the growing regulatory demands for detailed product and material information. As the European Union and other jurisdictions introduce stricter requirements for sustainability reporting and circularity, organizations must be able to provide verifiable data on recycled content, lifecycle impacts, and compliance with standards. DPPs offer a practical solution, streamlining the process of data collection, management, and disclosure, and helping companies remain competitive in a rapidly evolving market.

Moreover, the DPP is not just a compliance tool, it has potential to be a catalyst for innovation. By centralizing and standardizing product data, DPPs would enable new business models based on reuse, remanufacturing, and closed-loop recycling. They empower manufacturers to design products with circularity in mind, recyclers to optimize their processes, and consumers to make informed choices. The cross-sectoral applicability of DPPs, already being piloted in domains like batteries and textiles, further underscores their potential to drive systemic change in different domains.

However, a critical examination reveals several challenges that must be overcome for data-driven initiatives to realize their full potential. The implementation of robust data systems can be costly and complex, particularly for small and medium-sized enterprises. Issues of data quality, standardization, and interoperability persist, with inconsistent formats and reporting practices undermining the utility of traceability systems. Confidentiality concerns and technological fragmentation further complicate data sharing, while the risk remains that DPPs could become mere compliance exercises if not purposefully aligned with strategic sustainability and business objectives.

Additionally, the environmental footprint of digital data systems cannot be ignored. The energy and resource demands associated with data collection, storage, and processing introduce new sustainability challenges. Efficient data management and a focus on minimizing unnecessary data collection are essential to ensure that the environmental gains from circularity are not offset by the burdens of digital infrastructure.

In summary, while data-driven initiatives like the DPP are foundational for advancing plastics circularity, their success depends on thoughtful implementation, harmonized standards, and a clear strategic purpose. Only then can the promise of data-driven circularity be fully realized, driving meaningful progress toward a more sustainable plastics economy. Ultimately, the transition to a more circular and sustainable economy will depend on our collective ability to harness the full potential of data by transforming information into action for the benefit of industry, society, and the environment.

8. Summary

This research report explores how data-driven solutions could be transforming the circularity of plastics, emphasizing the growing importance of digital tools, standards, and regulatory frameworks in enabling sustainable practices across the plastics value chain. The report begins by clarifying the concept of data in the circular economy, highlighting its role in transparency, traceability, and informed decision-making. It notes that data can range from broad annual recycling statistics to granular, real-time process measurements, and stresses that high-quality, well-managed data is becoming essential for compliance and competitiveness, especially as new EU regulations demand detailed product and material information.

The document reviews the current state of data-driven initiatives, such as Digital Product Passports, which are being piloted in sectors like batteries and textiles. These passports compile lifecycle data to enhance transparency and support circular business models. The report also discusses advanced technologies that optimize polymer production and recycling, as well as machine vision and robotics for waste sorting.

A part of the report is dedicated to standards and certification systems, such as ISCC PLUS, which ensure traceability and sustainability in recycled plastics. Recent European standards now differentiate between sorted plastics and recyclates and introduce classifications like Data Quality Levels (DQL) for digital trading, paving the way for broader adoption of Digital Product Passports.

Cross-sectoral insights are provided, showing how data-driven circularity is being applied in electronics, food, and agriculture. The report highlights the evolution of data sharing technologies, the opportunities and challenges they present—including privacy, security, interoperability and the regulatory landscape shaped by the EU Data Act, Data Governance Act, and Corporate Sustainability Reporting Directive.

Ultimately, the report concludes that robust data frameworks and collaborative data ecosystems are foundational for advancing plastics circularity. Organizations that invest in these areas will be best positioned to meet regulatory requirements and market demands, driving the transition to a more circular and sustainable economy. However, their success depends on thoughtful implementation, harmonized standards, and a clear strategic purpose for data collection and processing.

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